SHORT COURSE VIII ON EXPLORATION FOR GEOTHERMAL RESOURCES

Nov. 21, 2013 / LSG-PM-IK-AW

Organized by UNU-GTP, GDC and KenGen and held at Lake Bogoria Hotel and Lake Naivasha Sopa Resort, Naivasha, Kenya, 31st October – 22nd November, 2013

Thursday 31st October

Participants arrive and travel to Lake Bogoria Hotel

19:00-22:00 **Opening dinner at Lake Bogoria Hotel**

Friday 1st November

08:00- 08:30 **Registration at Lake Bogoria Hotel**

Opening lectures: Chair – Godwin Mwawongo

08:30-08:45	**Welcoming address – Dr. Silas Simiyu, GDC**			
08:45-09:00	**Aim of the short course – Organization of the course and field work programme**			
	Peter Omenda			
09:00-09:30	**Geothermal manifestations – definitions and information**			
	Lucy Njue	pres.		(101)
09:30-10:00	**Geothermal alteration**			
	John Lagat		paper	(102)
10:00-10:30	*Coffee break*			
10:30-12:00	**Overview of geothermal surface exploration methods**			
	Leaky Ochieng	pres.	paper	(103)
12:00-12:30	**Geological mapping – An introduction**			
	Risper Kandie	pres.	paper	(104)
12:30-13:00	**Geophysical mapping – An introduction**			
	Ammon Omiti	pres.	paper	(105)
13:00-14:00	*Lunch*			

Session cont.: Chair – Cyrus Karingithi

14:00-14:30	**Geochemical mapping – An introduction**			
	Kizito Opondo	pres.	paper	(106)
14:30-15:00	**Geothermal mapping using temperature measurements**			
	Hilary Mwawasi	pres.	paper	(107)
15:00-16:00	**Environmental baseline studies for geothermal development**			
	Gabriel Wetangula	pres.	paper	(108)
16:00-16:30	*Coffee*			

Saturday 2nd November - Geothermal field work

09:00-12:30 **Tour of Ol Kokwe Island in Lake Baringo**
12:30-14:00 *Lunch at Lake Baringo Hotel*
14:00-16:00 **Visit to manifestations around Lake Baringo geothermal prospect**
16:00-16:30 Drive back to the hotel
Session leader: Isaac Kanda/Charles Muturia
Facilitators: Lucy Njue, Risper Kandie

Sunday 3rd November - Geothermal field work

09:00-09:30 Drive to Lake Bogoria
09:30-11:00 **Visit to Lake Bogoria hot springs**
11:00-13:00 **Geophysical measurements - DC/TEM/MT**
Session leaders: Charles Muturia/Ammon Omiti
13:00-14:30 *Lunch break*
14:30-17:00 **Geophysical measurements – Gravity/Magnetics**
Session leader: Charles Ogada/Raymond Mwakirani

Monday 4th November - Geothermal field work

09:00-09:30 Drive to Lake Bogoria
09:30-13:00 **Heat flow measurements**
Session leaders: Urbanus Kioko/Hillary Mwawasi
13:00-14:30 *Lunch Break*
14:30-18:00 **Fieldwork on geochemistry**
Session leaders: Kennedy Kamunya / Jeremiah Kipngok

Tuesday 5th November - Geothermal field work

09:00-16:00 **Drive to Iten to traverse across Kerio Valley, the western flank of the Rift. Study exposed geological structures.**
16:00-18:00 Drive back to Bogoria Hotel
Session leaders: Isaack Kanda/Risper Kandie

Wednesday 6th November

07:00-10:30 Drive to Menengai caldera
10:30-12:30 **Tour Menengai geothermal prospect**
13:30-14:30 *Packed lunch at Menengai*
14:30-19:00 Drive from Nakuru to Lake Naivasha Sopa Lodge
Session leaders: Isaack Kanda, Fredrik Ongeri

Arrival of the Icelandic instructors
Arrival at JKIA – transport to Lake Naivasha Sopa Lodge

19:30-22:00 **Opening dinner at Sopa Lodge NVS - hosted by KenGen**

Thursday 7th November

08:00-09:00 **Registration at Sopa Resort**

Opening Ceremony: Chair – Peketsa Mangi

09:00-10:30 **Opening addresses:**
Geoffrey Muchemi, Geothermal Development Manager, KenGen
Dr. Meseret Teklemariam, ARGeo Program Manager, UNEP
Ludvik S. Georgsson, Director, UNU-GTP
Dr. Silas Simiyu, MD & CEO, GDC
Simon Ngure, Ag., MD & CEO, KenGen
Honourable Davis Chirchir, Cabinet Secretary, Ministry of Energy and Petroleum
10:30-11:00 *Tea break*

Geothermal energy in perspective: Chair – Isaack Kanda

11:00-12:00	**Geothermal energy in the world from energy perspective**			
	Ludvik S. Georgsson	pres.	paper	(201)
12:00-13:00	**Strategies and scenarios for geothermal resource development: The experience of East Africa**			
	Meseret Teklemariam	pres.	paper	(202A)
		pres.		(202B)
13:00-14:00	*Lunch*			
14:00-15:00	**Geothermal systems in global perspective – definitions – the resources**			
	Kristjan Saemundsson	pres.	paper	(203)
15:00-15:45	**Geothermal energy utilization in Kenya**			
	Martha Mburu	pres.	paper	(204)
15:45-16:15	Coffee break			

Hydrology of geothermal systems: Chair – Ludvik S. Georgsson

16:15-17:15	**Basic hydrogeology**			
	Janet Suwai	pres.	paper	(205)
17:15-18:00	**Hydrology and physical processes in geothermal systems**			
	Knutur Arnason	pres.	paper	(206)

Friday 8th November

Geothermal and geological mapping: Chair – Knutur Arnason

08:30-09:30	**Structural geology – tectonics, volcanology and geothermal activity**			
	Kristjan Saemundsson	pres.	paper	(301)
09:30-10:00	**Introduction to types and classification of common rocks**			
	Marietta Mutonga	pres.		(302)
10:00-10:45	**Infrared and satellite images, aerial photography**			
	Joseph Mutua	pres.	paper	(303)
10:45-11:15	*Tea Break*			
11:15-12:00	**Geology and gradient wells**			
	Kristjan Saemundsson	pres.	paper	(304)
12:00-13:00	**Geohazards in geothermal exploitation**			
	Kristjan Saemundsson	pres.	paper	(305)
13:00-14:00	*Lunch*			
14:00-18:00	**Field mapping of geological structures in Olkaria**			
	Risper Kandie and Kristjan Saemundsson			

Saturday 9th November

Geophysical exploration: Chair – Halldor Armannsson

08:30-09:30	**Overview of geophysical methods used in geothermal exploration**			
	Ludvik S. Georgsson	pres.	paper	(401)
09:30-10:30	**Resistivity of rocks**			
	Knutur Arnason	pres.	paper	(402)
10:30-11:00	*Tea break*			
11:00-12:00	**Resistivity methods – DC and TEM**			
	Ludvik S. Georgsson	pres.	paper	(403)
12:00-13:00	**Resistivity methods – MT**			
	Knutur Arnason and Charles Muturia	pres.	paper	(404)

13:00-14:00 Lunch

Session continued: Chair – Ludvik S. Georgsson

14:00-15:30 **Interpretation of geophysical data: TEM – MT**
Processing and interpretation of TEM and MT data, Knutur Arnason
Magnetotellurics (MT), Raymond Mwakirani pres. (405)
15:30-16:00 *Coffee break*
16:00-17:15 TEMTD, a program for separate or joint 1D inversion of TEM and MT data
Knutur Arnason pres. paper (406)
The static shift problem in MT, Knutur Arnason

Sunday 10th November

Session continued: Chair – Kristjan Saemundsson

08:30-09:30 **Gravity and magnetic methods**
Nicholas Mariita pres. paper (501A)
pres. paper (501B)
09:30-10:30 **Seismic methods – refraction and seismic monitoring**
Antony Wamalwa pres. paper (502)
10:30-11:00 Tea break
11:00-12:30 **Geophysical surveys of high temperature fields – a case for Olkaria and Menengai geothermal fields, Kenya**
Nicholas Mariita pres. paper (503)
12:30-14:00 Lunch

Session continued: Chair – Isaac Kanda

14:00-16:00 **Interpretation of geophysical data: Indirect methods and joint interpretation**
Gravity and magnetic methods, Antony Wamalwa
Seismic methods, Antony Wamalwa
3D joint inversion of MT and TEM data, Charles Muturia and
Knutur Arnason pres. paper (504)
16:00-16.30 Coffee break
16:30-17:30 **Case example: Integration of geophysical field data, Hengill area, Iceland**
Knutur Arnason pres. paper (505)
pres.

Monday 11th November

Geochemical exploration: Chair – Dan Odongo

08:30-09:30 **Application of geochemical methods in geothermal exploration**
Halldor Armannsson pres. paper (601)
09:30-10:30 **Geothermal sampling and analysis**
Halldor Armannsson pres. paper (602)

10:30-11:00 Tea break
11:00-11:45 **Geothermometry**
Cyrus Karingithi pres. paper (603)
11:45-12:30 **Monitoring practices**
Sylvia Malimo pres. paper (604A)
pres. paper (604B)
12:30-14:00 Lunch

Session continued: Chair – Wellington Kivure

14:00-15:30	**Computer programs in geothermal geochemistry**			
	Halldor Armannsson	pres.		(605)
15:30-16.00	*Coffee break*			
16:00-17:30	**Case examples: Chemistry in exploration of a geothermal area**			
	Theistareykir high-temp. area, NE-Iceland, Halldor Armannsson	pres.	paper	(606)
	Menengai high-temperature area, Kenya, Isaac Kanda	pres.	paper	(607A)
			paper	(607B)

Tuesday 12th November

Drilling and Resource assessment: Chair – Charles Muturia

08:30-09:30	**Geothermal well drilling**			
	Dickson Munyoki	pres.	paper	(701)
09:30-10:00	**Drilling in the Menengai geothermal field**			
	Lilian A. Okwiri	pres.	paper	(702)
10:00-10:45	**Challenges of preparing prospects in the Kenya rift for deep drilling for geothermal: Case example Olkaria Domes**			
	Kizito Opondo	pres.		(703)
10:45-11:15	*Tea break*			
11:15-12:00	**Introduction to geophysical well logging and testing**			
	Cornel Ofwona	pres.	paper	(704)
12:00-13:00	**Assessment of resource potential with examples from Kenya**			
	Cornel Ofwona	pres.	paper	(705)
13:00-14:00	*Lunch*			

Practical sessions in Geophysics and Geology

14:30-18:00	**Practical sessions in Geophysics and Geological Laboratory**			
	Ammon Omiti and Doreen Njathi			

Wednesday 13th November

Environmental sciences: Chair – Peketsa Mangi

08:30-09:30	**EIA – General procedures**			
	Joshua Were	pres.	paper	(801)
09:30-10:15	**EIA – Example from Bjarnarflag in Iceland**			
	Halldor Armannsson	pres.	paper	(802)
10:15-11:00	**Legal requirements for geothermal energy development – a case study for Kenya**			
	Elizabeth Mwangi-Gachau	pres.	paper	(803)
11:00-11:30	*Tea break*			
11:30-12:15	**Biodiversity conservation, air quality and noise assessment**			
	Thecla Mutia	pres.	paper	(804A)
			paper	(804B)
12:15-13:00	**Socioeconomic aspects of geothermal development**			
	Haron Kiraison			
13:00-14:00	*Lunch*			

Session continued: Chair – James Kahutu

14:00-18:00	**Practical session – Environmental sampling (gas, noise etc.) and a visit to the KenGen environmental laboratory and geochemical laboratory**			
	Kennedy Kamunya and Cornelious Ndetei			

Thursday 14th November

Geothermal power plants and direct use of geothermal: Chair – Elizabeth Gachau

08:30-09:15	**Binary power plants and low-temperature power plants**			
	Martha Mburu	pres.		(901)
09:15-10:00	**Operation and maintenance of power plants**			
	Henry Wesula	pres.		(902)
10:00-10:30	*Tea break*			
10:30-11:00	**Direct use of geothermal energy**			
	Jack Kiruja	pres.	paper	(903A)
		pres.	paper	(903B)
11:00-11:30	**Direct utilization in Kenya – Case study of DUDC Olkaria**			
	Peketsa Mangi	pres.	paper	(904)
11:30-12:00	**Case example from the Oserian flower farm**			
	Martha Mburu	pres.		(905)
(12:00-13:00)	**Geothermal power plants for high-temperature steam (incl. WHG)**			
	Clety Kwambai (actually given on Saturday)	pres.		(1008)
13:00-14:00	*Lunch*			

Linux, WinGlink and mapping resources: Chair – Antony Wamalwa

14:00-14:45	**Linux and free software – advantages and possibilities**			
	Knutur Arnason	pres.		(906)
		pres.		
14:45-15:15	**WinGlink software – advantages and possibilities**			
	Charles Muturia	pres.		(907)
15:15-16:00	**Data presentation and making of maps**			
	Knutur Arnason	pres.		(908)
16:00-16:30	*Coffee break*			
16:30-17:30	**Using GPS in the field**			
	Knutur Arnason			

Friday 15th November

Field trip: Team Leaders –Dickson Munyoki and Peketsa Mangi

07:30-13:00	**Field trip to geothermal utilisation plants and Olkaria geothermal field**
13:00-14:00	*Lunch break – packed lunch*
14:00-17:00	**Tour of Hell's Gate National Park and swimming at DUDC**

Arrival of instructors from other E-African countries.

Saturday 16th November

Status of geothermal exploration in E-Africa: Chair – Peketsa Mangi

08:30-09:15	**Geothermal exploration in Kenya – status report and discussion**			
	Geoffrey Mibei	pres.	paper	(1001)
09:15-10:00	**Geothermal exploration in Ethiopia - status report and discussion**			
	Solomon Kebede	pres.	paper	(1002)
10:00-10:30	**Geothermal exploration in Tanzania – status report and discussion**			
	Taramaeli Mnjokava	pres.	paper	(1003)
10:30-11:00	**Geothermal exploration in Uganda – status report and discussion**			
	Vincent Kato	pres.	paper	(1004)

11:00-11:30 *Tea break*

11:30-12:00 **Geothermal exploration in Eritrea – status report and discussion**
Ermias Yohannes pres. paper (1005)

12:00-12:30 **Geothermal exploration in Djibouti – status report and discussion**
Participants pres. paper (1006)

12:30-13:00 **Geothermal exploration in Rwanda – status report and discussion**
Uwera Rutagarama pres. paper (1007)

13:00-14:00 *Lunch*

Session continued: Chair – Uwera Rutagarama

14:00-14:20 **Geothermal exploration in Burundi – status report and discussion**
Participants pres. (1009)

14:20-14:40 **Geothermal exploration in DR Congo – status report and discussion**
Participants pres. (1010)

14:40-15:00 **Geothermal exploration in Malawi – status report and discussion**
Participants pres. (1011)

15:00-15:20 **Geothermal exploration in Mozambique – status report and discussion**
Participants pres. (1012)

15:20-15:40 **Geothermal exploration in Zambia – status report and discussion**
Participants pres. (1013)

15:40-16:00 **Geothermal exploration in Yemen – status report and discussion**
Participants pres. (1014)

16:00-16:20 *Coffee break*

Session continued: Chair – Vincent Kato

16:20-16:40 **Geothermal exploration in the Comoros – status report and discussion**
Participants pres. (1015)

16:40-17:00 **Geothermal exploration in Sudan – status report and discussion**
Participant pres. (1016)

17:00-17:20 **Geothermal exploration in Nigeria – status report and discussion**
Participants pres. (1017)

17:20-17:40 **Geothermal exploration in Niger – status report and discussion**
Participant pres. (1018)

17:40-18:00 **Geothermal exploration in Cameroon – status report and discussion**
Participant pres. (1019)

Sunday 17th November

Status of geothermal exploration in E-Africa, continued: Chair – Taramaeli Mnjokava

08:30-09:30 **GIS introduction**
Fred Wekesa pres. paper (1101)

09:30-10:30 **Geothermal potential of E-Africa – the way to realise it**
Meseret Teklemariam pres. paper (1102)

10:30-11:00 *Tea break*

11:00-13:00 **Discussions and the way forward – possible approach in various countries in Africa discussed**
- led by Meseret Teklemariam and Knutur Arnason

13:00-14:00 *Lunch*

14:00-18:00 **Free time to go to Naivasha**

Monday 18th November

Planning of geothermal projects: Chair – Ermias Yohannes

08:30-09:30	**What does geothermal cost and the financing of it – the Kenyan experience?**			
	Paul Ngugi	pres.	paper	(1201)
09:30-10:30	**Planning of geothermal projects in Kenya**			
	Paul Ngugi	pres.	paper	(1202)
10:30-11:15	**Practical session – Planning of geothermal projects (A case of KenGen)**			
	Joseph Munyasya	pres.		(1203)
11:15-11:45	*Tea break*			
11:45-12:45	**Planning of geothermal projects in Iceland**			
	Halldor Armannsson	pres.	paper	(1204)
12:45-14:00	*Lunch*			

Case examples: Chair – Solomon Kebede

14:00-14:45	**Geothermal exploration and development of the Olkaria field**			
	Kizito Opondo	pres.	paper	(1205)
14:45-15:30	**Geothermal exploration of the Torfajökull high-temperature field**			
	Kristjan Saemundsson	pres.	paper	(1206)
15:30-16:15	**Geothermal exploration and development of the Krafla high-temperature field**			
	Knutur Arnason	pres.	paper	(1207)
16:15-16:45	*Coffee break*			
16:45-17:30	**Geothermal exploration of the Menengai geothermal field**			
	Geoffrey Mibei			
17:30-18:00	**East African geothermal settings – different types of rifts**			
	Kristjan Saemundsson	pres.	paper	(1209)

Tuesday 19th November

Project work: Team leaders – Charles Muturia and Ammon Omiti
Facilitators – Raymond Mwakirani, Jeremiah Kipngok, Lucy Njue, Risper Kandie, Ammon Omiti, Edwin Wafula

08:30-10:30	**Project work – Organizing groups**
10:30-11:00	*Tea break*
11:00-13:00	**Introducing the projects**
	Ammon Omiti
13:00-14:00	*Lunch*
14:00-17:00	**Project work continuing in organized groups**
15:30-16:00	*Coffee break*

Instructors from other E-African countries leave together with some Icelanders.

Wednesday 20th November

Project work cont.: Team Leaders – Ammon Omiti and Charles Muturia
Facilitators – Raymond Mwakirani, Jeremiah Kipngok, Lucy Njue, Risper Kandie, Ammon Omiti, Edwin Wafula

08:30-13:00	**Project work continuing in organized groups**
13:00-14:00	*Lunch*
14:00-17:00	**Project work continuing in organized groups**

15:30-16:00 *Coffee break*

Thursday 21st November

Project work cont.: Team leaders – Ammon Omiti and Charles Muturia
Facilitators – Raymond Mwakirani, Jeremiah Kipngok, Lucy Njue, Risper Kandie, Ammon Omiti, Edwin Wafula

08:30-13:00 **Project work continuing in organized groups**
13:00-14:00 *Lunch*

14:00-17:00 **Project work continuing in organized groups**
15:30-16:00 *Coffee break*

Friday 22nd November

Presentation of the project work: Chair – Dan Odongo

Team leaders – Ammon Omiti and Charles Muturia
Facilitators – Raymond Mwakirani, Jeremiah Kipngok, Lucy Njue, Risper Kandie, Ammon Omiti, Edwin Wafula

08:30-13:00 **Presentations of projects**
13:00-14:00 *Lunch*

Final afternoon: Chair – Ludvik S. Georgsson

14:00-15:00 **Course review (instructors and trainees)**
15:00-16:00 **Conclusions and closing remarks**
16:00-17:00 *Coffee break*
17:00-18:30 **Final closing ceremony**
Mr. Ludvik S. Georgsson – UNU-GTP
Mr. Albert Mugo, Dir. KenGen
Dr. Silas Simiyu, MD GDC

19:30-22:00 **Closing dinner – at Lake Naivasha Sopa Resort – hosted by GDC**

Saturday 23rd November

All trainees depart from Lake Naivasha Sopa Resort for their home countries.

Secretariat meeting (UNU-GTP, KenGen and GDC)

Presented at *Short Course VIII on Exploration for Geothermal Resources*,
organized by UNU-GTP, GDC and KenGen, at Lake Bogoria and Lake Naivasha, Kenya, Oct. 31 – Nov. 22, 2013.

HYDROTHERMAL ALTERATION MINERALOGY IN GEOTHERMAL FIELDS WITH CASE EXAMPLES FROM OLKARIA DOMES GEOTHERMAL FIELD, KENYA

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ABSTRACT

In geothermal environments, primary minerals usually tend to alter to secondary (hydrothermal alteration) minerals that are either stable or at least metastable in these environments. The formation of these hydrothermal alteration minerals is usually dependent on the temperature, permeability, pressure, fluid composition, initial composition of the rock and the duration of the hydrothermal activity. These factors are largely independent, but the effects of one or more of the factors can exert a dominant influence in the location and extent of hydrothermal alteration.

Case study examples have been derived from studies done on the three exploration wells at Olkaria Domes geothermal field where appraisal drilling is currently underway. The main hydrothermal minerals in the geothermal field are albite, amphibole (actinolite), biotite, calcite, chlorite, chalcedony, epidote, fluorite, garnet, illite, K-feldspar (adularia), mordenite, secondary Fe-Ti oxides, sulfides (pyrite), titanite (sphene) and quartz. In addition, minor amounts of wairakite and prehnite are present. The occurrences and distribution of these hydrothermal minerals indicate that the minerals in all the wells show prograde variation patterns. The correlation of between the formation, interpreted hydrothermal alteration and fluid inclusion temperatures indicate that there have been temporal changes in the Olkaria Domes systems with part of the field indicating cooling whereas other parts indicate heating.

1. INTRODUCTION

1.1 Definitions and terminology

1.1.1 Minerals

A mineral is defined as an element or a chemical compound that is normally crystalline and has formed as a result of geologic processes. Although any of the hundreds of minerals can group together to form a rock, only six are very common. These common minerals are referred to as the "rock forming minerals" and include quartz, feldspars, micas, amphiboles, pyroxenes and olivine. Others include ferromagnesian minerals, oxides, sulphides, carbonates and native elements.

1.1.2 Rock

By definition, a rock is a solid mass or compound consisting of at least two minerals (although there are some exceptions when a rock may consist entirely of one mineral). The minerals comprising the rock can be identified using common field-testing methods for individual minerals, particularly where the texture is sufficiently coarse-grained enough to distinguish the individual minerals with the naked eye or a hand lens. Where the grain sizes of the minerals comprising the rock are too fine-grained to recognize discrete minerals, petrographic methods can be used for reliable identification in many cases.

Petrographic methods involve the use of a microscope to examine the optical properties of discrete minerals magnified through the microscope lens. Properties include the behavior of refracted, reflected and transmitted light either through a thin slice of the rock (called a thin section), or of a sample plug (for reflected light). The light source is adjusted to provide light, which polarized in one or two directions. Different minerals have characteristic optical properties, which can be used with tables of optical mineral properties to identify the mineral.

2. HYDROTHERMAL ALTERATION MINERALOGY

2.1 What is hydrothermal alteration?

Rock alteration simply means changing the mineralogy of the rock. The primary minerals are replaced by the secondary minerals because there has been a change in the prevailing conditions subjected to the rock. These changes could be changes in temperature, pressure, or chemical conditions or any combination of these. Hydrothermal alteration is a change in the mineralogy as a result of interaction of the rock with hot water fluids, called "hydrothermal fluids". The fluids carry metals in solution, either from a nearby igneous source, or from leaching out of some nearby rocks.

Hydrothermal fluids cause hydrothermal alteration of rocks by passing hot water fluids through the rocks and changing their composition by adding or removing or redistributing components. Temperatures can range from weakly elevated to boiling. Fluid composition is extremely variable. They may contain various types of gases, salts (briney fluids), water, and metals. The metals are carried as different complexes, thought to involve mainly sulphur and chlorine.

2.2 Sources of hydrothermal fluids

There are three main possible sources of hydrothermal fluids, though it could be a combination of any or all the three.

- Near surface groundwater (called "meteoric" water) is possible the main source of hydrothermal fluids. Evidence from some ore deposits suggests meteoric waters may mix with juvenile or metamorphic waters during late stages of mineralization.
- Another source can be the magmatic rocks themselves, which exsolve water (called "juvenile" water) during the final stages of cooling.
- In metamorphic terranes a potential source of the fluids is dehydration reactions, which take place during the metamorphic event. With increasing temperature of metamorphism, early, low temperature, hydrous minerals recrystallize into new, higher temperature, anhydrous minerals. The excess water circulates through the surrounding rocks and may scavenge and transport metals to sites where they can be precipitated as ore minerals.

Hydrothermal fluids in plutonic settings are thought to circulate along a large-scale convective path. It would be analogous to a pot of boiling water: hottest water rises fastest directly above the heat source, and at the surface changes flow direction to horizontal, and finally downwards along the sides of the

pot. In a similar manner, hydrothermal fluids circulate upward and outward from an igneous intrusion at depth. Porous and permeable host rocks (those containing lots of interconnected pore spaces) allow this to happen more readily, for example, in coarse-grained sandstone. Some types of rocks, like shale or slate, are extremely impermeable. A layer of shale can cause damming or ponding of the hydrothermal fluids, which can lead to a concentration of mineralization behind the impermeable barrier. Fluid migration can be also facilitated by the presence of lots of thin layers.

Hydrothermal fluids also circulate along fractures and faults. A formation, which has a well-developed fracture system, may serve as an excellent host rock. Veins form where the fluids flow through larger, open space fractures and precipitate mineralization along the walls of the fracture, eventually filling it completely. Fault zones are excellent places for fluids to circulate and precipitate mineralization. Faulting may develop breccia and gouge, which is often a good candidate for replacement style mineralization. The form of mineralization and alteration associated with faults is highly variable, and may include massive to fine-grained, networks of veinlets, and occasionally vuggy textures in some breccias.

3. SAMPLING

3.1 Rig site during drilling of geothermal wells

Cuttings from geothermal wells are normally sampled after every 2 m interval, but in cases where the sample was too little and unrepresentative, up to 4 m depth interval is sampled. Preliminary analysis of the cuttings and cores are normally done at the rig site by use of a binocular microscope and specimen samples which are representative of all the rock units penetrated are selected for detailed laboratory analysis of hydrothermal alteration minerals and fluid inclusion studies. For exploration drilling a few cores can be cut, but for appraisal and production drilling, cores are rarely cut as the stratigraphy and the formations are well understood and also the fact that it costs more to cut a core.

The problem with cuttings generally, is that the rock chippings in some of the samples are fine, usually smaller than the crystals hence bringing about difficulty in identifying some lithologic units conclusively. Also when the soft parts of the hydrothermally altered rock are ground during drilling, only the harder components reach the surface, hence less representative of the rock unit penetrated. Another problem is when cutting chips derived from a specific depth may have fallen from a shallow level due to cave-ins resulting to mixing of cuttings. Geosweeps are, however, carried out where mixing of cuttings is suspected. Time delays in sample cuttings to reach the ground result in depth difference between the true and the indicated depth and are usually greater for deeper samples. This anomaly is corrected by reconciling the depths with the drill logs and calculating for the error.

3.2 Field sampling during geological surface exploration

In the field, hydrothermally altered samples are found where there are active or extinct hydrothermal activities. Hydrothermal minerals such as quartz, sulphur, zeolites, silica and clays are deposited at the vents where hydrothermal fluids leak on the surface. The sample here is scooped, and detailed descriptions are made including the sampling location. The sample is then stored in the sample bags for further laboratory analyses.

4. ANALYTICAL METHODS

4.1 Stereo microscope analysis

Binocular analysis of the cuttings, cores or field samples are done using the binocular microscope. A sample is scooped from the sample bag into a petri dish and washed with clean water to remove

impurities and dust. Wetting the cuttings is necessary to enhance visibility of samples and obscure features such as finely disseminated sulphides e.g. pyrite. The sample is then placed on a mounting stage of the binocular microscope and among the essential features noted are the colour(s) of the cuttings, rock type(s), grain size, rock fabrics, original mineralogy, alteration mineralogy and intensity.

4.2 Petrographic microscope analysis

Representative samples from all the lithologic units encountered in the well/field are selected and thin sections are prepared for petrographic studies. The thin sections are analyzed using the petrographic microscope. The petrographic microscope is used to confirm the rock type(s) and the alteration minerals, additional alteration minerals not observed by the binocular microscope, and to study the mineralogical evolution of the alteration minerals.

4.3 X-ray Diffractometer analysis

The X-ray Diffractometer is used to qualitatively or quantitatively identify individual minerals e.g. clays and zeolites. Samples are selected from all the lithologic units and analysed for clays. The <4 microns fractions are prepared for x-ray diffraction by use of a mechanical shaker to separate the phylosilicates from the rock matrix. Count data were collected from 2°-14° at intervals of 0.02°, 2θ for a time of 1 second. Crystals of the mineral to be identified e.g. zeolites, carbonate, clays and sulphides are picked from the rock samples and ground by using an automatic milling machine. Count data were collected from 4°-56° at intervals of 0.04°, 2θ for a time of 1 second. The procedure of preparing clay and zeolite samples for XRD analysis is shown in Appendices I and 2.

4.4 Fluid Inclusion analysis

Double-polished thick sections (approximately 70 microns) of cuttings, which contain abundant quartz and calcite in veins, are used to prepare samples for fluid inclusion analysis. Fluid inclusions are small portions of fluid, which are trapped in a solid crystal as it grew or recrystallized. The fluids are thus samples of the original brine from which the crystal grew or a later fluid which bathed the crystal during crystallization. Primary fluid inclusions are concentrated along the first-order growth discontinuities or occur as isolated inclusions distributed within the crystals. Secondary fluid inclusions are trapped along healed cracks. If the crystal cools, the liquid will contract at a faster rate than the solid and a vapor bubble will form. At ambient temperatures, all types of inclusions contain a liquid aqueous solution and a gas bubble. This bubble forming process could be reversed to determine the temperature of mineral formation or temperature of homogenization (T_h). The inclusion is heated until the fluid homogenizes in a single phase (i.e. bubble disappears) and the T_h is measured.

4.5 Electron Microprobe analysis

Electron microprobes permit the non-destructive, major and trace element analysis of small areas (~4μm diameter) of solid materials in situ. Thin sections, which contain the minerals that are required for to be analysed in abundance e.g. epidote, are prepared for analysis. The analysis of minerals is carried out using Scanning Electron Microprobe Quantometer (SEMQ). The analysis is normally done at 15 kV with sample current of 15 nA and a beam diameter of 2-3 micrometers.

5. APPLICATION OF HYDROTHERMAL ALTERATION IN GEOTHERMAL SYSTEMS

5.1 Geothermometers

Hydrothermal minerals commonly used as geothermometers based on studies carried out in the Olkaria field are shown in Figure 1 below. First appearance of well-crystallized epidote indicates temperature of over 240ºC in Olkaria field. Presence of chlorite and epidote indicate temperatures of

220-340ºC and appearance of actinolite-tremolite occurs at 280-350ºC. Presence of garnet normally indicates temperatures of over 300°C. Smectite is an indicator of temperatures of less than 220°C.

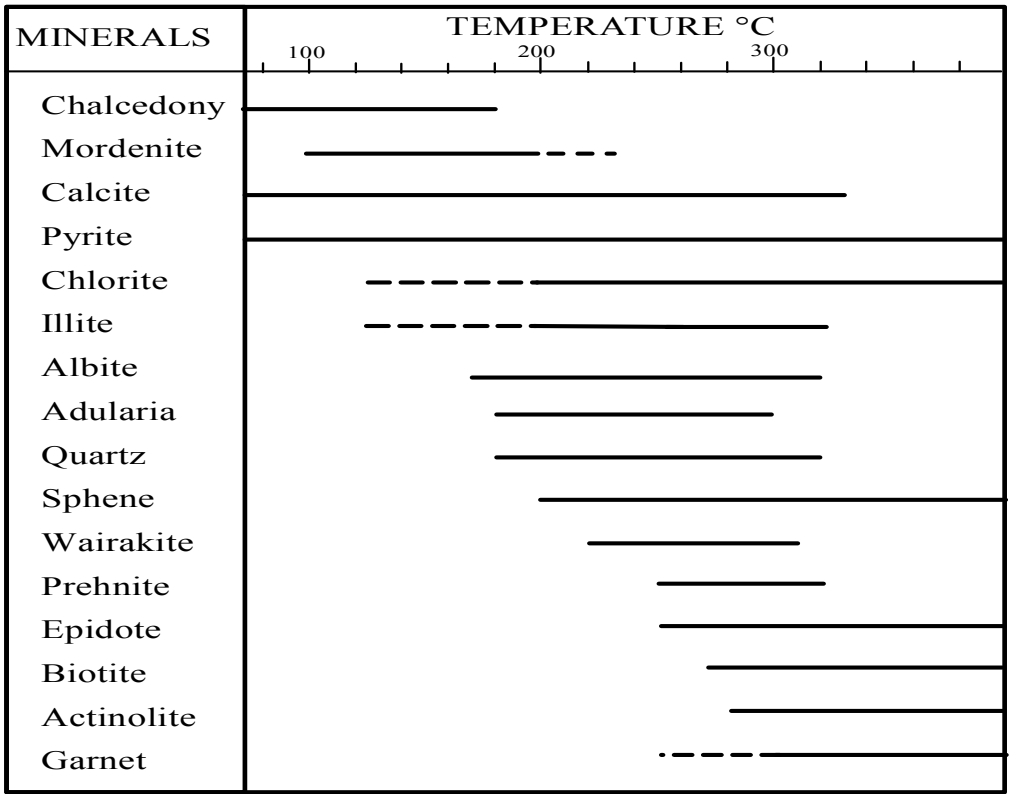

FIGURE 1: Common hydrothermal alteration minerals used as geothermometers and their temperature stability ranges. Dotted sections indicate mineral outside their usual stability ranges (modified from Reyes, 1990)

5.2 Permeability indicators

Indicators of high permeability in Olkaria geothermal system apart from high intensity alteration, bleaching of rocks, sheared or fractured rocks includes abundance of veins are quartz, illite adularia, abundant calcite and abundant pyrite. These minerals are commonly found in or adjacent to aquifers penetrated by wells and occur as alteration of the rock and in veins often as well formed crystals. Consequently indicators of low permeability apart from low alteration intensity and the absence of the above mentioned minerals are; prehnite, pyrhotite, abundant laumontite, abundant sphene instead of epidote occurring as rock alteration or tight veins.

5.3 Fluid chemistry

Acid alteration is accompanied by intense hydrogen metasomatism, base cation leaching and sulphate metasomatism (Hemley and Jones, 1964). In general acid-altered rocks are composed of residual elements: aluminium, titanium, iron, silica, some potassium, and calcium, with most of the base cations in the originals rock being leached away. Potassium is relatively immobile compared to other base cations; it occurs in alunite at low pH and high sulphate activity, and illite at higher temperatures, higher pH and high silica activity (Hemley et al 1967). In a neutral ph suite, less hydrolysis occurs and cations are less mobile. Alteration here largely involves the reshuffling of elements in the original rock into secondary minerals, and since replacement is often incomplete, primary chemical trends are usually retained.

5.4 Thermal history

The thermal history of a geothermal field can be obtained by studying the fluid inclusion homogenization temperatures (T_h), which are reliable predictors of past to present subsurface temperatures. These temperatures are correlated with the measured stable formation temperatures and interpreted hydrothermal alteration temperatures. Interpreted alteration mineral temperatures and fluid homogenization temperatures (T_h) that are above their stability and measured temperatures respectively indicate that the geothermal system has undergone some heating whereas those that are below indicate that geothermal system has undergone some cooling.

5.5 Setting the production casing

The temperature ranges of minerals (especially clays and calc silicates) supported by fluid inclusion homogenisation temperatures and Standard Formation Temperature Tests (SFTT) are used to determine the depth that the production casing is set during drilling especially exploration wells. This ensures that the cold zones or the unwanted aquifers are cased off during drilling and hence no incursion of cold fluids into the well occurs.

5.6 Predicting scaling and corrosion tendencies of a well

Acid fluids in wells form scales primarily composed of e.g. anhydrite, barite and pyrite corrode the well liners (Reyes, 1989). Acid-sulphate fluids may also attack the casing externally, reducing it largely to iron oxides and iron oxyhydroxides. The sulphides and the iron oxyhydroxides in the formation may be used to determine the corroding tendencies of fluids.

6. ALTERATION MINERALOGY (CASE EXAMPLE OLKARIA DOMES)

6.1 Primary minerals

The lithology of Olkaria domes is composed of unconsolidated pyroclastics that are dominant in the shallow levels overlying a volcanic sequence whose lithological composition is dominated by comenditic rhyolite, trachyte, basalt, tuff and some doleritic and syenitic dykes. The primary minerals found in the area are those normally contained in acid to basic rocks. Like elsewhere, primary minerals in Olkaria domes field are unstable and therefore tend to alter into those phases that are either stable or at least metastable in geothermal environments. The degree of primary textures is a function of formation permeability and the type, abundance, and grain size of primary minerals. Alteration of primary minerals occurs similarly in most geothermal fields, but some are specific to some fields. Shown below in Table 1 are the main primary minerals contained in Olkaria Domes rocks arranged according to decreasing susceptibility to hydrothermal fluids. Note that the susceptibility is the reverse or Bowen's reaction series where the earlier formed minerals are the last to alter whereas the later formed are the first to alter.

6.2 Alteration mineralogy

In the Olkaria Domes geothermal field, hydrothermal alteration minerals appear both as replacement of the primary minerals, as well as fillings in vesicles, vugs and fractures. The distribution and abundance of the hydrothermal minerals were obtained from the petrographic and XRD studies of drill cuttings samples taken after every 2 m from the 3 exploration wells drilled in the area.

The main hydrothermal minerals in Olkaria Domes field are albite, amphibole (actinolite), biotite, calcite, chlorite, chalcedony, epidote, fluorite, garnet, illite, K-feldspar (adularia), mordenite, secondary Fe-Ti oxides, sulfides (pyrite), titanite (sphene) and quartz. In addition, minor amounts of wairakite and prehnite are present. Mineral associations in vesicles are common and consist of two or

more of the following minerals; chlorite, quartz, calcite, epidote and pyrite with the paragenetic sequence varying with depth and from one well to another.

TABLE 1: Primary minerals, order of replacement and alteration products of Olkaria Domes volcanics (modified from Browne, 1984a)

Order of replacement	**Primary phases**	**Alteration products**
Increasing order	Volcanic glass	Zeolites, clays, quartz, calcite
	Olivine	Chlorite, actinolite, hematite, clay minerals
	Pyroxenes, amphiboles	Chlorite, illite, quartz, pyrite, calcite
	Ca-plagioclase	Calcite, albite, adularia, quartz, illite, epidote sphene
	Sanidine, orthoclase, microcline	Adularia
	Magnetite	Pyrite, sphene, haematite
	Quartz	No alteration

6.3 Description and distribution of alteration minerals in Olkaria Domes

The distribution of hydrothermal minerals in wells OW-901, OW-902 and OW-903 are shown in Figures 2-4, respectively. Below is a description of the hydrothermal alteration minerals encountered in the Olkaria Domes wells. The elevations of wells OW-901, OW-902 and OW-903 are 1890 m, 1957, and 2043 m respectively.

Adularia
Adularia occurs below 1238 masl in well OW-901; below 1197 masl in well OW-902 and below 1315 masl in well OW-903. The mineral forms minute anhedral to euhedral crystals that are pseudo-orthorhombic and are usually diamond shaped. It occurs as replacement of plagioclase or primary K-feldspars and is occasionally deposited in veins as well as forming incrustations in fissured rocks. Where it occurs as a replacement of plagioclase or K-feldspars, there is nearly an isochemical transformation to an optically and structurally different phase –adularia. In pseudomorphs after plagioclase phenocrysts, it produces a streaky extinction suggesting that the pseudomorphs are made up of numerous overlapping crystals of rhombic section. The mineral becomes rare until it disappears at 404 masl in well OW-901, 79 masl in well OW-902 and 441 masl in well OW-903.

Actinolite
Actinolite is green to greyish green in colour, forms radiating fibers or acicular crystals and also massive to granular aggregates in the groundmass and has a moderate birefringence. The mineral is formed as a replacement of ferromagnesian minerals in association with epidote and chlorite. Actinolite appeared in the deeper hotter parts of wells OW-901 and OW-903 (below 150 masl in well OW-901 and below 143 masl in well OW-903) but was conspicuously absent in well OW-902.

Albite
The term albitization here is referred to replacement of primary K-feldspar and plagioclase phenocrysts by hydrothermal albite. Albitization occurs below 1116 masl in well OW-901, below 1265 masl in well OW-902 and below 1203 masl in well OW-903. Albatized K-feldspar has a low refractive index and shows no zoning but typical chessboard like twinning is common.

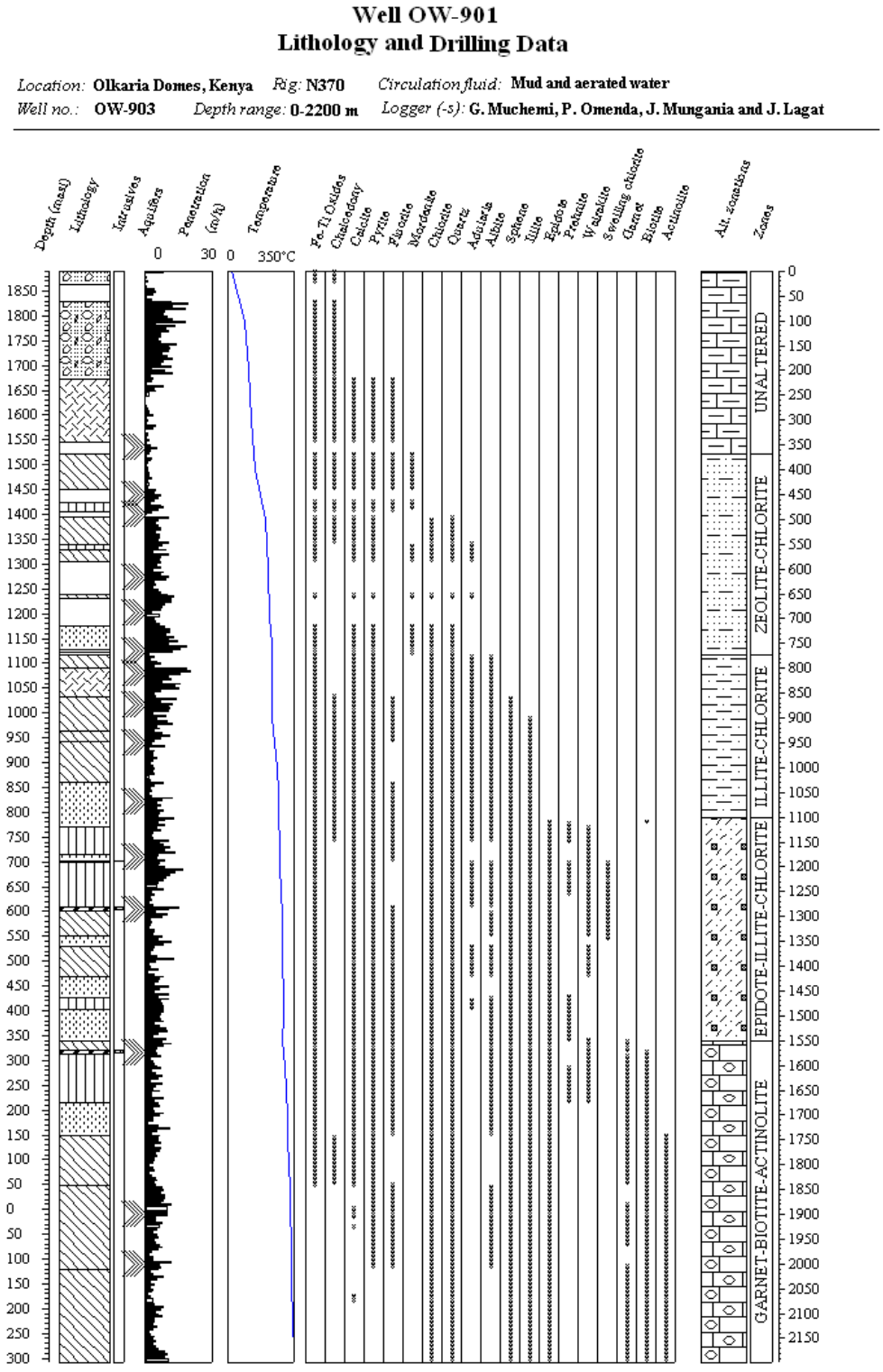

FIGURE 2: Lithology, distribution of hydrothermal alteration minerals and zonations in well OW-901

Biotite

Authigenic biotite is occasionally present in several geothermal systems (e.g. Salton Sea, McDowell and Elders, 1980; Cerro Prieto, Schiffman et al., 1984; Philippines, Reyes, 1990; Ngawha, Cox and Browne, 1998 and Aluto-Langano, Teklemariam et al., 1996). Biotite at Olkaria Domes occurs

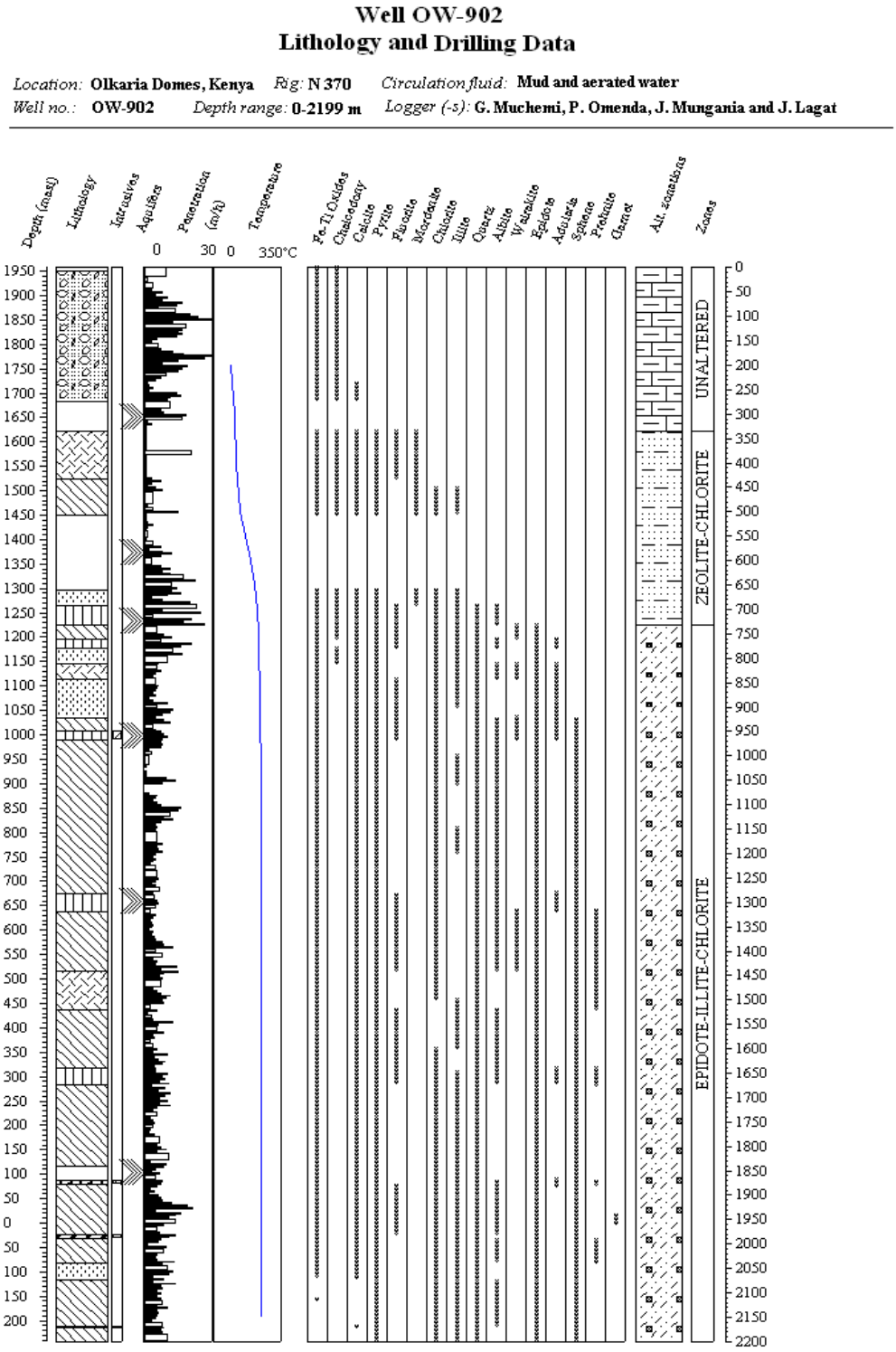

FIGURE 3: Lithology, distribution of hydrothermal alteration minerals and zonations in well OW-902. For lithology legend, see Appendix 3

sparingly at around 860 masl and continuously below 312 masl in well OW-901 and continuously below 517 masl in well OW-903. The mineral was, however, not encountered in well OW-902. Biotite forms weakly pleochroic, pale-green to brown-green crystals, which range from patchy aggregates of grains to sheet-like forms with sometimes-radial fan-shaped arrays. In association with garnet and actinolite, biotite is commonly used as an indicator of high temperatures of over 280°C (Bird et al 1984).

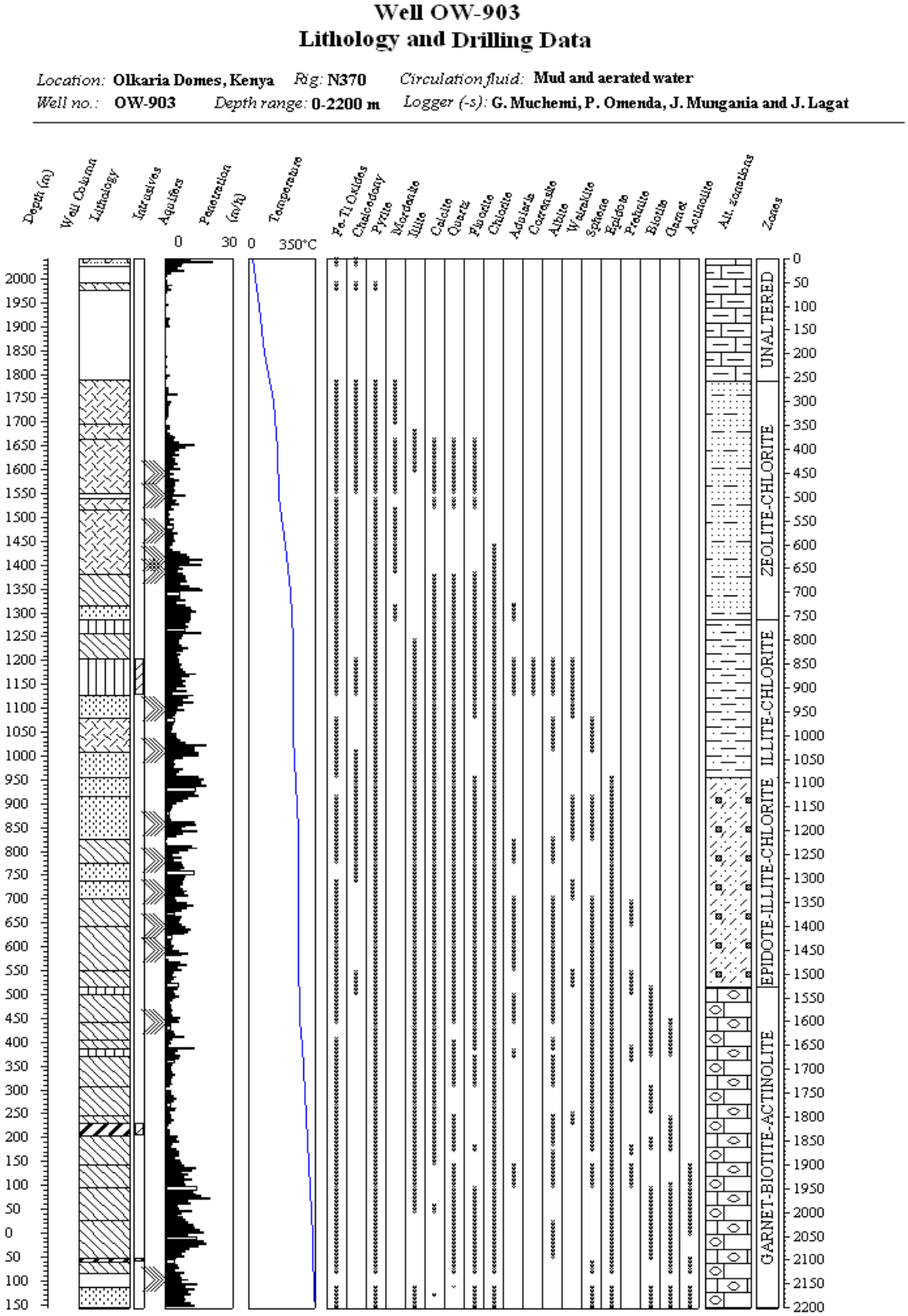

FIGURE 4: Lithology, distribution of hydrothermal alteration minerals and zonations in well OW-903. For lithology legend, see Appendix 3

Chalcedony

In well OW-901 chalcedony occurs from the surface (1890 masl) to 1340 masl, at 1032-740 masl and at the deeper parts of the well at 150-48 masl where it is seen to be partly transformed into quartz. In well OW-902, it occurs from the surface (1957 masl) to 1145 masl except for basaltic formation at

1197-1177 masl where it was absent. In well OW-903, it occurs from the surface of the well (2043 masl) to 1539 masl, at 1203-1127 masl and from 1009-737 masl. Colourless, white, or bluish-grey cryptocrystalline chalcedony lines vesicles and coat fractures and veins. The open space cryptocrystalline silica deposits generally have massive, banded, or botryoidal texture. At greater depths where temperatures are high, chalcedony in vesicles is seen transforming or is completely transformed into quartz but the chalcedonic outline is still preserved.

Chlorite

Chlorite occurs below 1390 masl in well OW-901, below 1507 masl in well OW-902 and below 1234 masl in well OW-903 down to the bottom of the three wells. Chlorite shows a wide distribution and a big variability in colours, forms and textures. It varies in colour from light-to-dark green, has low birefringence and occasionally shows anomalously blue, brown or purple interference colours and presents two different forms. In the upper levels of the volcanic sequences, chlorite appears in small intergranular patches whereas at the deepest levels, chlorite is idiomorphic, forming radial aggregates in veinlets and vugs in association with quartz, calcite, epidote, amphibole and pyrite. Within veins, chlorite occurs as microspherules enclosed within epidote, but it may also replace primary pyroxene, and the matrix. XRD analyses of chlorite show conspicuous peaks at 7.0-7.2 Å and 14.0-14.5 Å in the untreated, glycolated and oven heated samples.

Epidote

The first appearance of epidote is from 780 masl in well OW-901, from 1225 masl in well OW-902 and from 955 masl in well OW-903 to the bottom of all the three wells. Epidote shows a systematic textural development with increasing depth. First crystals are anhedral and form fine-grained aggregates and in deeper zones they are idiomorphic, tabular, radiated or fibrous. Epidote is found filling fractures, vesicles, and replacing primary plagioclase and pyroxene and in most cases forms mineral associations with mainly quartz, chlorite and sometimes calcite, wairakite and pyrite. Microprobe analyses of epidote from well OW-901 at 288 masl (Karingithi, 2002) shown in Table 2 indicate that the mineral is a solid solution between epidote and clinozoisite.

TABLE 2: Epidote solid solution chemical formulae and mole fraction
(data from Karingithi 2002)

Well	Chemical Formulae	Ca	Fe	Al	Si	X_{epi}	X_{czo}
OW-05	$Ca_{1.94}Fe_{1.07}Al_{1.93}Si_{3.01}O_{12}(OH)$	1.94	1.07	1.93	3.01	0.36	0.64
OW-19	$Ca_{1.99}Fe_{1.11}Al_{1.92}Si_{2.98}O_{12}(OH)$	1.99	1.11	1.92	2.98	0.37	0.63
OW-28	$Ca_{2.01}Fe_{0.79}Al_{2.34}Si_{2.90}O_{12}(OH)$	2.01	0.79	2.34	2.90	0.25	0.75
OW-33	$Ca_{1.96}Fe_{0.92}Al_{2.16}Si_{2.95}O_{12}(OH)$	1.96	0.92	2.16	2.95	0.30	0.70
OW-34	$Ca_{1.92}Fe_{0.81}Al_{2.26}Si_{2.94}O_{12}(OH)$	1.92	0.81	2.26	2.94	0.26	0.74
OW-901	$Ca_{2.05}Fe_{0.88}Al_{2.09}Si_{2.97}O_{12}(OH)$	2.05	0.88	2.09	2.97	0.30	0.70
Average		1.98	0.93	2.12	2.96	0.31	0.69

Fluorite

In all the three wells fluorite occurs intermittently, to the bottom of the wells from 1675 masl, 1621 masl and 1663 masl in wells OW-901, OW-902 and OW-903 respectively. Fluorite is dark brown, pink to reddish orange in colour and occurs in veins in association with calcite and quartz. It forms a typical cubic and to a lesser extent the octahedron as well as combinations of these two and other rarer isometric habits. A vein filling analyzed for mineral identification qualitatively using the XRD in well OW-901 at 1578-1576 masl consisted of both calcite and fluorite. Fluorite crystals picked in well OW-903 at 1221-1219 masl were analyzed qualitatively using the XRD and the diffractogram showed strong peaks at 3.16 Å and 1.93 Å.

Garnet
Garnet occurs as clusters of anhedral to subhedral crystals in association with epidote, biotite, amphibole and chlorite in veins in rocks below 1550 masl in well OW-901 and below 405 masl in well OW-903. Microscopic studies failed to identify garnet in OW-902, but it was detected by the electron microprobe at 9-3 masl. The exact depth of its first occurrence and distribution is not therefore certain. Garnet has a moderately high relief, exhibits no cleavage and is isotropic. Table 6 shows the electron microprobe analyses of garnet from 288-286 masl in well OW-901, 9-3 masl in well OW-902 and 27-25 masl in well OW-903 by Karingithi (2002). The results indicate garnet to be a solid solution between andradite and grossular. Presence of garnet normally indicates temperatures of over 300°C (Bird et al 1984).

TABLE 3: Garnet solid solution chemical formulae and mole fraction
(data from Karingithi 2002)

Well	Chemical Formulae	Ca	Fe	Al	Si	X_{and}	X_{gro}
OW-05	$Ca_{2.95}Fe_{1.29}Al_{0.73}Si_{2.94}O_{12}$	2.95	1.29	0.73	2.94	0.64	0.36
OW-19	$Ca_{2.97}Fe_{1.16}Al_{0.82}Si_{2.99}O_{12}$	2.97	1.16	0.82	2.99	0.58	0.42
OW-28	$Ca_{3.09}Fe_{1.25}Al_{0.79}Si_{2.88}O_{12}$	3.09	1.25	0.79	2.88	0.61	0.39
OW-33	$Ca_{3.03}Fe_{1.01}Al_{1.06}Si_{2.89}O_{12}$	3.03	1.01	1.06	2.89	0.49	0.51
OW-34	$Ca_{2.96}Fe_{1.13}Al_{0.97}Si_{2.89}O_{12}$	2.96	1.13	0.97	2.89	0.54	0.46
OW-901	$Ca_{2.98}Fe_{1.20}Al_{0.84}Si_{2.91}O_{12}$	2.98	1.20	0.84	2.91	0.59	0.41
OW-902	$Ca_{3.01}Fe_{1.20}Al_{1.07}Si_{2.84}O_{12}$	3.01	1.20	1.07	2.84	0.53	0.47
OW-903	$Ca_{2.88}Fe_{1.30}Al_{0.88}Si_{2.66}O_{12}$	2.88	1.30	0.88	2.66	0.60	0.40

Illite
Illite is detected below 990 masl in well OW-901, below 1557 masl in well OW-902 and below 1243 masl in well OW-903. The mineral is light green to white in colour, replaces K-feldspar and occurs as a vein and vesicle-filling mineral. XRD analyses of illite show no change at the 10 Å XRD in the untreated, glycolated and oven-heated samples (Grim, 1968).

Mordenite
White fibrous radiating hemispherical crystals of acicular mordenite are deposited in vesicles of lavas, open spaces between breccia fragments and perlitic cracks of partly altered glass in the upper few hundred meters of the three wells. Qualitative XRD analysis of the mineral showed strong peaks at 9.08 Å and 3.35 Å. In Icelandic geothermal systems, mordenite forms over a temperature range of about 75°C to around 230°C (Kristmannsdóttir and Tómasson, 1978). The measured temperature range at the depths where mordenite occurs in Olkaria Domes is in the range 100-220°C which is comparable to that of Icelandic systems.

Oxides
Oxidation is simply the formation of any type of oxide mineral. The most common ones to form are mainly iron oxides, but many different types can form, depending on the metal cations present. Sulfide minerals often weather easily because they are susceptible to oxidation and replacement by iron oxides. Oxides form readily in the surface or near surface environment, where oxygen from the atmosphere is more readily available and at the baked contact between the cold and the hot rock. Oxidation was noted in all the three wells from the surface to near the bottom of the wells where it becomes rare to none at all.

Prehnite
Prehnite is a rare mineral in Olkaria Domes wells and occurs intermittently below 770 masl in well OW-901, below 639 masl in well OW-902 and below 701 masl in well OW-903. The mineral becomes rare disappearing completely below 214 masl in well OW-901, below -81 masl in well OW-

902 and below 95 masl in well OW-903. It occurs as a vein-filling mineral mainly in association with albite, epidote, chlorite, calcite and quartz. It is recognized in thin section by its sheaf like 'bow-tie' structure, good cleavage in one direction and strong birefringence. Three analyses of prehnite in well OW-901 at 288-286 masl indicate an average composition of $Ca_{2.4}Fe_{0.8}Al_{1.2}Si_{3.3}O_{10}(OH)_2$ (Karingithi, 2002). The few analyses may not be representative, but they may indicate substantial concentration of iron (Fe) in the prehnite.

Pyrite
Pyrite crystals are present in well OW-901 from 1675 masl, becoming rare until it disappears below -120. In well OW-902 it occurs from 1621 masl to the bottom of the well and in well OW-903 it occurs from 1991 masl to the bottom of the well. It occurs as euhedral cubic crystals with brassy yellow luster in reflected light. Tiny cubic pyrite crystals were deposited in fractures, vesicles and veins and as disseminations in the groundmass. XRD analysis of pyrite indicate strong peaks at 3.13 Å, 2.71 Å, 2.42 Å, 2.21 Å and 1.91 Å

Quartz
Quartz is colourless to white in colour and occurs in euhedral to subhedral crystals. It is identified both as open space (vesicle) fillings and vein filling mineral. In well OW-901, quartz occurs from 1395 masl to the bottom of the well, in well OW-902, it occurs from 1265 masl to the bottom of the well and in well OW-903 it occurs from 1663 masl to the bottom of the well. Euhedral open space quartz crystals up to 2 mm long were deposited later than chalcedony in basaltic formation at 1203-1127 masl in well OW-903. Most of these quartz deposits consist of tiny euhedral to subhedral crystals that formed on top of botryoidal chalcedony in vesicles, veins and fractures. The same rock unit also consists of thin veins of quartz or tiny colourless crystals that formed in open spaces without earlier chalcedony deposits.

Sphene
In well OW-901, sphene was encountered from 1032 masl to the bottom of the well, in well OW-902, it occurs from 1035 masl to the bottom of the well and in well OW-903, it occurs sporadically from 1079 masl to the bottom of the well. Sphene occurs mainly as irregular grains and rarely as clear euhedral crystals having acute rhombic sections. The mineral occurs mainly as a result of alteration of ferromagnesian minerals in association with chlorite, quartz and calcite.

Swelling chlorite and corrensite
Swelling chlorite was encountered in a basaltic formation at 686-588 masl in well OW-901. XRD analysis of the clay showed peaks for the untreated run at 14.28 Å, the glycolated run swells to 16.74 Å and the oven heated run collapses to 14.16 Å. Corrensite was also identified in a basaltic formation in well OW-903 at 1143-1137 masl. The untreated sample peak is at 29.30 Å, the glycolated peak swell to 31.30 Å and the oven heated run collapses completely.

Wairakite
Wairakite occurs rarely and intermittently below 770 masl in well OW-901, below 1225 masl in well OW-902 and below 103 masl in well OW-903, disappearing at depth in all the three wells. The mineral is found as open space filling in association with quartz and calcite. XRD analysis indicated strong peaks at 3.39 Å and 5.56 Å.

6.4 Fluid inclusion geothermometry

The homogenization temperatures (T_h) of fluid inclusions in Olkaria Domes field samples were measured to determine the formation temperatures during their entrapment. These inclusions are all hosted by calcite and quartz, which occurs widely in the geothermal system. The T_h values at 240 masl in well OW-901 ranged from 238-272°C in quartz veins and from 280-320°C in calcite veins. The formation temperature at this depth is 314°C. The lowest T_h value (238°C) in quartz veins from this well is 76°C below the measured formation temperature and the highest value (272°C) is 42°C

below to the measured formation temperature (314°C). The average value for the inclusions in quartz veins is 256 °C and is 58 °C below the measured formation temperature. In the calcite veins the lowest T_h value of 280°C is 34°C below the measured formation temperature and the highest T_h value (320°C) is 6°C above the measured formation temperatures (314°C). The average value for the inclusions in the calcite vein is 301°C and is 13°C below the measured formation temperature. These measurements indicate the inclusions in calcite vein represent close to the current formation temperatures whereas the quartz veins indicate past cooler conditions. If this interpretation is valid, it implies that the silica in quartz precipitated from hotter fluids is mostly derived from the primary feldspars of the rock and not of the earlier quartz precipitated under cooler conditions.

In well OW-902 at 689 masl T_h values in inclusions hosted in quartz veins ranged from 210-256°C with an average of 237°C, whereas the formation temperature at this depth is 247°C. In well OW-902, the highest value from the T_h value (256°C) is equivalent to the boiling point curve value (256°C) and 8°C above the measured formation temperature of 247°C. The lowest T_h value (210°C) is 37°C lower than the maximum measured formation temperature. The average T_h value of 237°C in this well corresponds fairly well with the present day conditions.

The T_h values of inclusions in quartz veins at 517 masl in well OW-903 varied widely between 178-275°C with an average of 219°C whereas the formation temperature at this depth is 265°C. The lowest T_h value of 178°C is 87°C lower than the measured formation temperature suggesting that the fluids were trapped when temperatures were lower than the present day values. The highest T_h measurement of 275°C is 10°C higher that the measured formation temperature indicating that the fluids in these inclusions were trapped at nearly the same temperatures as current measured formation temperatures. The fluid compositions could not be determined because the inclusions were very tiny and was difficult to measure the melting temperature (T_m)

6.5 Measured, hydrothermal alteration and fluid inclusion temperatures

In any geothermal system, there is always some uncertainty whether observed minerals distribution and zonations reflect current formation temperatures or are related to some previous thermal events or regimes. In the Greater Olkaria geothermal area as in other geothermal fields throughout the world, hydrothermal alteration minerals are important indicators of subsurface thermal changes. A correlation between measured, hydrothermal alteration and fluid inclusion temperatures indicate how a particular geothermal system has evolved with time.

Figure 5 shows the correlation between measured, interpreted hydrothermal alteration and fluid inclusion temperatures in well OW-901. Geothermometry of alteration minerals and fluid inclusions in well OW-901 indicate that there has been some heating. However, calcite veins with homogenization temperatures averaging 301°C closely reflect current conditions in the reservoir. High temperature hydrothermal alteration minerals e.g. epidote, biotite, actinolite and garnet seem to be in equilibrium with the present geothermal system in well OW-901, with all the minerals occurring within their temperature stability ranges.

The correlation between measured, interpreted hydrothermal alteration and fluid inclusion temperatures in well OW-902 shown in Figure 6 indicate probable cooling with hydrothermal minerals occurring below their stability temperature ranges. Here garnet occurs where the measured formation temperature is below its temperature stability range indicating it is relict. Fluid inclusion temperatures, however, seem to reflect current conditions with the average homogenization temperature of 237°C being close to the measured formation temperatures of 247°C.

Well OW-903 (Figure 7) had average fluid inclusion temperatures in quartz veins way below the measured formation temperatures with an average of 219°C while the measured formation temperature at that depth is 265°C. This indicates that there has been heating in the system since the inclusions were trapped. The interpreted hydrothermal alteration temperatures indicate that the alteration

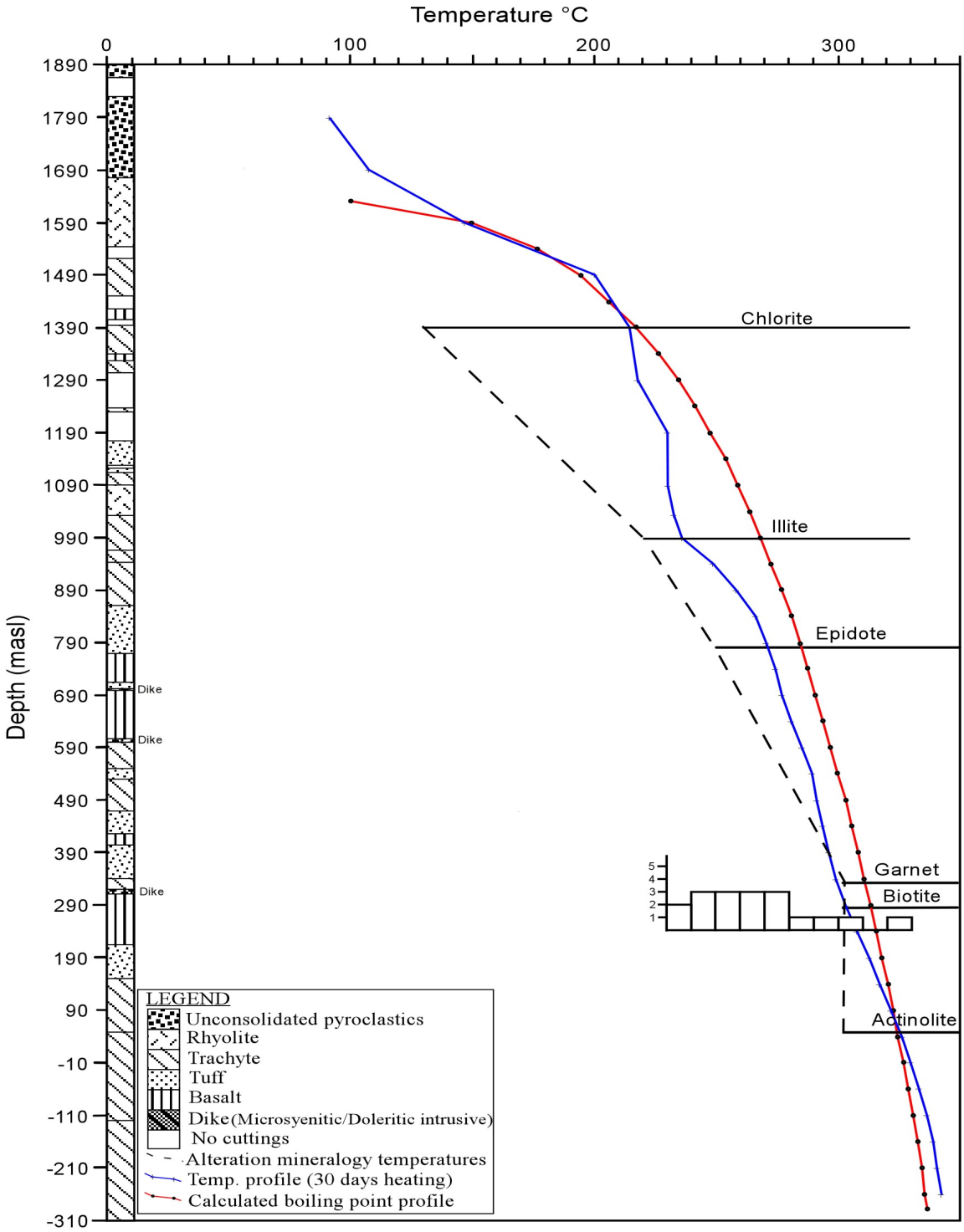

FIGURE 5: Plot of lithology and correlation between measured, interpreted hydrothermal alteration minerals and fluid inclusion temperatures with depth of well OW-901

minerals are in equilibrium with the geothermal system with illite, epidote, biotite, garnet and actinolite all occurring within their temperature stability ranges.

Index minerals used to construct isograds across wells OW-901, OW-903 and OW-903 in Olkaria Domes field include actinolite, chlorite, epidote, garnet and illite. Isograds give a general picture of the temperature distribution in a geothermal system. Strictly speaking, however, a definite isograd (e.g. the epidote isograd) does not necessarily represent a definite temperature. The distribution of

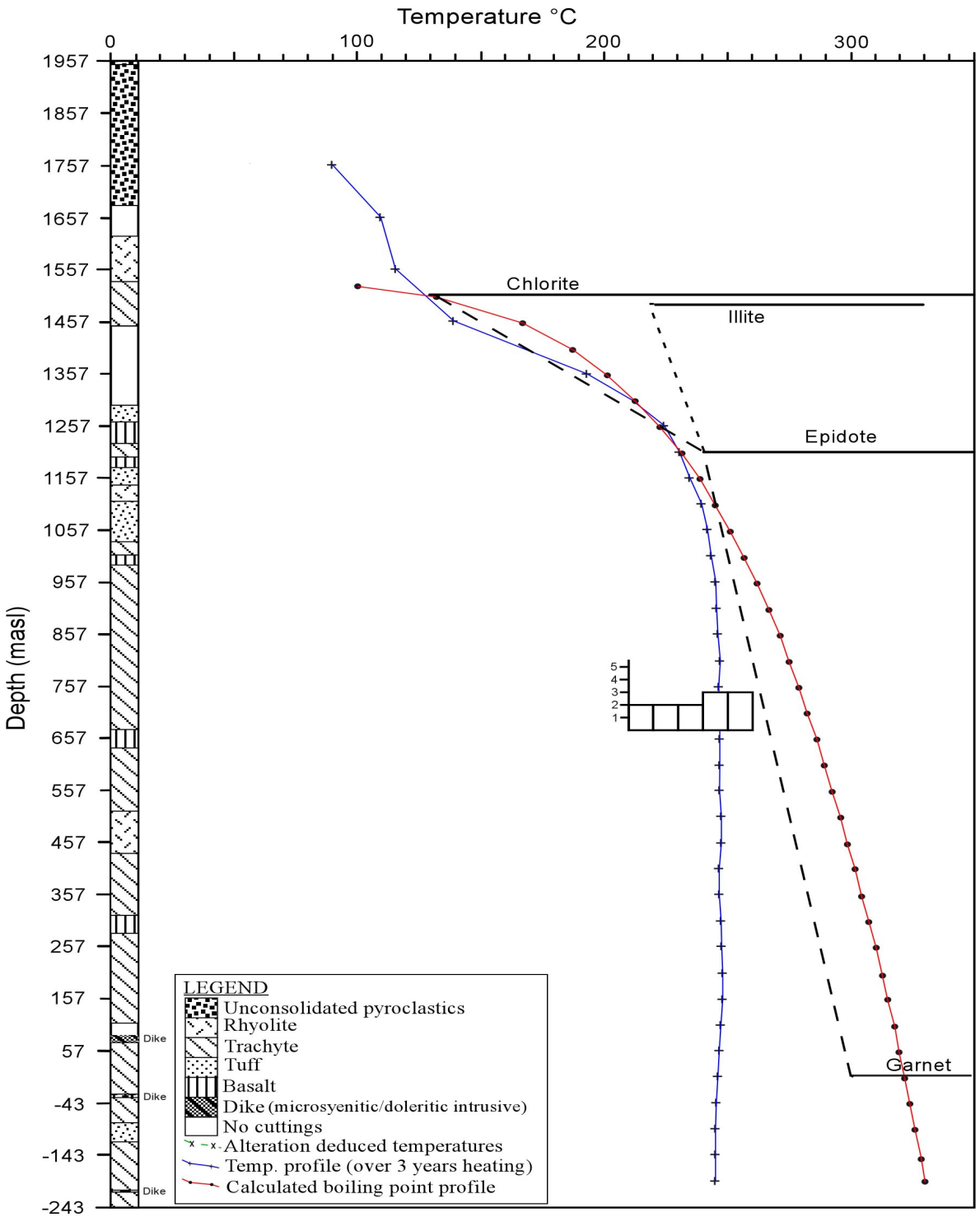

FIGURE 6: Plot of lithology and correlation between measured, interpreted hydrothermal alteration minerals and fluid inclusion temperatures with depth of well OW-902

hydrothermal minerals isograds is not distinctly parallel to the isothermal contours (Figure 8) indicating that hydrothermal alteration is not a function of subsurface temperature only but the rock composition also influences the kinetics of the hydrothermal alteration minerals formation. The isograds clearly indicate high and shallow temperatures towards well OW-901 and low temperatures towards well OW-902. In well OW-902, below 1000 masl, the temperature becomes more or less isothermal, with very little or no change with depth. Biotite and actinolite were not encountered in the well, but garnet was encountered at temperatures well below its stability temperature range.

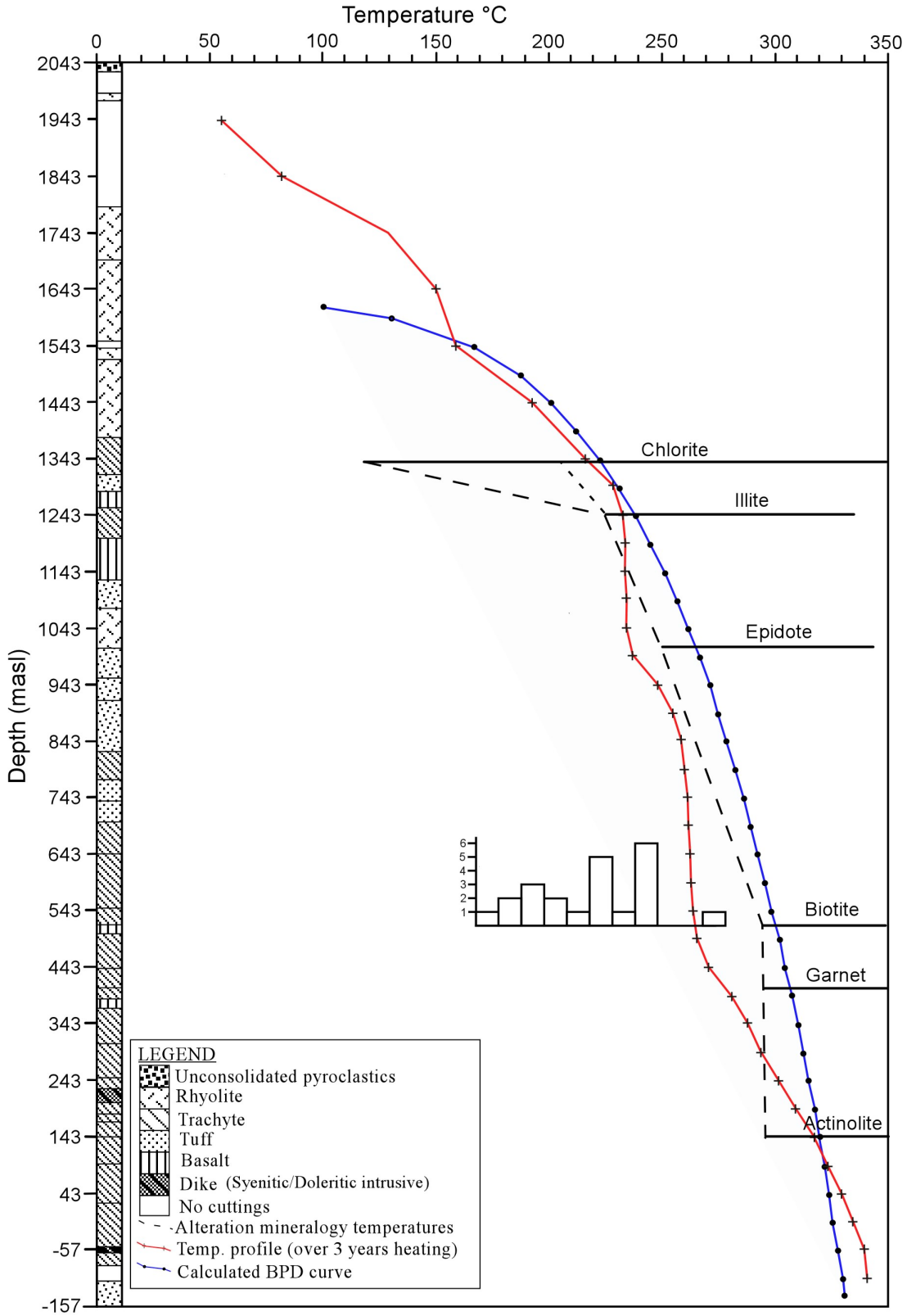

FIGURE 7**:** Plot of lithology and correlation between measured, interpreted hydrothermal alteration minerals and fluid inclusion temperatures with depth of well OW-903

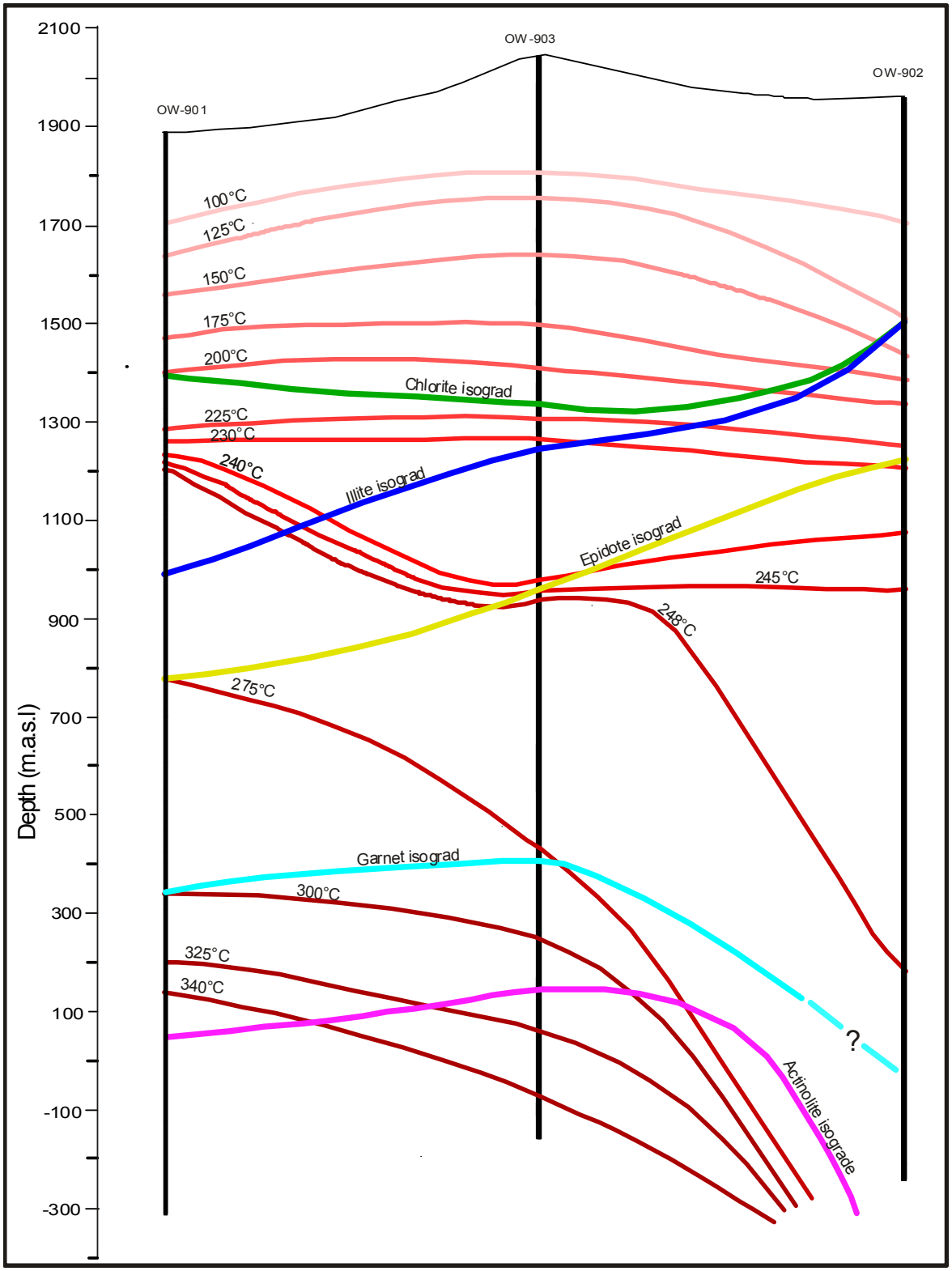

FIGURE 8: Plot of epidote, illite, chlorite, actinolite and garnet isograds and measured temperature isotherms across wells OW-901, OW-903 and OW-902

7. ALTERATION TYPES

There are as many alteration types as there minerals. The following types are the most commonly described types:

Propylitic: (Chlorite, epidote, actinolite and tremolite) Propylitic alteration turns rocks green, because the new minerals formed are green. These minerals include chlorite, actinolite and epidote. They usually form from the decomposition of Fe-Mg-bearing minerals, such as biotite, amphibole or pyroxene, although they can also replace feldspar. Propylitic alteration occurs at high temperatures. Propylitic alteration will generally form in a distal setting relative to other alteration types. Presence of chlorite and epidote indicate temperatures of 220-340ºC and appearance of actinolite-tremolite occurs at 280-350ºC.

Sericitic: (Sericite) Sericitic alteration alters the rock to the mineral sericite, which is a very fine-grained white mica. It typically forms by the decomposition of feldspars, so it replaces feldspar. In the field, its presence in a rock can be detected by the softness of the rock, as it is easily scratchable. It also has a rather greasy feel (when present in abundance), and its color is white, yellowish, golden brown or greenish. Sericitic alteration implies low pH (acidic) conditions. Alteration consisting of sericite + quartz is called "phyllic" alteration. Phyllic alteration associated with porphyry copper deposits may contain appreciable quantities of fine-grained, disseminated pyrite which is directly associated with the alteration event.

Potassic: (Biotite, k-feldspar, adularia) Potassic alteration is a relatively high temperature type of alteration, which results from potassium enrichment. This style of alteration can form before complete crystallization of magma, as evidenced by the typically sinuous, and rather discontinuous vein patterns. Potassic alteration can occur in deeper plutonic environments, where orthoclase will be formed, or in shallow, volcanic environments where adularia is formed.

Albitic: (Albite) Albitic alteration forms albite, or sodic plagioclase. Its presence is usually an indication of Na enrichment. This type of alteration is also a relatively high temperature type of alteration. The white mica paragonite (Na-rich) is also formed sometimes. Albite is precipitated in vugs and fractures at >280ºC.

Silicification: (Quartz) Silicification is the addition of secondary silica (SiO_2). Silicification is one of the most common types of alteration, and it occurs in many different styles. One of the most common styles is called "silica flooding", which results form replacement of the rock with microcrystalline quartz (chalcedony). Greater porosity of a rock will facilitate this process. Another common style of silicification is the formation of close-spaced fractures in a network, or "stockworks", which are filled with quartz. Silica flooding and/or stockworks are sometimes present in the wall rock along the margins of quartz veins. Silicification can occur over a wide range of temperatures.

Silication: (Silicate minerals+/-quartz) Silication is a general term for the addition of silica by forming any type of silicate mineral. These are commonly formed in association with quartz. Examples include the formation of biotite or garnet or tourmaline. Silication can occur over a wide range of temperatures. The classic example is the replacement of limestone (calcium carbonate) by silicate minerals forming a "skarn", which usually form at the contact of igneous intrusions. A special subset of silication is a style of alteration called "greisenization". This is the formation of a type of rock called "greisen", which is a rock containing parallel veins of quartz + muscovite + other minerals (often tourmaline). The parallel veins are formed in the roof zone of a pluton and/or in the adjacent country rocks (if fractures are open). With intense veining, some wallrocks can become completely replaced by new minerals similar to the ones forming the veins.

Carbonatization: (Carbonate minerals) Carbonitization is a general term for the addition of any type of carbonate mineral. The most common are calcite, ankerite and dolomite. Carbonatization is also usually associated with the addition of other minerals, some of which include talc, chlorite, sericite and albite. Carbonate alteration can form zonal patterns around ore deposits with more iron-rich types occurring proximal to the deposit.

Alunitic: (Alunite) Alunitic alteration is closely associated with certain hot springs environments. Alunite is a potassium aluminum sulfate mineral, which tends to form massive ledges in some areas. The presence of alunite suggests high SO_4 gas contents were present, which is thought to result from the oxidation of sulfide minerals.

Argillic: (Clay minerals) Argillic alteration is that which introduces any one of a wide variety of clay minerals, including kaolinite, smectite and illite. Argillic alteration is generally a low temperature event, and some may occur in atmospheric conditions. The earliest signs of argillic alteration include the bleaching out of feldspars. A special subcategory of argillic alteration is "advanced argillic". This consists of kaolinite + quartz + hematite + limonite, feldspars leached and altered to sericite. The presence of this assemblage suggests low pH (highly acidic) conditions and temperatures of <220ºC. At higher temperatures, the mineral pyrophyllite (white mica) forms in place of kaolinite.

Zeolitic: (Zeolite minerals) Zeolitic alteration is often associated with volcanic environments, but it can occur at considerable distances from these. In volcanic environments, the zeolite minerals replace the glass matrix. Zeolite minerals are low temperature minerals, so they are generally formed during the waning stages of volcanic activity, in near-surface environments. Zeolitization occurs at over <220ºC.

Serpentinization and Talc Alteration: (Serpentine, Talc) Serpentinization forms serpentine, which recognized softness, waxy, greenish appearance, and often massive habit. This type of alteration is only common when the host rocks are mafic to ultramafic in composition. These types of rocks have relatively higher iron and magnesium contents. Serpentine is a relatively low temperature mineral. Talc is very similar to the mineral serpentine, but its appearance is slightly different (pale to white). Talc alteration indicates a higher concentration of magnesium was available during crystallization.

Oxidation: (Oxide minerals) Oxidation is simply the formation of any type of oxide mineral. The most common ones to form are haematite and limonite (iron oxides), but many different types can form, depending on the metals, which are present. Sulfide minerals often weather easily because they are susceptible to oxidation and replacement by iron oxides. Oxides form most easily in the surface or near surface environment, where oxygen from the atmosphere is more readily available. The temperature range for oxidation is variable. It can occur at surface or atmospheric conditions, or it can occur as a result of having low to moderate fluid temperatures.

8. FACTORS AFFECTING HYDROTHERMAL ALTERATION

Factors that influence the distribution and kind of mineral assemblages present in hydrothermal systems include permeability, rock and water composition, temperature, pressure and duration of hydrothermal alteration (Browne and Ellis, 1970). These factors are largely independent, but the effects of one or more of the factors can exert a dominant influence in the location and extent of hydrothermal alteration.

- Permeability: Permeability of the rocks controls the access of thermal fluids, which cause hydrothermal alteration of the rocks and precipitation of secondary minerals in open spaces. Rocks, which have very restricted permeability or are completely impervious to fluid, will be only slightly altered. Crystallinity of the host rock is of importance because glass is more easily altered than crystalline rock.
- Chemical composition: The chemical composition of the host rock determines the availability of components to form alteration minerals as well as possible fugitive components from the presumed magmatic heat source.
- Temperature: Temperature is the most significant factor in hydrothermal alteration because most of the chemical reactions require elevated temperatures and also minerals are thermodynamically stable at high temperatures.

- Pressures: Pressures at the depths penetrated by drill holes in geothermal fields in the world are not sufficient to greatly affect hydrothermal alteration minerals transformation (Browne and Ellis, 1970). The main effect of pressure on hydrothermal alteration is an indirect one in that it controls the depth at which boiling occurs.
- Duration of the hydrothermal alteration: A geothermal system has a beginning and it should have an end. The earth is naturally cooling and for old systems where there is no renewed activity, we have extinct geothermal systems. In plate boundaries where there is continuously activity, the geothermal systems are continually being kept alive by renewed heat sources.

9. CONCLUSIONS

The study of hydrothermal mineralogy is important in exploration and development in geothermal fields all over the world. These studies coupled with geophysical logging techniques, fluid inclusion geothermometry, completion tests, standard formation temperature tests (SFTT), discharge fluid chemistry, stratigraphy and structural geology will always give an understanding and the nature of a geothermal system. Below are some of the problems that can be solved by the above-mentioned methods;

1. Setting the production casing during drilling especially in exploration wells.
2. Understanding the reservoir by modelling the inflow, upflow and the outflow zones of the geothermal system/field.
3. Understand the nature of the reservoir and know whether temporal changes in have occurred in the past.
4. Understand the fluids chemistry so as to predict future problems in the wells/fields such as casing corrosion, acid inflow, cold-water incursion and scaling tendencies.

Exploring new geothermal fields and siting next appraisal or production wells.

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APPENDIX 1: Preparation of samples for clay mineral analysis

Into a clean test tube place approximately two spoonfuls of drill cuttings. Wash the cuttings to remove the dust with distilled water and fill the tube to approximately two-third full with distilled water. Place the tubes in a mechanical shaker for 4-6 hours depending on the intensity of alteration of the cuttings.

Allow the particles to settle for 1-2 hours, until those particles less than approximately 4 Å are left in suspension. Pipette a few milliliters from each tube and place approximately 10 drops on a labeled glass plate, not making the film thick. Make a duplicate of each sample and let them dry at room temperature overnight.

Place one sample at the desiccator containing glycol ($C_2H_6O_2$) solution and the other in a set of desiccator containing hydrated calcium chloride ($CaCl_2.H_2O$). Store it at room temperature for at least 24 hours. Thicker samples need more time at least 48 hours.

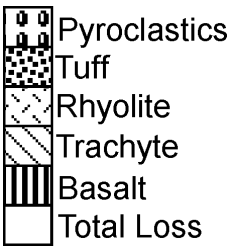
Run both sets of samples in the range 2-14° at intervals of 0.02°, 2θ for a time of 1 second on the XRD machine.

Place one set of samples (usually the glycolated one) on an asbestos plate and insert in a preheated oven. Heat the samples at 500-550°C for one hour making sure the oven temperatures does not exceed 600°C. When the samples have cooled, run them in the range 2-14° on the XRD machine.

APPENDIX 2: Preparation of samples for XRD qualitative mineral analysis

Handpick grain fillings from vein fillings or vesicles under the binocular microscope and put them in an agate bowl.
Crush the samples to a grain size of 5-10 Å. Acetone is usually added to prevent loss of sample while powdering.
Smear the sample on quartz plate and let the acetone dry.
Run the sample from 5°-56° at intervals of 0.04°, 2θ for a time of 1 second on the XRD machine.

APPENDIX 3: Legend of the rocks encountered in Olkaria domes used in Figures 1, 2 and 3



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OVERVIEW OF GEOTHERMAL SURFACE EXPLORATION METHODS

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ABSTRACT

Geothermal surface exploration invariably entails a multi-geoscientific process, which are holistically aimed at defining the geometry and characteristics of the geothermal system prior to drilling. The scientific disciplines commonly involved are geology, geochemistry, and geophysics. Geological approach generally aims at understanding the various lithologies, volcanological evolution, structural controls, and hydrological regimes of the system. Geophysical exploration helps in determining the geometry (shape, size and depth) of the heat sources, reservoir and cap rock. It also aims at imaging structures that are responsible for the geothermal system, and delineating the areal extent of the geothermal resource. The most commonly used geophysical methods are electromagnetic/electric, gravity, magnetics and seismics. These methods ultimately depend on the various intrinsic properties of rocks such as resistivity/electrical conductivity, density, magnetic susceptibility, elastic moduli/velocity respectively. Geochemical exploration relies mostly on sampling and analysis of water, steam and gas from the thermal manifestation in order to characterize the fluids, estimate equilibrium reservoir temperature, determine the origin, evaluate mixing scenarios, determine the suitability of the fluids for the intended use and locate recharge areas and direction of fluid flow. Additional geochemical studies entails soil diffuse degassing measurements aimed at identifying gas leakages that usually mimic active faults and structures.

1. INTRODUCTION

Geothermal energy has become a viable alternative and sustainable source of energy in many countries. The energy is commonly manifested on the terrestrial surface in the form of fumaroles, hot springs, geysers, steaming grounds and altered grounds. The economically usable geothermal energy is that which occurs close to the earth's surface where it can be tapped by drilling wells up to 3,000 m below the earth's surface. Such shallow heat sources are in most cases attributed to volcanic activity, which are commonly associated with plate boundaries, which is reminiscent of the East African Rift system and other geodynamic environments. The essential components of a geothermal system include; heat source, permeable reservoir, cap rock and recharge regime. Ideally, multiple geoscientific disciplines such as geophysics, geology and geochemistry are commonly employed in the geothermal exploration, in order to define the aforementioned components.

1.1 Objectives of geothermal exploration

The objective of geothermal exploration is to obtain adequate information about the properties and features of a prospective geothermal system before embarking on drilling. Most of the information include but not limited to:

- Identify areas with potential geothermal energy
- Estimate equilibrium reservoir temperatures
- Characterize thermal fluids
- Define the geometry (shape, size and depth) of the resource.
- Rank the prospect areas in order of development priority
- Develop a conceptual model
- Locate suitable drilling targets
- Determine the pre-exploitation values of environmentally sensitive parameters.

1.2 Phases of geothermal development

Geothermal development is essentially a sequential and a systematic process of exploring of productive sites with the ultimate aim of geothermal power production. The development phases begin with reconnaissance and exploration, pre-feasibility, feasibility and finally power plant construction (Figure 1). Árnason and Gíslason **(**2009) deduced that successful surface exploration reduces the cost of later stages in the development and thus saves a lot of money in the end. At the onset of a geothermal exploration project it is normally uncertain whether results will be economically, technically and environmentally feasible. Geothermal exploration therefore invariably necessitates risk. It is with respect that, exploration process is commonly carried out on a step-by-step basis, and is divided into several phases in order to minimize cost and maximize information for each phase. Each of these phases gradually eliminate the less interesting areas and focus on the most promising ones.

The exploration programme should be designed to suit the type of resource expected, the amount of energy expected to be produced from the project and the timeframe for the development. Ideally before kicking off, an exploration exercise it is pertinent to begin with collection of available information from previous work, topographic, geological, structural and geothermal maps of the prospect area of interest. It is common practice that reconnaissance provides preliminary information about the geological and structural settings, most suitable sites and location of the thermal surface expressions as well as their characteristics. An inception report is normally prepared after obtaining the valuable information from the reconnaissance and a detailed exploration plan subsequently developed. Detailed exploration entails extensive geological and geochemical studies, a range of geophysical techniques including gravity, magnetic and resistivity surveys. Interpretation of these integrated geoscientific studies leads to prioritisation of targets for exploration drilling programmes. The application of sound scientific method and analysis during these early phases increases the probability of success with subsequent drilling and development **(**Árnason and Gíslason, 2009).

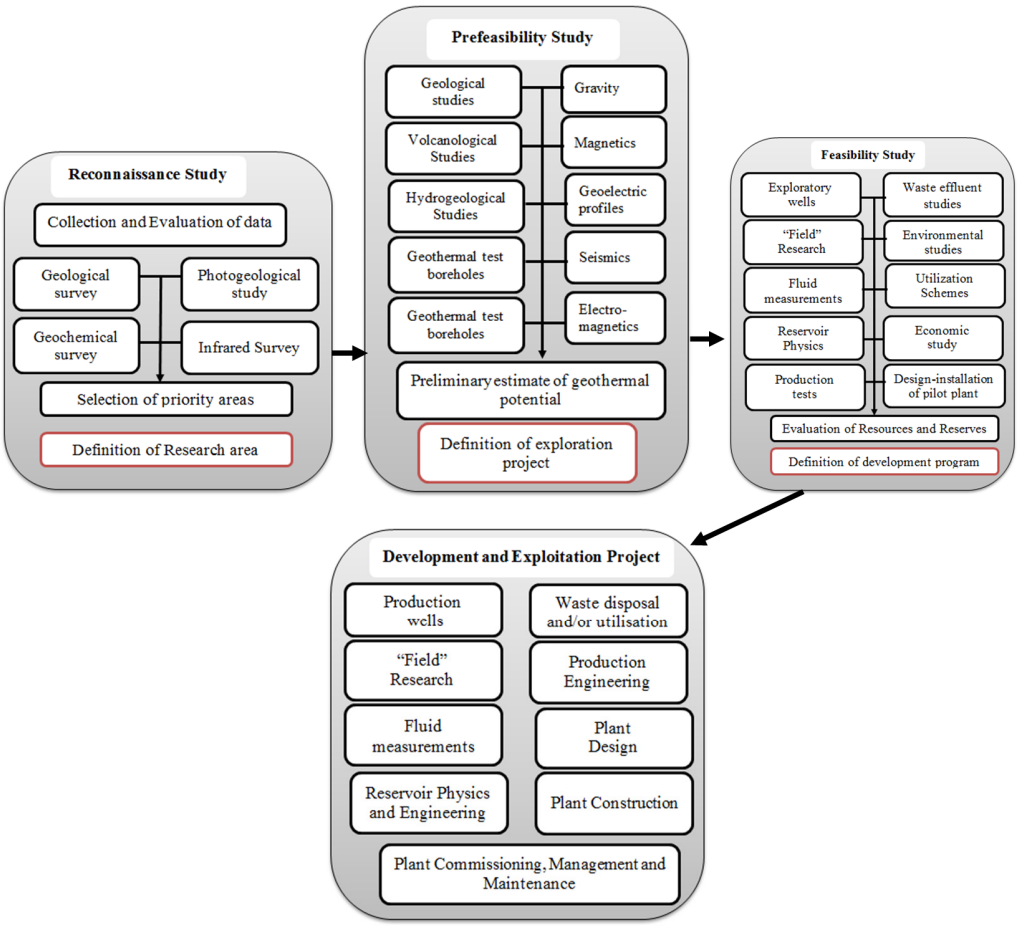

FIGURE 1: Simplified geothermal development flow chart (modified from Manzella & Pipan, 2009). Many factors influence choice of methods and include: geological conditions, availability of surface manifestations, geographical setting – terrain, cost, time factor (time required to produce results), specific needs or requirements which is tied to the projected use of the resources (Árnason and Gíslason, 2009; Wanjie, 2012)

2. EXPLORATION METHODS

The various scientific disciplines employed in geothermal exploration are geological studies geochemical studies, various geophysical techniques and environmental baseline survey.

2.1 Geological studies

Geological studies invariably starts at the incipient reconnaissance stage, which entails preliminary mapping of the lithologic units and structures, mapping of thermal surface manifestations and possibly relate to the structures and or volcanism in the prospect of interest.

Detailed geological studies is performed in the geothermal field and its surroundings (Árnason and Gíslason, 2009). This comprehensively entails mapping rock units, types (Figure 2) and their chronological sequence. Petrological and petrochemical rock analysis is performed to be able to distinctively understand the rocks units. Structural mapping is done in the effort to distinguish the types of faults and fissures that transect the

geothermal prospect of interest, and be able to discern the structural controls of the system. In cases of volcanic settings, eruptive centres, calderas, fissures, rock units, intrusions are mapped and radiometrically dated in order to understand the volcanological evolution and the stratigraphy.

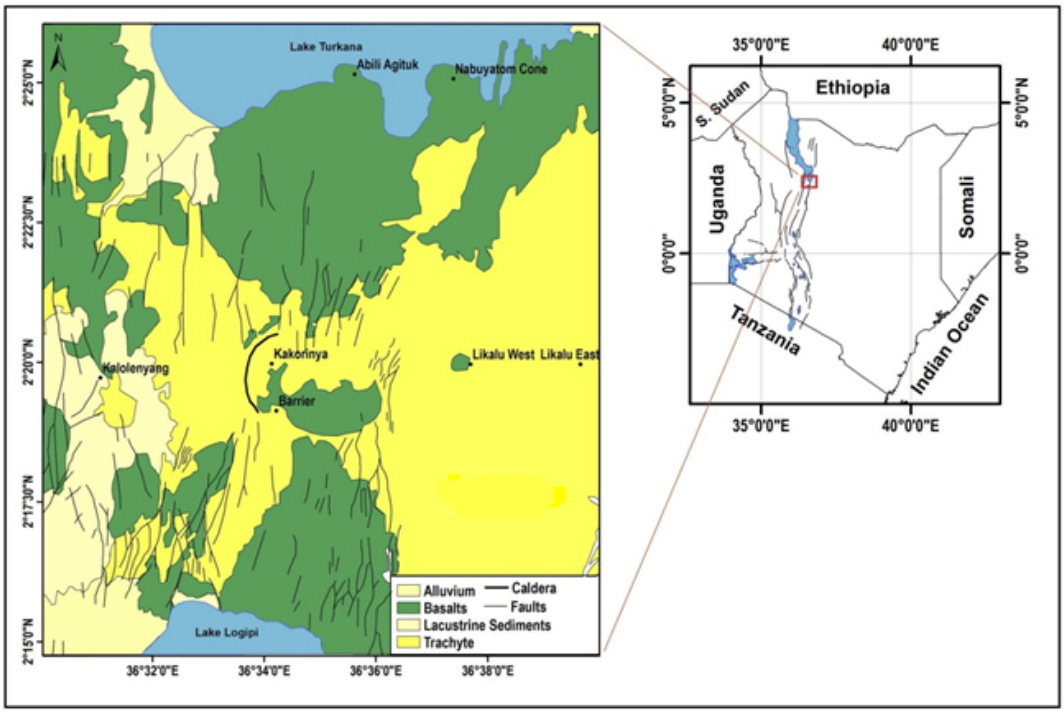

FIGURE 2: Simplified geological and structural map of Barrier Volcanic Complex (modified from GDC, 2011)

Detailed mapping of geothermal alteration on the surface is performed and alteration minerals analysed using XRD. The chronology of the surface alteration is studied in order to understand the temporal variation in the surface activity. An exhaustive mapping of thermal manifestations is performed and the physical properties of surface manifestations are measured and recorded, including temperature, flow rate, conductivity etc. **(**Árnason and Gíslason, 2009).

2.1.1 Photogeology and remote sensing

Photogeological maps and remote sensing images can be used to carry out mapping of geological structures during the reconnaissance and/or the detailed mapping. They serve as an important tool in mapping structures and/or thermal manifestations and other geological features of interest especially and makes it easy to access the remote, highly inaccessible rugged terrains and unexplored areas. The applications of remote sensing to geothermal exploration relies on spectral and spatial properties of airborne and spaceborn remote sensing platforms, i.e. LIDAR (Light Detetion and Ranging), ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) (Figure 3).

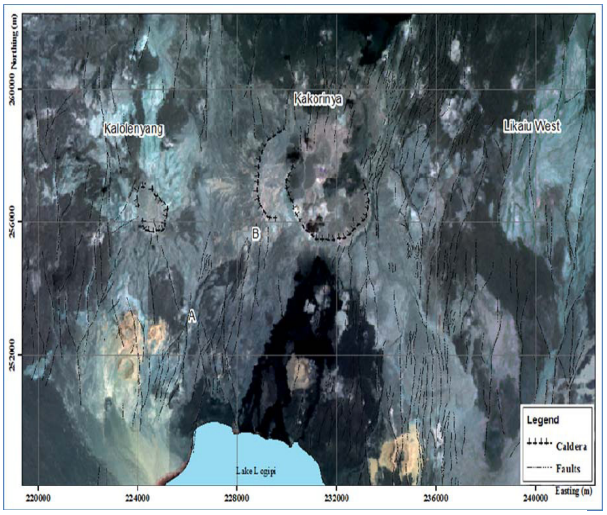

FIGURE 3: ASTER imagery of the Barrier Volcanic Complex (Mutua and Mibei, 2011)

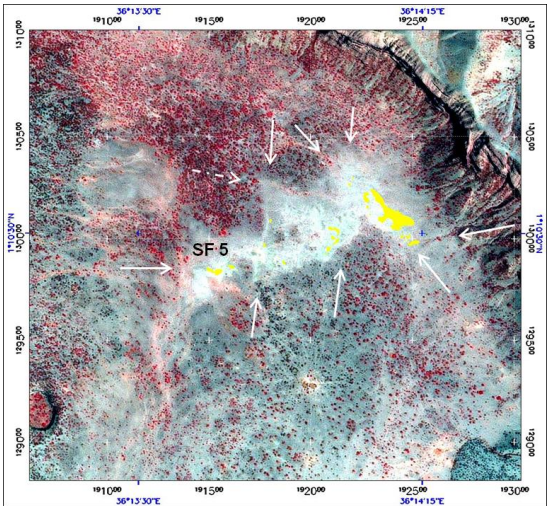

FIGURE 4: Spot image for thermal infrared for Silali caldera (GDC and BGR, 2012)

The imagery of optical, near-Infrared and thermal-Infrared (Figure 4) region of the electromagnetic spectrum can be used to identify surface expressions of geothermal resources (Pipan, 2009). The geothermal manifestations such as sinter/tufa, hydrothermal alteration products (clays, sulfates), thermal anomalies have distinct spectral signatures that can facilitate recognition on the remote sensing imagery.

2.1.2 Hydrological studies

Hydrological studies are performed in order to understand the recharge, flow regime (out flow and water budget) into the system. This is normally achieved by detailed mapping of groundwater (water rest level), cold springs, lake levels and groundwater level and ultimately developing a potentiometric map.

2.2 Geochemical studies

Geochemical exploration for geothermal resources involves sampling, analysis and interpretation of discharge of thermal fluids from fumaroles, hot springs and steaming grounds. The main objectives of geochemical studies are to characterize the thermal fluids, establish their origin, flow direction (upflow, outflow), evaluate mixing scenarios, estimate the equilibrium reservoir temperature and determine the suitability of the fluids for the intended use.

Fumarole and hot spring sampling procedures are those described by Arnórsson et al. (2006), while the analysis of the essential chemical parameters usually done as described by (Ármannsson and Ólafsson, 2006; 2007; Arnórsson et al., 2006). The following subsection provides more details on the information obtained from geochemical surveys.

2.2.1 Classification of thermal fluids

Geothermal waters have been classified with respect to their anion and cation contents into alkali-chloride water, acid sulphate water, acid sulphate-chloride water and bicarbonate water. The ubiquitous Giggenbach (1991), Cl-SO_4-HCO_3 ternary diagram (Figure 5) is used in the classification of waters based on the major anions. The Giggenbach (1988) Na-K-Mg ternary diagram (Figure 6) involving the simultaneous use of a

Na/K and $K/Mg^{0.5}$ ratio is used to establish the equilibrium between the fluids and hydrothermal minerals and ultimately determine the suitability of the waters for ionic solute geothermometry.

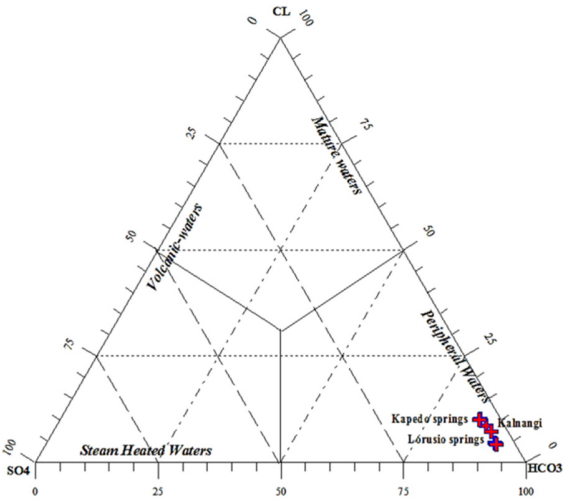

FIGURE 5:Cl-SO_4-HCO_3 of Silali springs

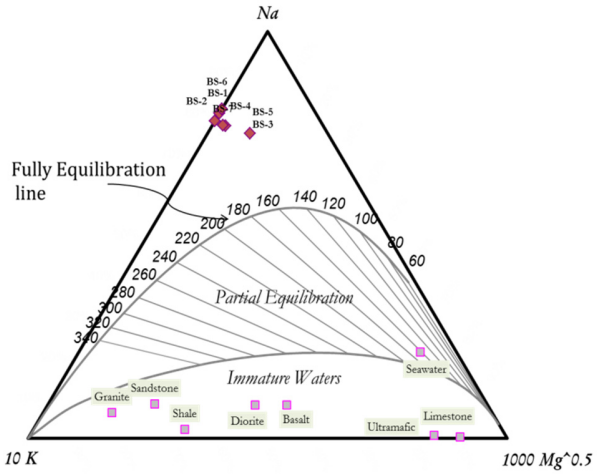

FIGURE 6: Na-K-Mg of the Logipi

2.2.2 Tracing the origin and mixing scenarios

Geothermal fluids are most commonly meteoric and oceanic water although fluids in andesitic geothermal systems, near subduction areas often contain significant proportions of evolved connate and magmatic waters (Ármannsson and Fridriksson, 2009). The knowledge of the origin of geothermal waters is very important in geothermal studies because it helps in discriminating the chemical properties of the thermal waters and also their sources of recharge (Oyuntsetseg, 2009). Stable isotopes studies (especially ^{2}H and ^{18}O) (Figure 7) play an important role in hydrogeological investigations of both thermal and non-thermal waters because the isotopes carry imprints of the origin of the waters.

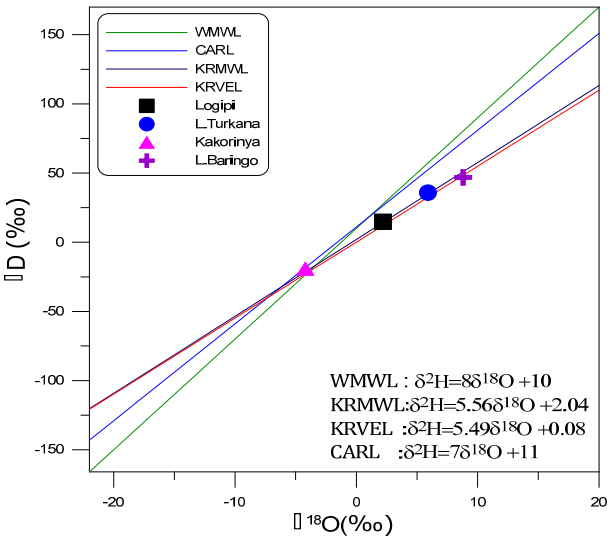

FIGURE 7: ^{2}H and ^{18}O plot for the BVC fluids (modified after Dunkley et al., 1993)

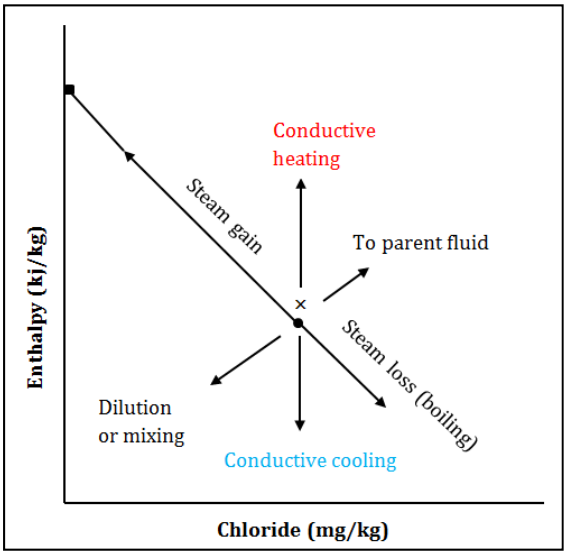

FIGURE 8: Chloride-enthalpy mixing model (modified after Nicholson, 1993)

Additionally conservative constituents (Cl, B) can be used for tracing origin, mixing and flow of geothermal fluids. Gas ratios can also be used to recognize flow directions and upflow zones (Nicholson, 1993). Furthermore, mixing models have been developed to allow estimation of the hot water component in mixed waters emerging in springs or discharged from shallow wells. There are essentially three kinds of mixing models: 1) the chloride-enthalpy (Figure 8) mixing model (Truesdell and Fournier, 1977); 2) the silica-enthalpy warm spring mixing model (Fournier, 1977); 3) the silica-carbonate mixing model (Arnórsson, 2000).

2.2.3 Estimation of reservoir temperature

Rock forming constituents (e.g. SiO_2, Na, K, Ca, Mg, CO_2, H_2) are used to predict subsurface temperatures and potential production problems such as deposition and corrosion (Ármannsson and Fridriksson, 2009). Many chemical and isotopic geothermometers are used to estimate the aquifer temperatures beyond the zone of secondary processes like boiling, cooling and mixing on the basic assumptions that the sampled fluids are representative of the undisturbed aquifers where local equilibrium conditions are achieved.

2.2.4 Soil diffuse degassing measurements

Soil diffuse degassing measurements of CO2, ^{222}Rn,^{220}Rn, and Hg is critical in delineating permeable zones (gas leakages) of the system that are associated with fractures, fissures and other geological structures. Measurements of the diffuse flow of CO_2 through soil in geothermal fields can be useful for the purpose of delineating fractures or other structures that direct flow of fluids in the geothermal reservoir (Fridriksson, 2009).

2.2.5 Determination of the suitability of utilizing the fluids.

The chemistry of the fluids provides a great insight in evaluating the appropriate uses of the fluids depending on the likelihood of scaling and corrosion. In this regard speciation programs are normally used to determine the equilibrium speciation and activity of the chemical species in the effort to predict the potential scaling and corrosion. The most common speciation programs are WATCH, Geochemist Work Bench, CHILLER, TOUGHREACT, FRACHEM and SUPCRT92.

2.3 Geophysical studies

Geothermal anomalies are linked to geophysical anomalies because changes in temperature and geothermal gradient can change subsurface physical properties that influence measurements at the surface (Pipan, 2009). In this respect, a geothermal system generally causes inhomogeneities in the physical properties of the subsurface, which can be observed to varying degrees as anomalies measurable from the surface. The changing physical properties can be measured using different geophysical methods and instruments (Table 1).

TABLE 1: Physical properties and the corresponding geophysical methods and instrument

Physical property	Geophysical method	Common equipment
Electrical conductivity/resistivity	Electromagnetic/electric	MT/TEM
Density	Gravity	Gravimeter
Magnetic susceptibility	Magnetics	Magnetometer
Elastic moduli/velocity	Seismics	Seismometer

It is worth noting that, some of the geophysical methods such as gravity, magnetics and seismics which are traditionally known to be used in the exploration of hydrocarbons are also used in geothermal exploration because they give valuable information on the subsurface geological structures and features. Geophysical methods in geothermal exploration basically aim at determining geometry (shape, size, depth) of the heat source, reservoir, cap rock. Additionally the methods aim at imaging structures that are responsible for the geothermal system, fluid pathways, stress field and delineating the areal extent of the geothermal resource. The following subsection provides more details on the various geophysical techniques used in the geothermal exploration.

2.3.1 Electric/Electromagnetic survey

Electric and electromagnetic methods provide the electrical resistivity (ρ) or its reciprocal electrical conductivity (σ) of the subsurface. The electrical resistivity depends basically on: temperature, pressure, clay content, rock mineral association, porosity structure, saturation- fluid content, salinity of the fluid and fluid movement. It is worth noting that, resistivity decreases with increasing porosity and increasing saturation. These indeed make it easier for resistivity survey in particular to locate anomalies that are directly related to the presence of geothermal fluids.

Electromagnetic (EM) sounding methods used in geothermal exploration are natural-source induction methods (magnetotellurics and audiomagnetotellurics), and controlled-source induction methods (CSMT, TEM), while electric methods (DC methods) include Schlumberger and Wenner sounding methods, the dipole–dipole and the bipole–dipole mapping method.

Deeper probing is commonly done by magnetotellurics (MT) while shallower probing is usually done using the central loop TEM method, (or DC methods). TEM soundings also help in the static shift correction of the MT data.

2.3.2 Gravity survey

Gravity survey measures variations in the Earth's gravitational field caused by differences in the density of sub-surface rocks. Gravity measurements give structural information and can also give indications on massive intrusions, which may act as heat sources. A Bouguer map should be produced to study density anomalies, and selected profiles might be measured with dense station spacing for more detailed structural studies such as buried faults (Rivas, 2013). Density reduction due to partial melts may also be detected by gravity anomalies. Positive gravity anomalies usually imply higher density values which are normally associated with plutonic intrusions and dykes, deposition of silicates from hydrothermal activities during greenschist metamorphism, while negative gravity anomalies implying lower densities values caused by higher porosities or by highly fractured parts of a rock, alteration minerals produced by circulation of hot water (Pipan, 2009). The primary use of gravimetric measurements is to help constrain the structural context of an area, outline trends of faults or the depth of the basement.

2.3.3 Magnetic survey

Magnetic measurements are performed using magnetometers either at the surface or airborne, if the objective is regional mapping and the measurements are dependent on the magnetic susceptibility of geological materials. Magnetic surveys can map demagnetized rocks due to thermal alteration and surveys give complementary structural information, which helps in the interpretation of other data. Pipan (2009) deduced that high-resolution aeromagnetic (HRAM) surveys have a resolution in the subnanotesla scale, such that magnetic surveys are no longer restricted to magmatic rocks but can also be used to map

intrasedimentary faults with elevated magnetite concentrations that generate small anomalies. Such HRAM surveys are often used in hydrocarbon exploration.

The magnetic susceptibility of a rock and the temperature at which it disappears depend strongly on the rock components, the more or less magnetic minerals (Rivas, 2013). The most useful magnetic minerals are magnetite, ilmenite, hematite and pyrrhotite. Silicate minerals, rock salt (halite) and limestones (calcite) have a very low magnetic susceptibility and are therefore not useful for magnetic measurements. Demagnetised rocks confirm the existence of a hot rock mass in the crust. The presence of dykes is revealed by high susceptibility. On the other hand circulation of hydrothermal fluids causes alterations in the rock which lead to a reduction in susceptibility. This reduction is a consequence of the destruction of the magnetite contained in the rocks. That way, units of volcanic rocks and lava flows can easily be distinguished from hydrothermally altered rock units, which make geomagnetic surveys a useful tool for geothermal prospecting at high enthalpy volcanic reservoirs (Pipan, 2009).

2.3.4 Seismic survey

Seismic survey depends on the elastic properties influencing the propagation velocity of elastic waves. Anomalously hot mass of rock delay the transit of the compressional (p) waves from earthquakes and reduce the amplitude of the shear (s) waves. Seismicity analysis gives information about fractured zones, active faults and some indications of the heat source of the system. The spatial distribution of the seismicity could also indicate the extension of the geothermal reservoir. Cooling of the heat source can produce micro-seismicity (Árnason and Gíslason, 2009). It can be a good practise, if a considerable number of seismic stations are deployed in geothermal prospects that are located in active geodynamic settings.

Results from volcano-seismic studies of many geothermal fields show that they are possible resource mapping tools for geothermal exploration and reservoir monitoring. The volcano-seismic approach can be useful as a stand-alone tool for analysing geothermal resource both at the exploration and exploitation stage that is cost effective in the long term (Simiyu, 2009; Rivas, 2013).

2.3.5 Heat flow measurements

The primary objective of heat flow measurements is to estimate amount of heat energy being lost naturally, analyse the distribution of heat loss features and locate hidden fracture zones. Heat loss is related to temperature gradients. Heat loss mechanisms are conduction, convection and radiation. In geothermal settings, heat is lost through conduction-mainly in contact with the system rock bodies, through convection: mainly through discharging fluids e.g. fumaroles, steaming ground, hot springs etc. High heat loss anomalies usually coincide with the structural trend and/or areas with thermal manifestations.

Soil temperature and heat flow measurements can often map structures, such as faults or fissures which control flow of geothermal fluids but are not immediately recognised on the surface. Heat flow maps can also give information about heat sources and aid in the interpretation of other data (Árnason and Gíslason 2009).

2.4 Conceptual model and well siting

Conceptual model is a descriptive or qualitative model incorporating, and unifying, the essential physical features of the systems in question (Grant and Bixely, 2011). A geothermal conceptual model (Figure 9) can incorporate information such as; size, temperature (indicated by isotherms), two-phase and steam-dominated zones, secondary aquifers, reservoir, permeable flow structures (faults, fractures, horizontal layers, etc.), flow patterns including upflow, outflow and recharge (indicated with arrows), processes like

mixing, chemical buffering or boiling, internal flow barriers like dikes or sealing, the cap-rock, the nature of the heat source. These information can be derived from the various geoscientific disciplines.
The process of developing a geothermal conceptual model entails but not limited to reviewing of all geoscientific resource data, developing relevant ideas and possible alternatives, drawing cross-sections and maps, studying geothermal system analogs and coming up with a story that binds the model. Mortensen and Axelsson (2013) affirmed that conceptual model aims at highlighting the distribution of temperature, pressure, permeability and fluid chemistry within the geothermal reservoir in order to delineate the direction of fluid flow and circulation (e.g., hot upflow, outflow and colder recharge) symbolized with arrows.

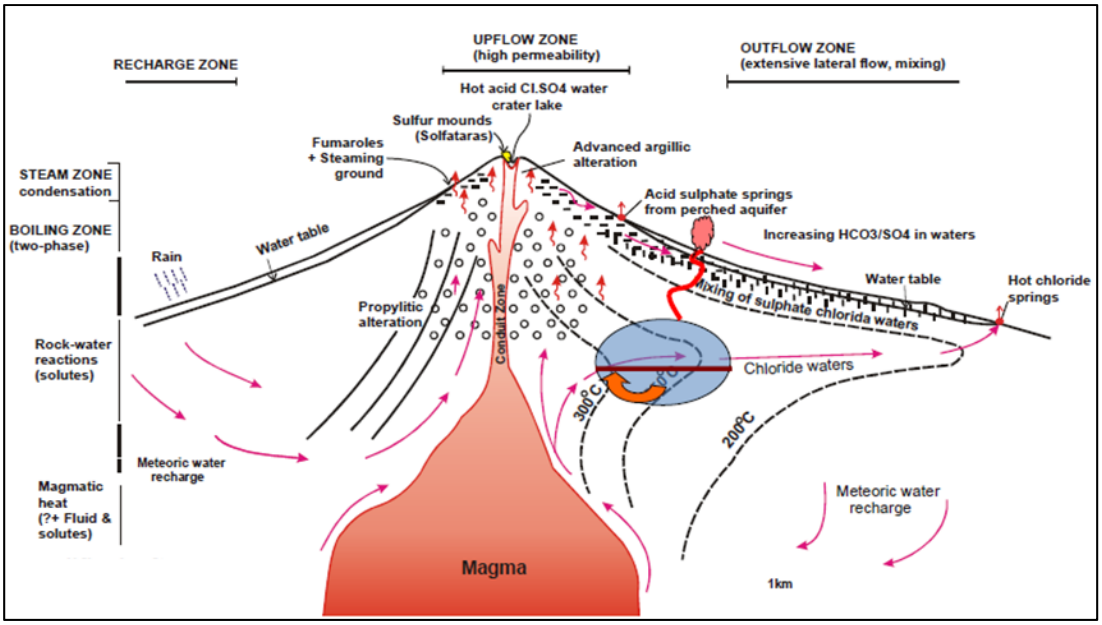

FIGURE 9: Conceptual model of volcanic geothermal system (modified after Nicholson, 1993)

Data integration of the geoscientific disciplines can either be GIS based or through other sophisticated software in order to develop a suitability model that can help in locating the suitable drilling targets. Different weights can be put on the various geoscientific methods depending on the amount of information each discipline gives about the system in question. Árnason and Gíslason (2009) deduced that a good practice is to prepare a comprehensive geothermal database that accompanies the geothermal map. Emphasis is put on investigating the relation of the thermal manifestations to tectonic features and volcanism, if present. This is done to get ideas on heat sources (magmatic or intrusive), hydrology, and flow paths in the permeable reservoir.

2.5 Environmental baseline survey

Geothermal is one of the most environmentally benign, renewable and indigenous energy resource in the world. During its exploitation, waste gases that include carbon dioxide and hydrogen sulphide and brine are released into the atmosphere. However, in most cases, the gas concentration levels are within the World Health Organization (WHO) permissible exposure limits, the brine can be re-injected fully, and by re-injecting the brine apart from disposal, it has an added benefit of recharging the reservoir as well. Nevertheless, sustainability and mitigation of environmental effects should be outlined and optimized prior to major financial commitment.

Environmental Baseline Survey (EBS) is invariably carried out and the output subsequently used in fully-fledged Environmental Social Impact Assessment (ESIA) study for the envisaged geothermal energy development project. The EBS involves socio-economic aspects of the project area, the meteorological conditions, the flora and fauna, water resources etc. Geothermal potential is generally localized in remote, arid and semi-arid regions in the Kenyan perspective. In the spirit of evaluation of the socio-economic pros and cons (Figure 10), the positive effects by and large do outweigh the negative effects of geothermal development.

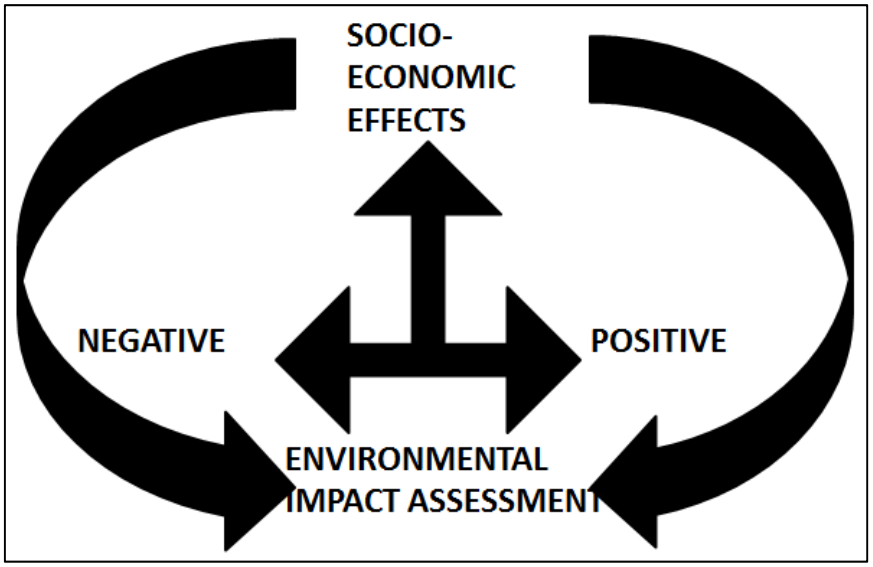

FIGURE 10: The Pros and cons of the socio-economic effects of geothermal project

3. CONCLUSIONS

- Geothermal exploration is indeed a multi-geoscientific process, which entails geology, geochemistry and various geophysical techniques, and in essence no single method can comprehensively unravel a geothermal system.
- The multi-skills process aims at determining the features and properties of a geothermal system; heat source, reservoir, cap rock, recharge and permeable regime.
- The epitome of exploration is to determine the existence of a geothermal resource and subsequently identify suitable drilling sites based on integrated data.
- Geothermal exploration is a sequential and a systematic process, and normally carried out on a step-by-step basis with each of the phases involved aimed at gradually eliminating the less interesting areas and focusing on the most promising ones.
- Successful surface exploration will save big money when geothermal project enters development phase.
- Sustainability and mitigation of any possible environmental effects should be outlined and optimized prior to major financial commitment.

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GEOLOGICAL FIELD MAPPING

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ABSTRACT

A map showing the distribution of rock units and structures across a region representation, usually on a plane surface is termed a geological map. A map showing the occurrence of structural features across a region, the distribution of rock units, and their type and age relationship is termed a geological map. Geological field mapping is the process of selecting an area of interest and identifying all the geological aspects of that area with the purpose of preparing a detailed geological report which must include a map. The three basic reasons why geological field work is carried out include exploitation of natural resources, as a requirement of the government and for academic purposes. Good geological mapping should be executed in three phases; planning, data collection and reporting.. Certain parameters must be considered when mapping geology, geological landforms, structures and geothermal manifestations the most important being detail, accuracy and precision. The resulting geological map should be compiled and interpreted with the input of all parties involved including expertise advice from those who have adverse experience in geology as well as other related disciplines.

1. INTRODUCTION

A *map* is a visual representation of an area - a symbolic depiction highlighting the relationships between elements of that space such as objects, regions and themes. A map showing the distribution of rock units and structures across a region, usually on a plane surface, is thus a geological map.

Geological field mapping is the process of selecting an area of interest and identifying all the geological aspects of that area with the purpose of preparing a detailed geological report and a map to summarize the report. A geological map will thus show the various rock types of the region, the structures, geological formations, geothermal manifestations, age relationships, distribution of mineral ore deposits and fossils etc. and all these features may be super imposed over a topographic map or a base map. The amount of detail shown in a map depends largely on the scale and a smaller scale will naturally disclose finer detail. Basically, the quality of a geologic map will depend upon the accuracy and the precision of the field work. Further still quality depends on the completeness with which certain data, both geologic and geographic are presented on the maps; and on the care with which scale, colours, conventions, etc are chosen to give the best results (Eckel, 1902). With the development of technology however, geological maps today are more precise than ever as a combination of accurate satellite imagery, aerial photographs, high tech geological equipment and Geographic Information Systems (GIS) advancements are applied.

The interpretation of a geological map depends on ones training, interest and the techniques used. It is also fundamental to be able to visualise scenarios that may have been involved during the formation processes of the features displayed as this forms an essential foundation for the analysis of geological maps. The ability to form a three- dimensional image from a two dimensional plan is in real sense the major part of geologic map interpretation (Bolton, 1989).

2. OBJECTIVES OF GEOLOGICAL FIELD MAPPING

Principally there are various reasons why geological field mapping is carried out all of which entail collecting variable amounts of field data. These reasons can, however be summarized into three broad objectives which may sometimes be interconnected; natural resources, government mandate and academic objectives.

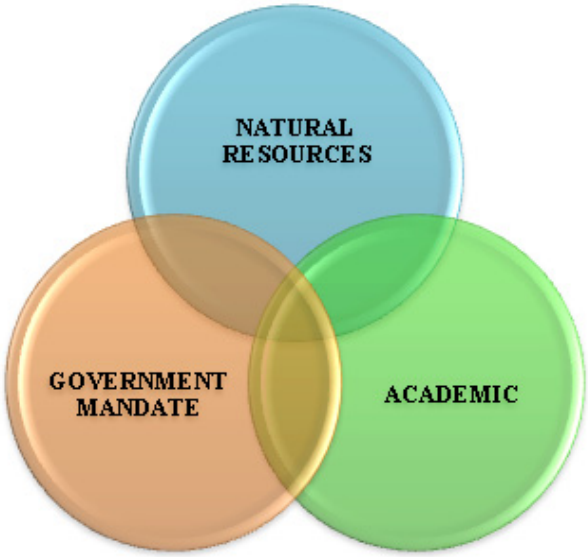

FIGURE 1: Objectives of geological field mapping.

2.1 Natural resources

These are naturally occurring materials that exist within the earth's crust and are extracted mostly for economic purposes. Exploitation of all natural resources requires the appreciation of basic geology and optimum utilization of a potential area requires that the resource is mapped out. Understanding the spatial distribution and deformation of rock units at the surface is critical in order to develop 3-dimensional models of the subsurface geology. Mineral and oil exploration proceeds in this way, particularly when considering the siting of boreholes (Epler, 1997). In geothermal fields, the geology of the area has to be thoroughly investigated and understood using a combination of geological, geophysical and geochemical methods before a decision is made on the productivity of that area. Geological mapping is usually the first task in any reconnaissance study as the question of whether or not a geothermal system exists can be answered using geological studies. Geophysical investigations answer the question of the extent of the system while geochemical investigations are used to estimate parameters such as the temperature of the system.

2.2 Government mandate

In order to better understand an unknown area, geological mapping is carried out by learning and/or government institutions. The maps created are thereafter used as references for planning purposes in development projects, prevention of adverse destruction during natural disasters such as earthquakes

(hazard preparedness) impact assessment studies, proper utilization of resources etc. Most government structures have a geology ministry/department that ensures that geological maps are available, that they are accurate and updated whenever changes arise. Ultimately all governments have an important role to collect and administer geological data, information and knowledge while protecting and preserving the area in question at the same time.

2.3 Academic

The third reason is to shed some light on the processes that have moulded the earth to what it is today. Processes in the subsurface are not fully understood and the in mapping geological features on the surface we get some insight into the more complex systems that we do not see. Therefore, in dealing with a limited data source, geologists are forced to leave no stone unturned in acquiring the basic data for developing models of geologic history and process, and, in contrast with many other sciences, to use a healthy dose of imagination in interpreting what is almost always an incomplete data set. (Epler, 1997). Many earth science institutes work tirelessly in creating models and proposing theories that may have explained various geological formations, structures and lithologies, where geological maps have been the foundation of these studies.

3. PHASES OF GEOLOGICAL MAPPING

Field mapping projects are carried out in three phases which have a stepwise relationship.

FIGURE 2: Phases of geological field mapping

3.1 Planning/research

This phase of mapping is mostly carried out in the office although a short reconnaissance field trip may be included. Once a field has been identified for mapping, it is only rational to learn everything in its regard so as to make a workable field programme. A field programme is a step-by-step guide that outlines the time to be spent in the field and the objectives of each day thus ensuring successful and satisfactory results. Compilation of all available and relevant data is implemented, in an effort to avoid duplication of work and most importantly simplify the field study. The number of days spent during the research phase may vary based on the purpose of the study, the detail required and availability of

funds. All possible geological reports and data, including aerial and satellite photographs, maps whether topographical, base maps, legislative boundary maps etc. must be obtained. The most important document however is the official approval by a government office and/or a local community. Without this one may be met with hostility and lack of cooperation by the locals and this may lead to an unsuccessful field study. A budget must also be prepared indicating the number of people to be involved in mapping, their daily allowance, fuel costs if vehicles are to be used, consumables and a miscellaneous kitty should be included. It is wise to involve the local community when employing casuals or language translators as they understand their environment better than anyone else and will thus be quick to pinpoint areas that maybe of interest. Furthermore, they are in the best suited to relate historical events where necessary. Issues that may hinder optimum productivity such as bad weather, wild animals and events of sudden sickness must be taken into consideration and planned for appropriately.

3.2 Observing/mapping/collecting

This phase is focal in any geological field mapping and is carried out in the field for the sole purpose of collecting data. This data may be collected in the form of photographs, measurements, notes and physical samples. Therefore, one must be fully equipped with all the necessary tools, be physically psyched and mentally prepared to make note of not only geological features but of the entire surrounding. For example, phreatophytes may be used to locate structures especially when they grow in a certain alignment. When good strategy is involved during the planning phase, unfortunate incidences in the field are addressed promptly with no major disruptions of the field program. In tropical countries such as Kenya, it is advisable to plan for field studies during the dry seasons. Thus it is in the best interest of everyone to commence mapping work very early in the morning so as to accomplish a substantial amount of work before the temperatures rise too high. In colder climates such as Iceland mapping is usually planned for the summer and may begin at anytime of the day and extend well into the night as daylight is prolonged to about twenty hours. Thus there should be no strict working hours in the field and this should be agreed upon among the field crew. Teamwork should be encouraged given that more observations are likely to be made and geological contentious issues discussed. A mapping project must be qualitative as well as quantitative. Accuracy whilst taking readings should be emphasized and no amount of information is too much therefore all possible data should be collected.

3.3 Reporting

It is often said that a report is as good as its data and thus the need to collect good accurate data cannot be overemphasized. Ultimately when all possible available data has been collected it is taken back to the office or laboratory for sorting, interpretation and analysis. This phase is the most challenging of all three as wrong analysis or misinterpretation of data can lead to an inaccurate report and in consequence misinformation. The resulting map or model is in most incidences drawn by persons of another section (for example cartography) who may have had no involvement in the field whatsoever. Thus it is crucial that the data collector, in this case the geologists, work closely with those involved in actual drawing of the map, since they can select the data that is relevant for final presentation in the map and that which is not.

4. TOOLS AND EQUIPMENT USED IN GEOLOGICAL FIELD MAPPING

- *Maps:* During the research phase all existing data and maps of the field in question are collected. All suitable maps available whether physical, political, relief, road, physical, and topographic should be carried to the field as it is possible that details in one may not be present in another. Most importantly for geological fieldwork, a geological map is expected to be handy especially as

a reference. Depending on the areal extent of the field and the detail required, the scale of the map is an important aspect to consider.

- *Aerial photographs and stereoscope:* This 3D imagery tool is very vital for all geological field work especially where large features such as volcanoes, calderas craters etc. are involved. In addition photos are also used to pinpoint thermally anomalous areas in geothermal fields when infrared thermography is applied. These photographs are studied with the aid of a stereoscope and are put to use before and during the field study; for planning in the case of the former and for confirmation purposes in case of the latter. Where aerial photographs may not exist, satellite imagery may be used although it may not possess the fine detail as seen on the aerial photographs.
- *Compass/Clinometer:* A compass is an instrument used for determining direction and has recently been supplanted by modern devices such as the Global Positioning System (GPS). However when acquiring a clinometer it is advisable to purchase one that has a built in compass in it. This is for the reason that a GPS can at times malfunction or it may not locate satellites in areas of thick/dense forest cover. A clinometer is an instrument used for measuring inclination, tilt and elevation of rock outcrops. This is particularly important in areas that have been subjected to tectonic movement. These days, however technology advancement ensures quick and easy measurement of strike and dip of a surface (bedding plane, foliation, fault plane etc.) in a single action. Unlike a conventional compass or clinometer, which needs two actions to fulfil a measurement, you place a GeoClino on a surface and measure the strike and dip that significantly saves time and labour. The build-in GPS makes it possible to measure latitude and longitude that can be saved in the GeoClino-G memory along with other measurements. It is also possible to use GeoClino as a normal GPS receiver.
- *GPS(Geographic Positioning System)* is a satellite based navigation system comprising three basic parts; the satellites in space, monitoring stations on earth and the GPS receivers. This equipment is used in geological field mapping for finding ones position, mapping lithologies, tracking structures, measuring elevation, storing sampling points and descriptions of formations when samples are collected. The GPS functions and capabilities are improving rapidly with advancement in technology and as such it is important to purchase one that is relatively modern.
- *Geological hammer* is basic equipment for any geologist as it is the tool used for collecting samples. The best geological hammers are the ones with a piece chisel head made of hardened steel and a rubber coated shock reduction handle. For harder formations, a crack geological hammer forged from fine grain carbon steel with fibreglass shaft fitted with comfortable shock-absorbing rubber grip, is recommended.

FIGURE 3: Chisel head and crack geological hammers

- *Hand held lens* is used to make the first analysis of rock samples in the field before further analysis is performed in the laboratories. The analysis needs to be detailed and descriptive giving all properties of the sample: rock type, colour, texture, identifiable mineralogy, alteration as well as the physical properties such as folding, foliation, intrusions, layering etc.

- *Sample bags* which best suit geological samples are canvas in fabric have a sewn in tie tape and a label tag on the outside to insert the sample number and location point. Plastic bags may be used where the sample is soft, disintegrated or wet.
- *Measuring tape* is important for taking actual measurements of lithologies and structures. For instance in lithologies that exhibit layering, it is necessary to measure the thickness of each layer precisely, as this can be used as a correlation tool with other similar sequences that may be encountered.
- *Field notebook, masking tape, marker pens:* All important observations must be written down in a concise, orderly and legible manner. The field note book should be hardcover for ease when writing and should easily fit into a pocket. Masking tape and marker pens are used for labelling samples before they are put into the sample bags.
- *Field camera* is the only back up memory in addition to the notebook. It is very important to take photographs of all interesting features ensuring a scale is used in each instance; video clips can also be of use. One must also remember to take a GPS reading for each photograph taken. Photographs are important for descriptive purposes especially during report writing and for making presentations.
- *Safety clothing*: These include sturdy shoes, clothes that are tough in fabric preferably jeans or khaki, hat and sunglasses to protect one from the sun a bag pack, plus a raincoat and wellington boots just in case of wet environments. Safety glasses and gloves are important especially when hammering rock samples. Safety clothing should aid one to be more effective by being comfortable and safe at the same time.
- *First aid kit:* Safety in the field is always a priority; nevertheless accidents cannot be ruled out thus the need to be prepared with a first aid kit. Furthermore, it is crucial that at least one person in the field crew be trained in basic first aid techniques.
- **Geologist imagination* is the most expensive equipment of all. Most of the earth processes have never been witnessed in an actual sense. Thus it took the imagination of the early scientists to have the models we have today. Most of these models have been tested over time and have been proven to be true. Consequently when carrying out geological field mapping, one needs to use their imagination when viewing geological formations and structures.

5. PARAMETERS TO CONSIDER IN GEOLOGICAL MAPPING

Geology. When mapping rock types, it is important to have a carefully laid out plan for the entire location so that traverses can be made without leaving out some areas. A careful study of aerial photographs and topographical maps can aid one to avoid areas that are impractical to traverse on foot or impossible to climb because they are too steep. In areas where there is thick soil cover, riverbeds, valleys or exposures on hill tops are sort after for outcrops.

Collecting fresh samples is a process performed carefully, ensuring that the sample is not altered. The sample size depends on its intended use, be it for binocular, petrographic, X-ray analysis, whole rock analysis or just for reference. However, a sample should not be too big as to become a problem to carry while in the field. When acquiring a sample for whole rock analysis, it is advisable to break it using another rock from the same formation to ensure that it is not contaminated by metals from the geological hammer.

Geological descriptions must be unambiguous such that other observers given the same sample would describe it the same way (Wyllie, 1999). Moreover, every fine detail must be included whether it is deemed geologically relevant or not.
Strike and dip are a technique of relating the orientation of a plane in three dimensional spaces. The technique is usually applied to the orientation of tilted layers of rock and thus one can easily see the disarticulation a formation has undergone. As mentioned earlier a clinometer is used for these measurements which should be carried out more than once with utmost precision.

Geological landforms. Geological landforms in this paper refer to features such as mountains/hills, calderas craters, canyons etc. The magnitude of these formations (usually large) can be estimated from aerial photographs and maps prior to the actual field work. The dimensions of these formations must therefore be obtained by actual measurement. The recommended method is to traverse the formation on foot while using a GPS to track the movements. For example, to map the dimensions of a caldera it is in best practice to first measure the rim by walking around it ensuring the GPS is in tracking mode. Since the elevation will be known by walking up the caldera one should then walk into it for further measurements. All lithologies should be mapped both in the interior and exterior of such formations. In some instances landforms such as calderas and craters may not be obvious on the surface due to erosion and weathering which may leave only a few exposures on the surface. If such outcrops are ignored it would be difficult to realise the connection if another exposure of the same kind is found in another location. Needless to say, a structure can easily be left out if work is carried out hurriedly.
Geological structures (Faults and fractures). Faults and fractures always indicate movement within the earth's crust. They are distinguished from each other by whether displacement (lateral or vertical) has taken place; faults show displacement whilst fractures do not. Differences aside, the mapping of these structures needs to be done meticulously due to the fact that these structures may easily be confused with simple erosional surfaces. Erosional surfaces may sometimes be an indication of an underlying structure. The disparity is whether any observable disturbance can be seen in the bedrock. Structures like geological features may not always be obvious on the surface. In volcanic areas, they may manifest as volcanic centres or fumaroles oriented in a linear direction which become obvious once a map is compiled. Thus it is imperative to be accurate in measuring all formations and structures with well calibrated equipment so that if extrapolations are to be made for modelling purposes the error margin is very slim.

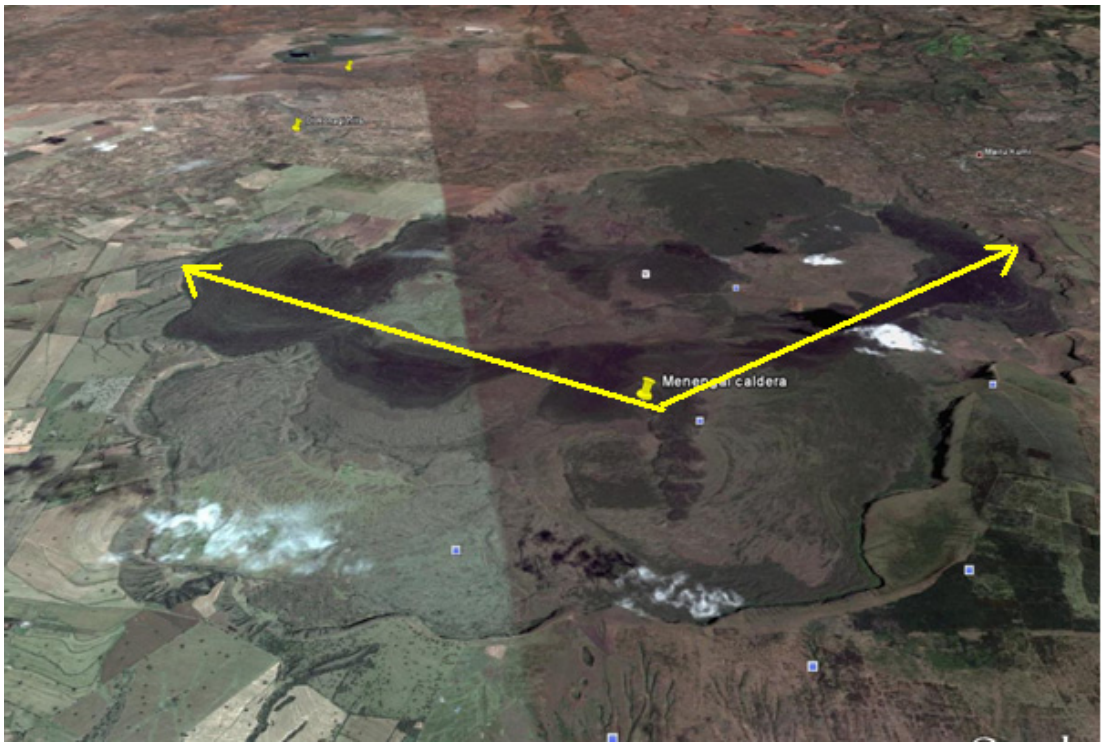

FIGURE 4: Satellite image of Menengai caldera. The dark lava flows on trachytic eruptive centres imply orientation to the northeast and northwest and these can be inferred as structures.

Geothermal manifestations. Geothermal manifestations, whether hot springs, fumaroles, altered or hot ground, geysers, steam jets or sulphur deposition, must be mapped and their extent measured. All observable characteristics should be fully described and photographs taken. Intrusive rocks must be analysed in detail making note of their composition, quantity, orientation and if any sequences can be

identified they should be numbered accordingly. All new mineralisation should be sampled regardless whether the same formation has been sampled elsewhere.

6. COMPILING GEOLOGICAL MAPS

With the aid of GIS (Geographic Information Systems), maps of good quality and great accuracy are produced. Evidently it is important to consult with the GIS department before field work to calibrate the GPS in a format/units that can easily be used with their software. Nonetheless, it is important for a geologist to draw a simple sketch map during field work for comparison purposes.

7. INTERPRETING GEOLOGICAL MAPS

Once a map is complete, the most important task ahead is interpreting it correctly. A map is basically a visual summary of an entire report and the two should complement each other. When the interpretation process is at hand, it is crucial to have group discussions with all those involved in the actual fieldwork. It is also deemed important to have discussions with those who are experienced in field of geology as well as other related scientific fields.

8. CONCLUSION

The following can be said to summarize geological field mapping:

- For geological field mapping to be carried out efficiently, it is essential that proper planning is executed.
- Once in the field, it is also important to be as detailed as possible in all descriptions, to be keen and observant.
- Measurements must be performed meticulously and, if necessary, more than once for confirmation purposes.
- Team work must be adhered to, throughout the entire process.

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GEOPHYSICAL FIELD MAPPING

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ABSTRACT

Geophysics is the study of the earth by the quantitative observation of its physical properties. In geothermal geophysics, we measure the various parameters connected to geological structure and properties of geothermal systems. Geophysical field mapping is the process of selecting an area of interest and identifying all the geophysical aspects of the area with the purpose of preparing a detailed geophysical report. The objective of geophysical field work is to understand all physical parameters of a geothermal field and be able to relate them with geological phenomenons and come up with plausible inferences about the system. Four phases are involved and include planning/desktop studies, reconnaissance, actual data aquisition and report writing. Equipments must be prepared and calibrated well. Geophysical results should be processed, analysed and presented in the appropriate form. A detailed geophysical report should be compiled. This paper presents the reader with an overview of how to carry out geophysical mapping in a geothermal field.

1. INTRODUCTION

Geophysics is the study of the earth by the quantitative observation of its physical properties. In geothermal geophysics, we measure the various parameters connected to geological structure and properties of geothermal systems. In lay man's language, geophysics is all about x-raying the earth and involves sending signals into the earth and monitoring the outcome or monitoring natural signals from the earth. Geophysical field mapping is the process of selecting an area of interest and identifying all the geophysical aspects of the area with the purpose of preparing a detailed geophysical report. Before any survey is undertaken, objectives of the study must be well defined and attainable. Since there exist numerous geophysical methods, the geophysicist must be able to choose methods that will be applicable in the area, cost effective and be able to give solution to the problem at hand. There are various reasons why we carry out geophysical surveys and they include: prospecting for geothermal resources, mineral resources (metallic and non metallic), petroleum and gas, water resources (surface and ground water), geo-hazard assessment (volcanic, seismic), engineering foundation design (geotechnical) and environmental issues.

In geothermal geophysics, we measure the various parameters connected to geological structure and properties of geothermal systems (Hersir and Bjornsson, 1991). A geothermal system is made up of four main elements namely, a heat source, a reservoir, fluid which is the carrier that transfers the heat and fluid path ways (e.g. faults and fractures). Parameters that characterise a geothermal system are temperature, porosity, permeability and chemical composition of the fluid. Our interest is in areas where we get high temperatures, high pressure, high porosity and good permeability and low content of dissolved solids and gases in the water.

1.1 Objectives

A study area is selected to answer specific geophysical questions based on literature review or specific interests. The main objectives for carrying out geophysical surveys in geothermal areas are:

- To detect and delineate geothermal resources
- To identify and locate exploitable reservoirs
- Estimate geophysical properties of the geothermal system
- To get a conceptual model that will assist in siting of the drill holes through which hot fluids at depth will be exploited.

2. GEOPHYSICAL METHODS

A wide range of geophysical surveying methods exists for exploration for geothermal energy as well as the monitoring of geothermal reservoirs under exploitation (Ndombi, 1981; Mariita, 1995; Simiyu and Keller, 1997). The type of physical property to which a method is sensitive to assists in deciding the method to be used in a particular survey depending on the outlined objectives. Geophysical method can be divided into the following two categories:

- Direct exploration methods - These are methods where the variation in physical properties is directly related to the geothermal system (e.g. temperature). They include thermal and electrical methods (DC and AC methods).
- Indirect exploration methods – In these methods, physical properties investigated do not directly relate to the geothermal system. An anomaly is caused by associated geological formations or structures (e.g. fault, dykes). They include structural methods (gravity, magnetic and seismic).

2.1 Main geophysical methods

Geophysical methods play a significant role in the investigation of geothermal prospects because they are the only means to finding deep subsurface structures at much lower costs than the most direct method, drilling. A relatively wide area can be surveyed within a short time using geophysical techniques although the methods are sometimes prone to major ambiguities in data interpretation. Geophysical surveying does not overrule the need for drilling but, if properly applied, it can optimise exploration programs by maximizing the rate of ground coverage and minimizing the drilling requirement.

The main geophysical methods applied in geothermal exploration are:

- Thermal methods (soil temperature, heat flow)
- Electrical methods (resistivity, self potential)

- Gravity method (rock density)
- Magnetic method (rock magnetization)
- Seismic methods – passive method (wave velocity, seismicity, geological structures)

It should be noted that there is no superior method thus integration of different geophysical techniques can be effective in mapping defined structures in tectonic regimes where geothermal resources can be found. However, electrical and electromagnetic methods are commonly applied in geothermal exploration. A geophysicist should carefully choose methods to be applied bearing in mind there are different methods for low and high temperature systems.

3. PHASES OF GEOPHYSICAL FIELD MAPPING

Geophysical project are implemented in four phases that are interrelated and important. They include desktop studies/planning, field reconnaissance, data acquisition and report compilation.

3.1 Desktop studies/planning

This phase of mapping is mostly carried out in the office. It involves identifying a field study and outlining objectives of the field survey and then planning how field work is to be done. Once the field is identified, the geophysicists compile all existing and relevant information on the field which includes literature review and map compilation. This is done to avoid duplication of work and most importantly simplify a field study by being more organised. A field plan is then drawn up which outlines how field work will be carried out in terms of number of personnel, duration of work, methods to be applied and resources needed. When preparing the field programme, various factors should be considered since they impact on the quality and quantity of data collected. They include, kind of survey applicable, availability of personnel, funds available, weather, objectives of the study and output required. It's advisable to carry out field surveys during favourable weather e.g. during dry seasons in tropical countries and during summer or fall in colder countries.

Resources such as maps (topographical, base maps), data and existing geological and geophysical reports are obtained and reviewed. A field budget must also be prepared that details costs involved such as fuel, consumables, casual /guards hire, number of personnel and their allowances and miscellaneous costs. Official approval by the government or institution must be obtained. Equipments to be used should be identified and arranged, calibrated and tested prior to the field work.

3.2 Reconnaissance

This phase of mapping is carried out in the field and aims at ensuring the area is suitable for the planned study. It involves assessing the road network and ensuring the area is accessible. Where to store the equipments and charge them should also be identified during this phase. Casual workers/ guards availability, weather patterns, fauna and flora in the area (e.g. buffalos in a park) and security issues should be looked at. Since geothermal resources occur mostly in traditionally important or protected areas, it's important to dialogue with the local community and obtain approval from them to carry out the study. This ensures lack of hostility and cooperation by the locals. It is prudent to involve the local community since they understand their environment better than yourself and can pinpoint areas that maybe of interest. They also may give you a historical background of the area.

3.4 Data acquisition

This phase aims at acquiring good geophysical data. It follows field reconnaissance and takes up more time than the other phases. For a successful survey, data should be acquired properly and in an organised manner. The field crew must be fully equipped with all the necessary tools, be physically psyched and mentally prepared to collect good data. Data may be digital or analogue. Accuracy while

taking measurements and setting parameters in the equipments should be emphasized at all times. Remember, garbage in, garbage out. Data should be well recorded and entered in a field book which ought to be water resistant. Remember to detail and write more than less using illustrations and sketches. Geological features, power sources, topography, location of measurements, date, time, equipment used, station number and name of operator must be well recorded in an organised and legible manner. It is a good practice to always view your data in the field and judge the quality and quantity of the data and repeat if necessary. This saves time and money. Copies of data and field book should be made. Above all, the field crew should work as a team for better results.

3.5 Report compilation

This phase ensures that a good detailed geophysical report is prepared. It involves reporting results obtained after data acquisition, processing and interpretation. It is the final stage in the survey and is done at the office. It is also the most challenging stage where keenness is extremely important.
The general problem in geophysical surveying is the ambiguity in data interpretation of the subsurface geology. This arises because many different geologic configurations could reproduce similar observed measurements (Dobrin and Savit, 1988). This basic limitation is brought about from the unavoidable fact that geophysical surveying attempts to solve a difficult inverse problem. In spite of this limitation, we can rely on geophysical data. During data interpretation process, it is crucial to have group discussions with all those involved in the actual fieldwork and those with field experiences form other scientific field.

Geophysicsl report should be detailed, legible, concise and informative. It should highlight location of anomalies and phenomenon causing the anomaly. The report should contain atleast the following chapters:

- Introduction – introduce the work undertaken, including location, objectives and climate
- Geological setting – give a brief description of the geological setting of the area including stratigraphy and structural setting
- Previous work – describe previous work done in the area and what were rhe conclusions and recommendations
- Methodology – Describe the methods used during the fieldwork
- Results – present your results and include maps
- Discusion – Discuss your results and interprete them interms of what they mean and represent. Some knowledge on geology is needed.
- Conclusions and recommendations – Give your conclusions and recommnedations in this section

It is advisable if you have some maps and cross sections include them in the appendix.

4. EQUIPMENTS AND TOOLS USED DURING FIELD WORK

Several equipments and tools and their accessories should be carried when carrying out a geophysical survey. The kind of equipment to carry is determined by the purpose of survey and methods used. This section will discuss common equipments and tools used during geophysicla surveys in geothermal fields.

1. **Maps –** As mentioned earlier, maps are collected during the planning stage. Maps that are of much help to a geophysicist include base,topographic and road network maps. It is important to note the scale of maps depending on the aerial extent of the survey area.
2. **Field notebook and pens -** All important observations must be written down in a concise, organised and legible manner. The fieldnote book should be hardcover, water resistant and not so big. Pens and pensils are a must have.

3. **Compass -** A compass is used for determining direction. It is important when carrying out all geophysical methods. It can also be used to determine strike directions and dip of fault planes.
4. **Hand held GPS (Geographic positioning system) -** This is a satellite based navigation system comprising three basic parts, the satellites in space, monitorng stations on earth and the GPS receivers. Although most geophysical equipments have inbuilt GPS systems, its advisable to always have a hand held one. This equipment is for finding and storing station location, tracking paths used, measuring elevation and helping one locate stations in the field.
5. **Field camera** – It is important as it stores visual memories/evidences of the field work. It is very important to take photographs of all intersting features ensuring a scale is used in each instance, video clips can also be of use. One must also remember to take a GPS reading for each photograph taken. Photographs are important for descriptive purposes especialy during report writing and for making presentations.
6. **Safety gadgets and first aid kit -** Safety clothings protects you from harsh field conditions. They include sturdy shoes, clothes that are tough in fabric preferably jeans or khaki, hat and sunglasses to protect one from the sun, a bagpack plus a raincoat and wellington boots just incase of wet environments. Safety clothing should aid one to be more effective by being comfortable and safe at the same time. First aid kit should be fully equiped.
7. **Batteries, battery chargers and solar systems -** One should make sure that either size D or 12V batteries are availed. Battery chargers are used to recharge the batteries while in the field. Solar panels are used in remote areas where there is no power source to charge the batteries.
8. **Masking tape/ leveling spirit –** Masking tape is used to hold various things together e.g. cables and mark them. Levelling spirit is useful especially when carrying out magnetotelluric (MT) and audio magnetotelluric (AMT) surveys. It ensures that the magnetic coils are well levelled.
9. **Hoe and Auger bit -** Used to make holes for the electrodes and vertical magnetic coils respectively During MT/AMT surveys.
10. **Field laptop –** Used for downloading data from the equipments and also pre processing data while in the field.
11. **Geophysical equipments** – These include equipments used in geophysics for different surveys. When carrying out a geophysical survey, the choice of equipment to use is dependent on the purpose of the study. Several equipments can be carried for a one field survey. These equipments are:
    a. Magnetometers
    b. Gravimeters
    c. Seismometers and data loggers
    d. Thermal methods tools
    e. Transient electromagnetic equipment (TEM)
    f. Magnetotelluric equipment (MT)
    g. Audio magnetotelluric equipment (AMT)
    h. DC method equipment

5. GEOPHYSICAL DATA PRESENTATION

Once geophysical data is acquired, a geophysicist is at task to present the results in a manner that a non- specialist will understand. A series of data manipulation techniques can be applied to the data to remove errors and ‘noise’. This data can be in three forms:

- Raw data – these are measurements directly from the instrument and contains background effects and errors. The specialists evaluates the accuracy of the data, edits and corrects it and does further processing. Data in this form is useful to the specialist only.
- Reduced/corrected data - this is data that have been processed to get rid of errors and various non relevant components. E.g. getting rid of power line effect in data and performing terrain corrections.

- Interpreted or modelled results – These are results derived by model calculation from data and depicts actual models of the subsurface (Karl, 2010). At this stage, the abstract or indirect data is converted into maps of specific physical characteristics of sub-surface rock formations. For example a model of actual resistivity distribution (1D, 2D, 3D) derived from apparent resistivity curves. This is the final product that a geophysicist produces and is useful even to the non specialist.

Data processing, analysis and interpretation is a challenging stage as one has to be quite keen and have some knowledge on data handling. After the field data is corrected if necessary, converted to appropriate units, modelled and interpreted, it is then presented to the user in a pictorial manner. It can be presented as:

1. Graphs – data graphs commonly show measurements as a function of distance, time or frequency.

2. Iso anomaly curves – these maps give an overview of the results but not all the details. Iso-resistivity maps are plotted at particular depths and show resistivity patterns at that depth. They are summaries of the observations and not geological interpretations.

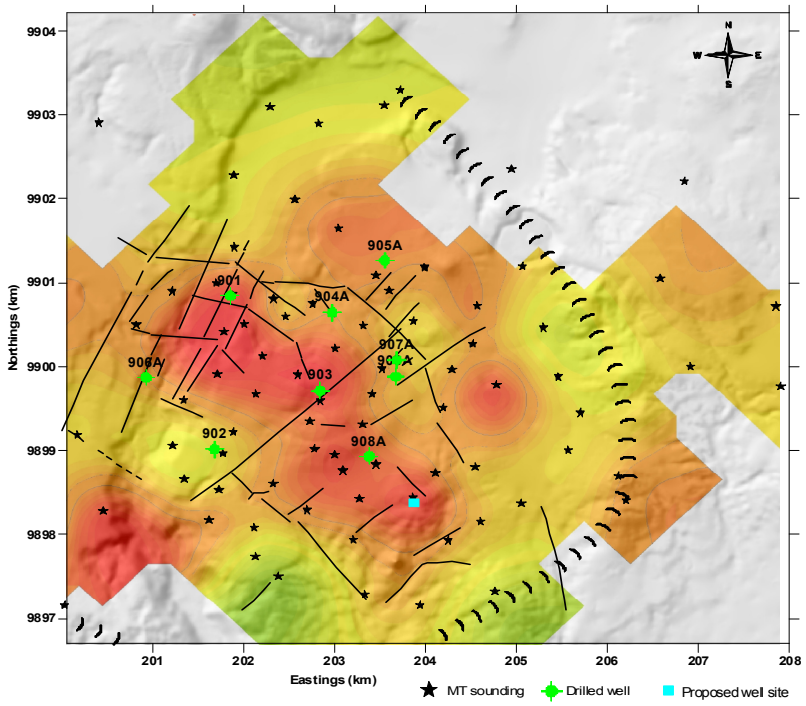

FIGURE 1: MT resistivity iso anomaly map at 700 masl of Domes area

3. Contour maps

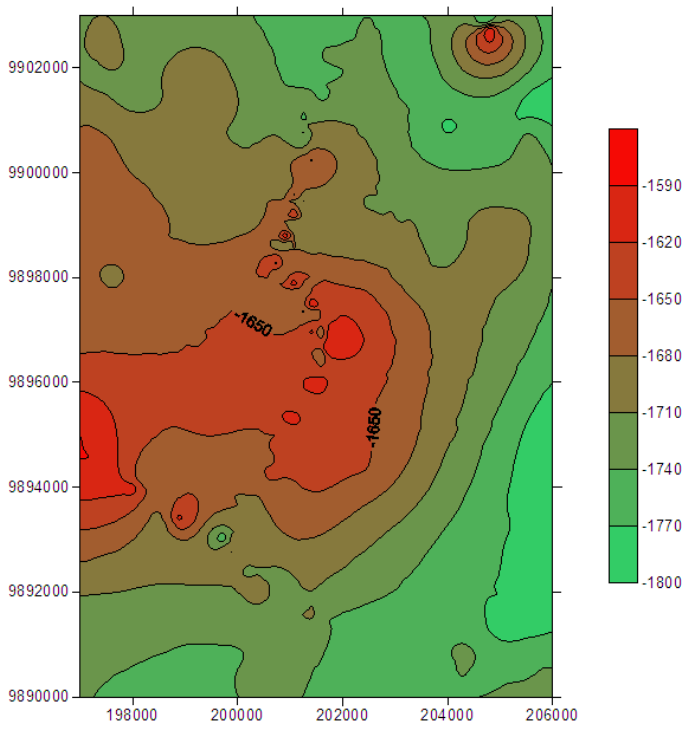

FIGURE 2: Gravity contour map of Longonot, Suswa and Olkaria showing the variation of the gravity anomalies in the area

4. Cross sections

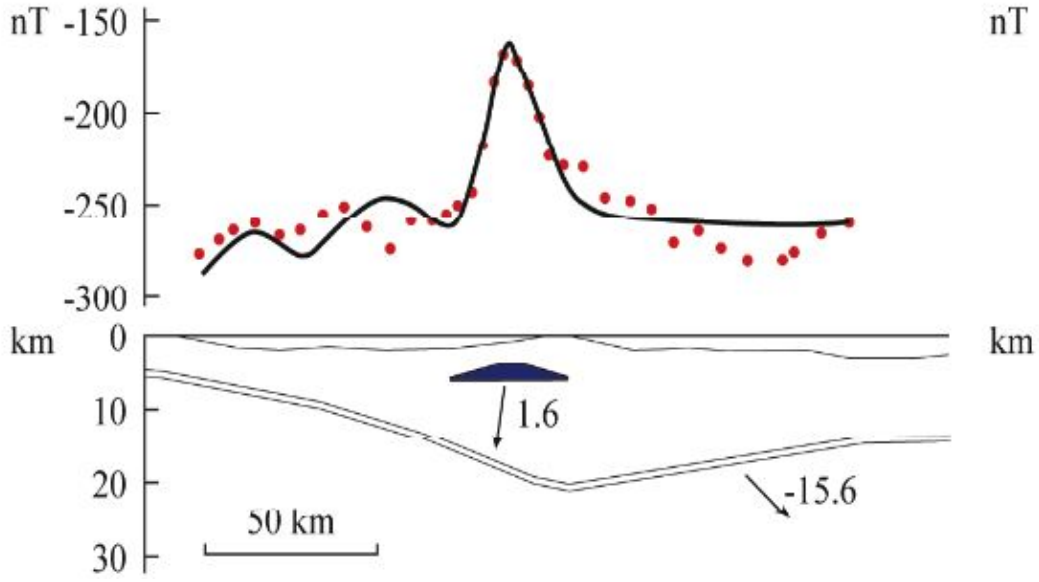

FIGURE 3: A cross section showing a 2D body modelled to fit the observed magnetic field anomaly. The red dots show observed field while the black line show the calculated field

5. Profiles or pseudo sections – profiles visualize continuous variation of the anomaly better than contour maps

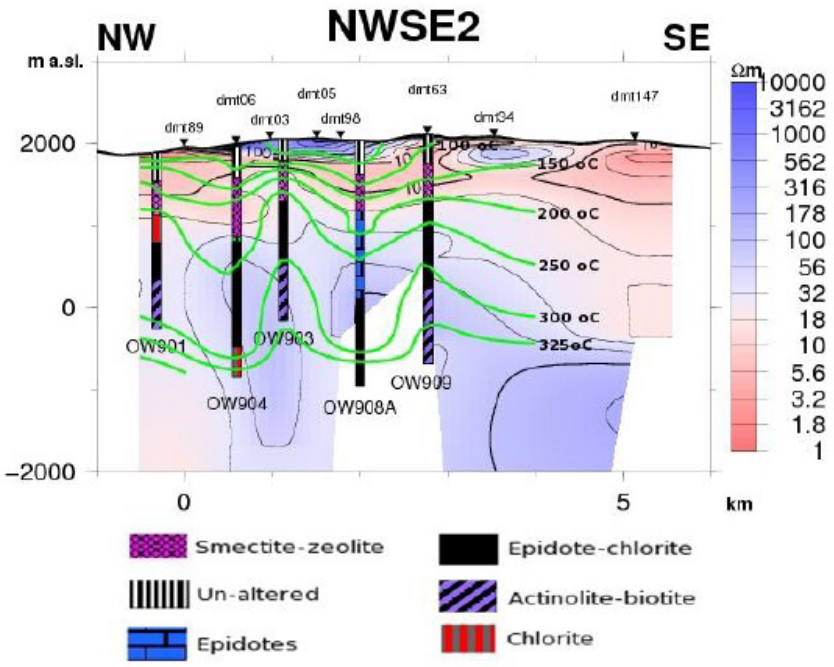

FIGURE 4: MT resistivity profile map across NW to SE in domes. Resistivity varies laterally and vertically

6. 2/3 dimensional maps

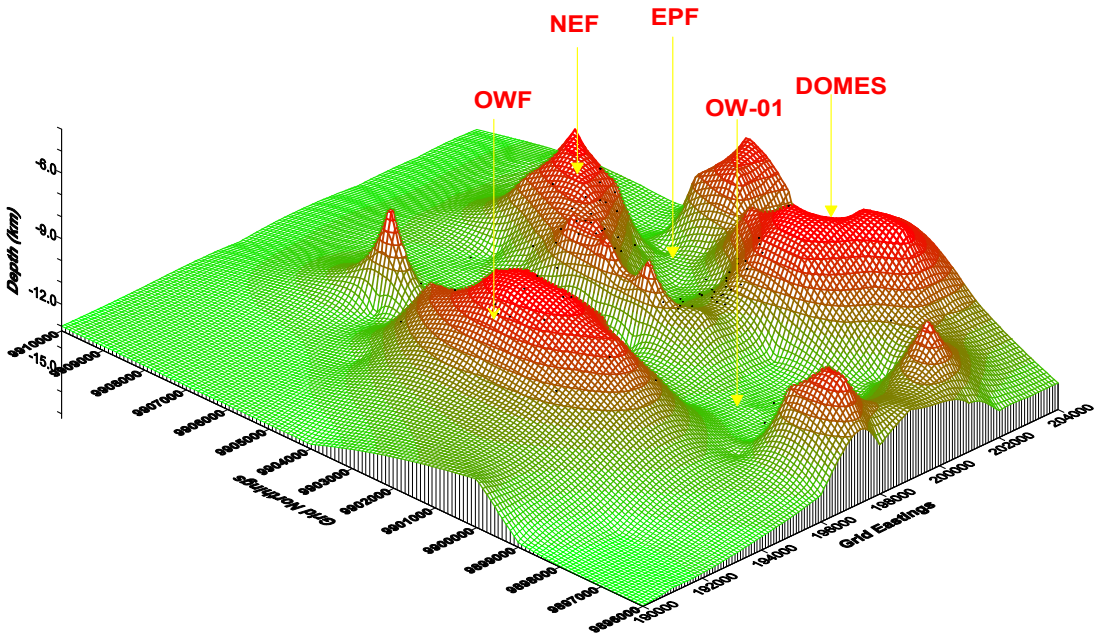

FIGURE 5: 3D plot of depth to attenuating heat sources (fluidized) beneath Olkaria area

6. CONCLUSIONS

In conclusion, geophysical mapping is paramount to geothermal exploration. As mentioned earlier, no single discipline supersedes the rest. Results from other disciplines should be regarded with greatest respect (and distrust). Each discipline should develop individual ideas about the geothermal field and when all the different data sets are in place, they must be interpreted jointly to synthesize a conceptual model which is consistent with all the data from different disciplines. The conceptual model is then used to site exploration wells.

It is essential to work as a team not only to complement individual capabilities but also create synergy for effectiveness and efficiency. Proper planning is pertinent to the overall success of the project. It's crucial that one adheres to the budget. Geophysical equipments are generally expensive and utmost care should be exercised when handling them. Accuracy during data acquisition is of great importance as repeating a measurement is expensive and should be done only when very necessary.

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INTERGRATED GEOPHYSICAL METHODS USED TO SITE HIGH PRODUCER GEOTHERMAL WELLS

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ABSTRACT

The aim of geophysical exploration is to measure the earth's physical properties in order to delineate geothermal fields, locate aquifers, site wells and provide information on which economical exploitation can be based on. During these measurements, emphasis is put on parameters that are sensitive to rock temperature, permeability, porosity and salinity of the fluids that are contained in the rock matrix.

By use of all geophysical method in one field and integrating all their data in interpretation, we have been able to site deeper wells that are good producers producing up to 16MWe. We have been able to map out various structures such as intrusive rocks (possible heat source), porosity variations, faults and dyke systems. We also liaise with other departments (e.g. geology and geochemistry) so as we can combine notes and come up with a detailed accurate conceptual model of the area.

1. INTRODUCTION

Kenya is endowed with a huge geothermal resource due to the presence of the Kenya rift which is part of the East African rift system (Figure 1). With increased emphasis on geothermal development, new exploration methods are needed in order to improve general understanding of geothermal reservoirs, characterize their extent and assess the potential for sustainable utilization and site high producer wells. Surface investigations geological, geochemical, and geophysical and reservoir studies indicate that the potential is over 7000Mwe if fully exploited. The geothermal activity is attributed to Neogene volcanic activity which has resulted to the presence of near surface heat generating sources. Geothermal fields of the Kenya rift occur in two types of environments. The main geothermal fields are associated with Quaternary volcanoes. The second type is associated with fissures that are related to active fault zones. In either case, these fields are dissected by numerous rift faults that give rise to a number of geothermal springs and fumaroles.

1.1 Objectives

Geophysical exploration is carried so as to answer specific geophysical questions based on literature review or specific interests. The main objectives for carrying out geophysical surveys in geothermal areas are:

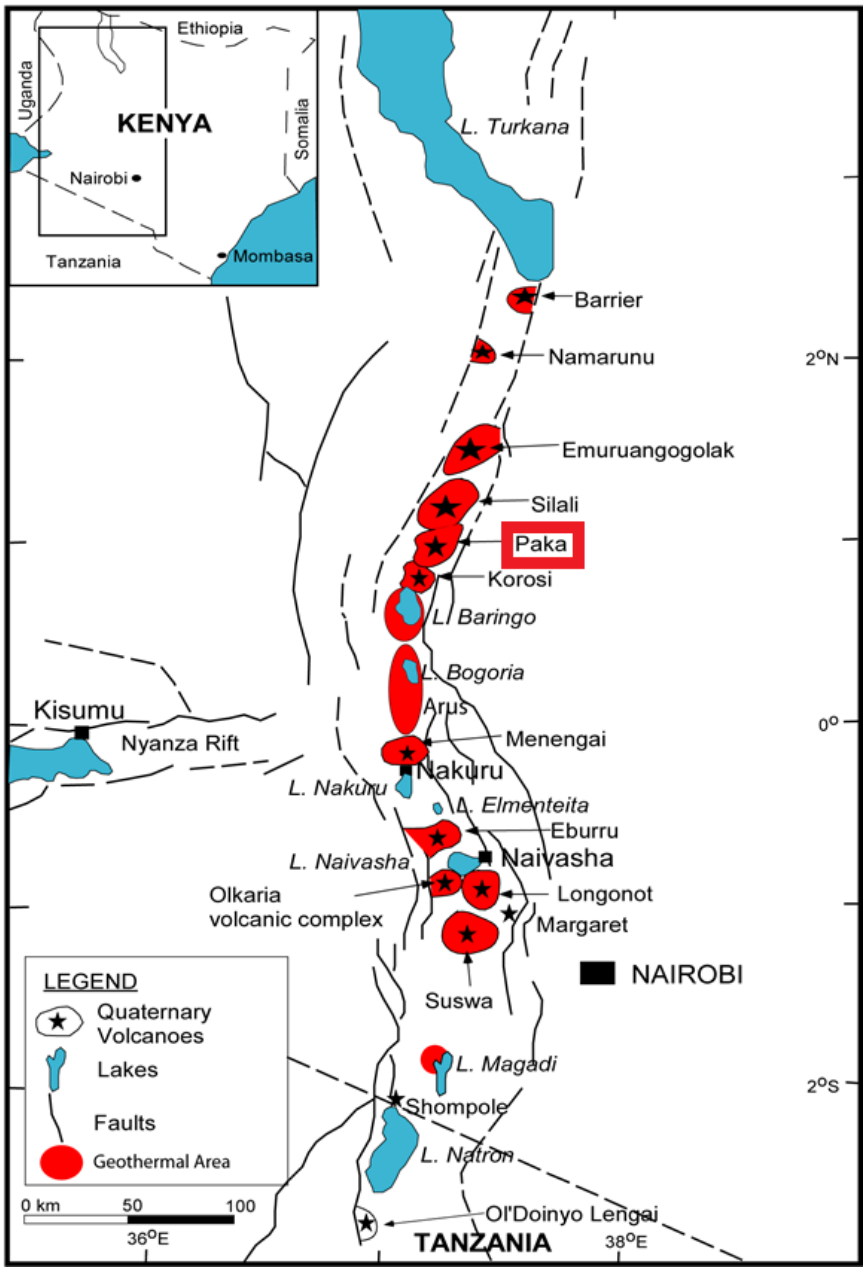

FIGURE 1: Map showing location of geothermal area along the Kenyan rift valley.

- To detect and delineate geothermal resources
- To identify and locate exploitable reservoirs
- Estimate geophysical properties of the geothermal system
- To get a conceptual model that will assist in siting of the drill holes through which hot fluids at depth will be exploited
- Drill a productive well

2. GEOPHYSICAL EXPLORATION

Geophysics is the study of the earth by the quantitative observation of its physical properties and its surroundings by methods such as seismic, electrical and electromagnetic, magnetic and radioactivity

methods. In geothermal geophysics, we measure the various parameters connected to geological structure and properties of geothermal systems. In lay man's language, geophysics is all about x-raying the earth and involves sending signals into the earth and monitoring the outcome or monitoring natural signals from the earth.

Geophysical methods play a significant role in the investigation of geothermal prospects because they are the only means to finding deep subsurface structures at much lower costs than the most direct method, drilling. A relatively wide area can be surveyed within a short time using geophysical techniques. Geophysical exploration does not overrule the need for drilling but, if properly applied, it can optimize exploration programs by maximizing the rate of ground coverage and minimizing the drilling requirement. Geophysical methods are widely used in terms of siting drilling targets.
A wide range of geophysical surveying methods exists for exploration of geothermal energy as well as monitoring of geothermal reservoirs under exploitation (Ndombi, 1981; Mariita, 1995; Simiyu and Keller, 1997). The type of physical property to which a method is sensitive to assists in deciding the method to be used in a particular survey depending on the outlined objectives.

2.1 Electrical/ electromagnetic methods

Electrical/electromagnetic methods are methods where the variation in physical properties is directly related to the geothermal system (e.g. temperature). They include thermal and electrical methods (DC and AC methods). These methods utilize direct currents or low frequency alternating currents to investigate the electrical properties of the subsurface. There are many electrical methods used in electrical prospecting depending on the source field. Some make use of naturally occurring fields within the earth while others require the introduction of artificially generated currents into the ground (Kearey and Brooks, 1994).

2.1.1 Thermal methods

Thermal methods directly measure temperature and heat (temperature surveys). No other methods have such a good correspondence with the properties of the geothermal system. There are approximately four sub-categories: temperature alone (direct interpretation, mapping); geothermal gradient (vertical variation of temperature measured in soil or drillholes); heat flow (calculated from the product of gradient and thermal conductivity); heat budgets (measuring spring flow and steam output and/or integrating heat flow). Measuring the temperature alone or the geothermal gradient is of direct significance in local geothermal work, while measuring the heat flow is more of a regional or global interest.

Heat can be exchanged in different ways such as by conduction (transfer of heat through a material by atomic vibration (often in steady-state); convection (transfer of heat by motion of mass, i.e. liquid, natural circulation of hot water); and through radiation (does not play any significant role in geothermal exploration). Conduction plays a significant role in the transfer of heat in the earth's crust. Thermal convection is usually a much more effective heat transfer mechanism than thermal conduction and is most important in geothermal systems

2.1.2 Electrical resistivity methods

An electrical method is either a sounding method or a profiling method, depending on what kind of resistivity structure is being investigated. Sounding method is used for mapping resistivity as a function of depth while profiling method maps resistivity at more or less constant depth and is used to map lateral resistivity changes. Electrical methods can either be DC or AC. In DC-methods, a constant current $\boldsymbol{I}$ (independent of time) is introduced into the ground through a pair of electrodes at the surface of the earth. The current creates a potential field in the earth. By measuring the electrical field $\boldsymbol{E}$ (potential difference over a short interval), the subsurface resistivity can be inferred. Schlumberger soundings, head-on profiling, dipole soundings and profiling are useful DC-methods.

For AC, transient electromagnetic method (TEM), magnetotellurics (MT) and audio-magnetotellurics (AMT) methods are common. In magnetotellurics (MT) and audio-magnetotellurics (AMT), fluctuations in the natural magnetic field of the earth and the induced electric field are measured. Their ratio is used to determine the apparent resistivity. The time domain or transient electromagnetic method (TEM) is a method where a magnetic field is built up by transmitting a constant current into a loop or grounded dipole; then the current is turned off and the transient decay of the magnetic field is measured. It is used to determine the resistivity.

Measuring the electrical resistivity of the subsurface is the most powerful prospecting method in surface geothermal exploration since resistivity is directly related to the properties of interest, like salinity, temperature, porosity (permeability) and alteration mineralogy. To a great extent, these parameters characterise a reservoir (Hersir and Björnsson, 1991). The specific resistivity, ρ, is defined through Ohm's law, which states that the electrical field strength $\boldsymbol{E}$ (V/m) at a point in a material is proportional to the current density $\boldsymbol{j}$ (A/m^2):

$$\boldsymbol{E} = \rho \boldsymbol{j}$$

The proportional constant, ρ, depends on the material and is called the (specific) resistivity and measured in Ωm. The reciprocal value of resistivity is conductivity ($1/\rho = \sigma$). Resistivity can also be defined as the ratio of the potential difference ΔV (V/m) to the current I (A); across material which has a cross-sectional area of 1 m^2 and is 1 m long.

$$\rho = \frac{\Delta V}{I}$$

2.2 Structural methods

Structural methods are also called indirect exploration methods. In these methods, physical properties investigated do not directly relate to the geothermal system since the anomaly is caused by associated geological formations or structures (e.g. fault, dykes). These methods are gravity, magnetic and seismic.

2.1.1 Magnetic methods

Magnetic methods in geothermal exploration are applied in mapping geological with an aim of locating and determining depth of concealed intrusives, tracing dykes and faults, locating buried lava, determining depth to basement, locating hydrothermally-altered areas, and paleomagnetism.
Magnetic method is a passive potential method that measures naturally occurring phenomena i.e. small, localized variations in the Earth's magnetic field. In magnetic surveying, we measure the strength of the earth's magnetic field, which will vary locally depending on the amount of magnetic material in the underlying rocks. Where the rocks have high magnetic susceptibility, the local magnetic field will be strong and such areas will show up as areas of high magnetic field strength. The magnetic properties of naturally occurring materials such as magnetic ore bodies and basic igneous rocks, allows them to be identified and mapped by this method. Strong local magnetic fields or anomalies are also produced by buried steel objects. The depth of penetration of magnetic surveys is unaffected by high electrical ground conductivities, which makes them useful on sites with saline groundwater, clay or high levels of contamination where the GPR and Electromagnetic methods struggle.

2.1.2 Gravity method

Gravity Method involves measurements of the gravitational field at a series of different locations over an area of interest. The objective is to associate variations with differences in the distribution of

densities and hence rock types. It is relatively cheap, non-invasive, non-destructive remote sensing method. Gravity method is a passive method, meaning no energy is needed to be put into the ground in order to acquire data thus the method is suited to populated area. Porosity and pore fluid content are probably the most important factors affecting density in the shallow sub-surface.

In geothermal exploration, the gravity method is used to detect geological formations with different lateral densities. Different types of rocks in the crust and mantle have different densities, hence different gravitational forces. The gravity force between two masses, m_1 and m_2, at a distance r apart, is given by Newton's law of gravitation (m_1 is the first mass and m_2 is the mass of the earth):

$$F = G\frac{m_1 m_2}{r^2}$$

where G is the universal gravitational constant, $G = 6.670 \times 10^{-11}$ Nm^2/kg^2.

Gravity variations are measured with a gravimeter. These are very sensitive mechanical instruments which measure the change in acceleration (g) at one place relative to another reference place (relative measurement). The unity for acceleration is m/s^2. A gravity unit (g.u.) is equal to 10^{-6} m/s^2. One g.u. is equal to 0.1 mgal. The sensitivity of gravimeters is about 0.005 mgal.

In order to obtain information about the subsurface density from gravity measurements, it is necessary to make several corrections to the measured gravity values before they can be represented in terms of geological structures. The final corrected value for the gravity anomaly is called the Bouguer anomaly.

2.2.3 Seismic method

Seismic method is a used for studying seismic energy propagation through the earth. This method is used to study seismic velocities of rock units in the subsurface with an aim of sub-surface strength, horizontal and vertical discontinuity of the sub-surface and structures hosting ground water, minerals etc. Depending on the instrumentation used and scope of the study, this method is capable of resolving depth of up to 10 km. The method can either be active or passive.

Active seismic measurement involves injecting sound into the ground and recording the energy that reflects back at different times and locations on the surface using geophone receivers. Processed seismic data can give information about subsurface geology, including rock types and fault structures. It can also be correlated with gravity surveys to define more accurate velocity models which provide more accurate depth estimates hence can assist in locating drilling locations. Passive seismic method makes use of natural induced micro-earthquake activities and can be used to delineate permeable fractures acting as a flow path for geothermal fluids and to delineate the brittle-ductile zone and also to monitor useful indicators in natural or induced reservoir phase changes during exploitation of a geothermal field (Simiyu et al, 1998).

3. INTEGRATED INTERPRETATION

Proper interpretation of geophysical data is paramount. It should be noted that there is no superior method thus integration of different geophysical techniques has been effective in mapping defined structures in tectonic regimes where geothermal resources are found. Exploration of the Olkaria geothermal resource started in 1956 with deep drilling commencing in 1973 (Ouma, 2010). In those days, geophysical methods used were not advanced in technology and were not many as is these days. DC methods were used for exploration of the Olkaria field. Wells X1 and X2, which were not productive, were sited using the results of the surface exploration.

Currently and for the past decade, geophysical methods have greatly revolutionised and technology grown tremendously. In Olkaria field we commonly carry out a variety of geophysical measurements such as MT, TEM, gravity, magnetic and seismic and use the results jointly to interpret and come up with the geophysical conceptual model.

Often we use these methods in combination. For example, magnetics is done along with gravity. Since geophysics is highly mathematical, it is sometimes prone to ambiguities in interpretation. At the interpretation stage, ambiguity arising from the results of one survey may often be removed by consideration of results from a second survey method. Furthermore, although many of the geophysical methods we employ require complex methodology and relatively complex mathematics in processing and interpretation of data, we derive much information is derived from a simple assessment of the survey data.

Figure 2 shows MT/TEM map at sea level showing the resistivity structure. High resistivity anomalies have been observed in a north west - south east trend from Olkaria west to Olkaria domes.

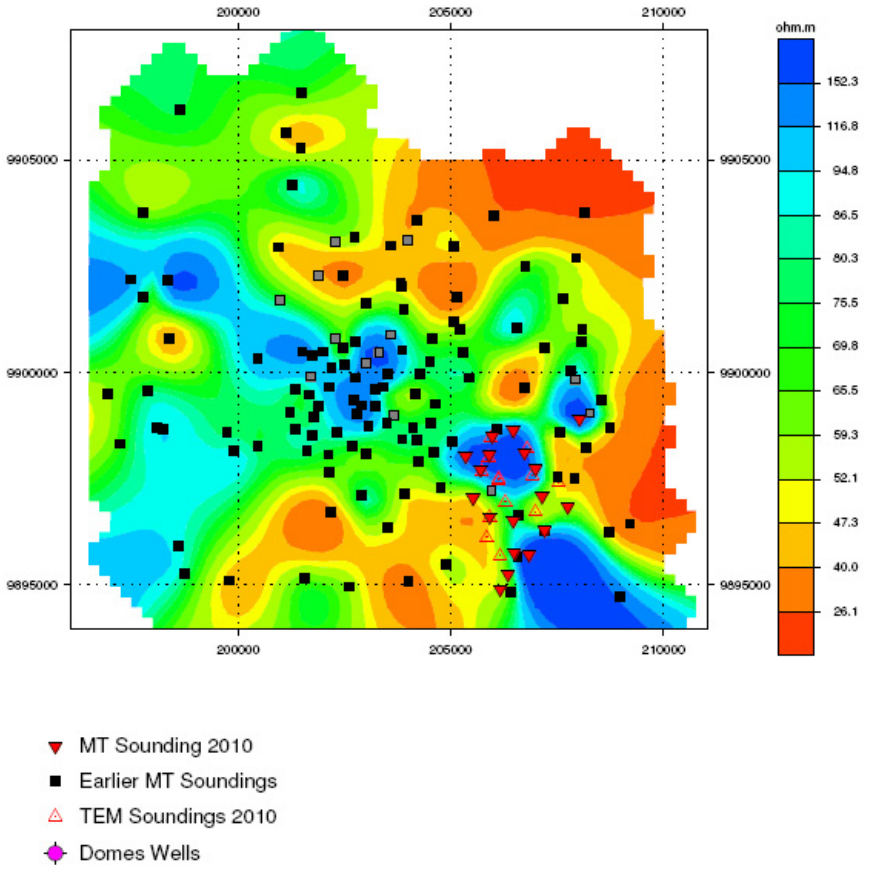

FIGURE 2: Map of the greater Olkaria area (GOGA) showing resistivity at sea level (approx. 2.5 km depth).

The resistivity anomaly can be well supported by the results of seismic studies in the area (Figure 3) where earthquakes tend to occur in a similar trend as the resistivity. Plot b shows the depths of events and can be used to map heat sources in Olkaria.

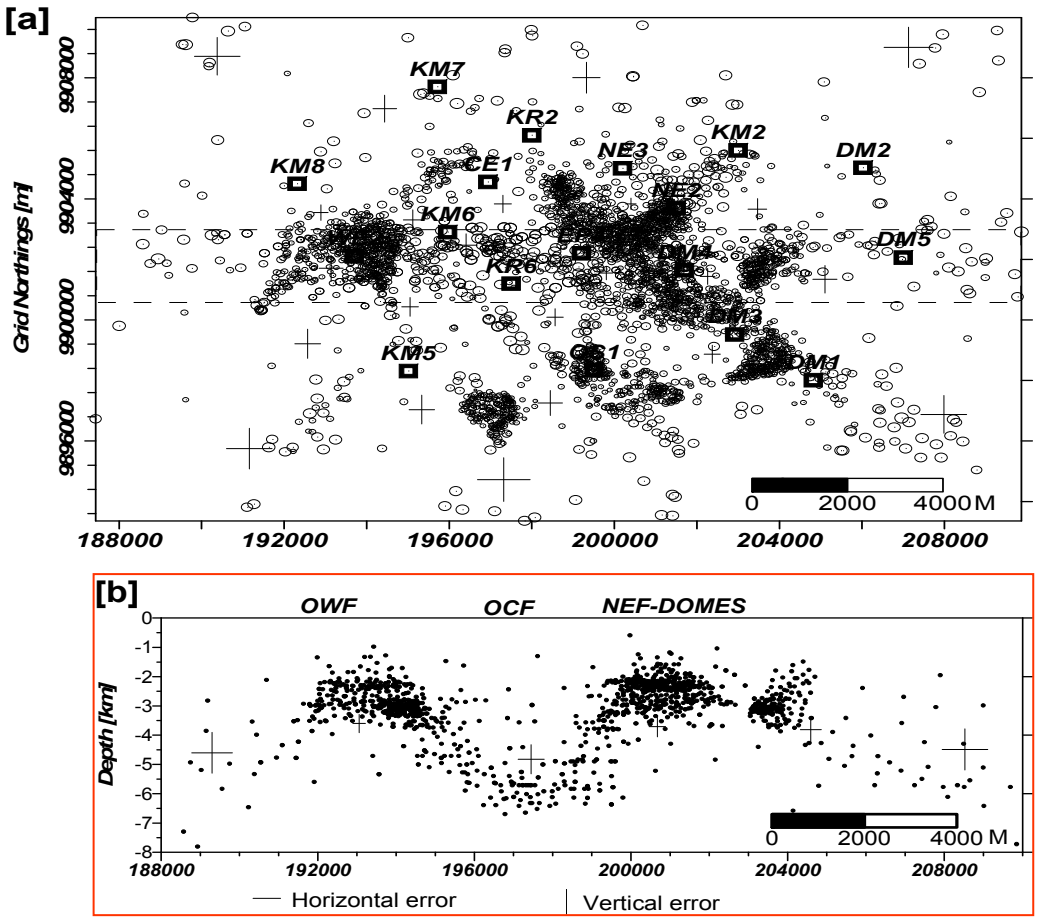

FIGURE 3: Plots with event distribution in Greater Olkaria area (GOGA) (Simiyu and Keller, 1997)

Figure 4 shows the total magnetic intensity over Olkaria and also shows high magnetic intensity is a NW-SE trend. This is much in line with the resistivity and seismic anomalies. Figure 5 shows a cross-

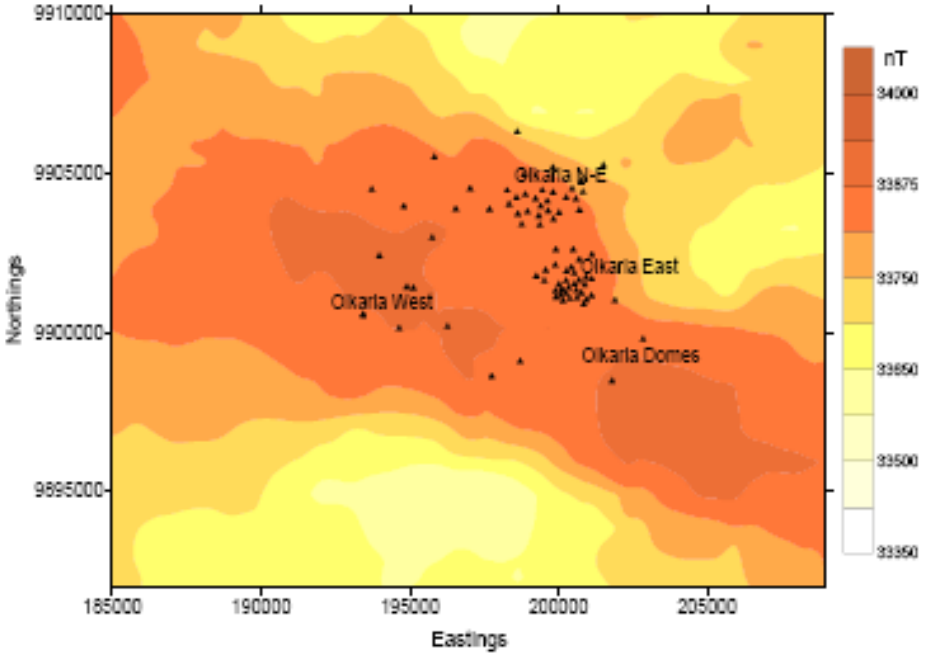

FIGURE 4: Map showing total magnetic intensity over Olkaria (Mariita, 1975)

section in Domes area oriented NW-SE. Alteration mineralogy has been integrated in this profile so as to aid in the interpretation. The alteration mineralogy and temperatures from geology are in line with the results obtained earlier.

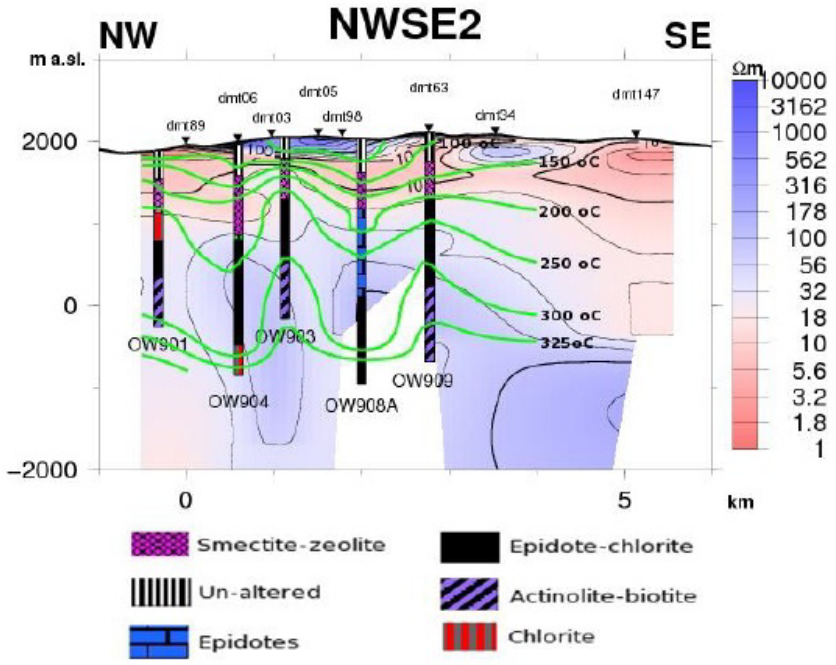

FIGURE 5: MT resistivity profile map across NW to SE in domes. Resistivity varies laterally and vertically.

By integrating results from all geophysical methods together with information from other geoscientific disciplines such as geology and geochemistry, we have been able to site with wells confidently and with accuracy.

3.1 Siting high producer wells

In the earlier days, geothermal wells were being drilled to a depth of about 2000 m. We are now able to drill wells up to a depth > 3000 m since the dynamics of the geothermal system are well understood. Intersection of faults is normally targeted during siting of wells since we expect good permeability. This information is provided by structural methods. Earlier sited wells produce an average of 3 MW while current wells produce and average of 9 MW. This has greatly reduced the cost of drilling since the number of well have been reduced by more than 50%.

By use of results of one geophysical method say MT and TEM, we may be able to site a well. Resistivity results will highlight reservoir zones and the heat source. For a complete geothermal system, we need to have all elements of a geothermal system i.e. heat source, reservoir, fluid channels, and a cap rock. We now need some geophysical results that can give information on the remaining parameters. We normally combine these results with seismic and magnetic results to be able to confidently site a high producer well.

4. CONCLUSION

Costs of geothermal power plants are heavily weighted toward early expenses such as well drilling and pipeline construction. During this stage, resource analysis of the drilling information is carried out. The risks of development and the time for construction can tremendously be reduced if the total number of production wells can be reduced by half. Well output variability exists in the Olkaria Geothermal field where two wells produce about 19 MWe contrary to earlier 6 wells that could produce the same output. If these high production wells were drilled at the beginning of the project, there would have been tremendous savings on the infrastructure and the total costs of developing the geothermal power plants. On average it takes about 45-60 days to drill wells to a depth of 3000 m. The time taken to develop Olkaria field would have been greatly reduced and at the same time realize greater output. Reducing the number of wells by half, the project costs and therefore the cost of steam per KWh will be reduced significantly and increase the number of plants that can be constructed.

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INTRODUCTION TO GEOCHEMICAL MAPPING

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ABSTRACT

Geochemistry plays a relatively crucial role in the exploration for geothermal resources and subsequent utilization. Its major contribution in geothermal resource assessment includes; estimation of subsurface temperatures, determination of the origin of the waters and flow patterns within the reservoir. The major tools used in geochemical mapping are water and gas. Geothermal waters have been classified with respect to their anion and cation constituents into alkali-chloride water, acid sulphate water, acid sulphate-chloride water and bicarbonate water. This paper discusses sampling and analyses of fumaroles and hot springs, soil gas survey, geochemical data interpretation.

1. INTRODUCTION

Geothermal systems can be defined and classified on the basis of their geological, hydrological and heat transfer characteristics. Active geothermal systems consist of hot fluid and hot rock within the upper part of the Earth's crust. The fluid is, for the most part or solely, meteoric water or seawater by origin, or a mixture thereof. Since the thermal energy of the earth crust is stored in large rock masses, a working fluid (water) is needed to carry and transfer this heat to the surface.

Generally, geothermal systems develop by deep density-driven convection of ground water. Yet, in some systems of relatively low temperature the convection may be driven by hydraulic head only. The water convection transports heat from the deeper to the shallower parts of geothermal systems. The heat source may be a magma intrusion (in volcanic geothermal systems) or the hot rock at the roots of the convection cycle (in non-volcanic geothermal systems).

Geothermal water can be broadly defined as ground water which has a temperature appreciably higher than that of the local average annual air temperature. Generally the geothermal water of an area contains large concentrations of dissolved minerals, such as sodium, calcium, sulphate, chloride, or silica higher than that of the local non geothermal ground water. The water warms as it descends, possibly along fault zones that overlie the magma chamber, until it absorbs enough heat to become lighter than overlying water. The warm water then rises to the surface. The mechanism for the circulation of the water is the same, regardless of whether the water becomes heated by the geothermal gradient or by the buried, cooling magma.

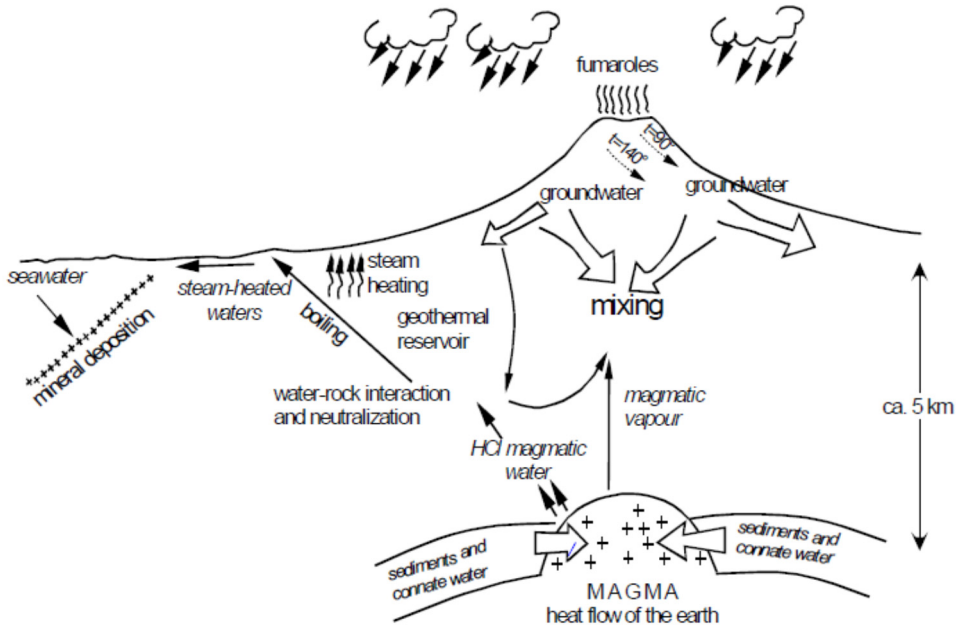

FIGURE 1: Diagram displaying geothermal fluid origin and flow pattern

2. WHY GEOCHEMICAL EXPLORATION?

Geothermal fluids rising to the surface include both hot water and steam with dissolved solutes and gases. They may be discharged from hot springs, fumaroles, soil and wells. The source of the dissolved constituents in the geothermal fluids is the rock with which the deep ground water has reacted and constituents present in the parent water. In the case of volcanic geothermal systems, the magma heat source may also supply chemical constituents to geothermal fluids through its degassing. The chemical composition and isotope ratios of geothermal fluids provide important information about the geological, chemical and hydrological characteristics of geothermal systems. An understanding of these characteristics is essential for the exploration and development of geothermal resources and the environmental impact of their utilization (see e.g. Truesdell 1976; Fournier 1977; Arnórsson et al. 2000).

Information gathering on the surface thermal manifestations, such as springs, shallow wells or natural artesian etc. and their physical and chemical characteristics is of primary importance in geothermal energy exploration. The major goals of geochemical exploration are to obtain the subsurface composition of the fluids in a geothermal system and use this to obtain information on temperature, origin, and flow direction, which help in locating the subsurface reservoir. Equilibrium speciation is obtained using speciation programs and simulation of processes such as boiling and cooling to get more information to predict potential deposition and corrosion. Environmental effects can be predicted and the general information is used as a contribution to the model of the geothermal system. This is one of the lowest cost exploratory techniques and is a useful starting point in any hydrothermal exploration program.

3. CLASSIFICATION OF GEOTHERMAL WATERS

It has proved difficult to obtain a genetic classification of subsurface waters (Ármannsson and Fridriksson, 2009), since water tends to flow away from its point of origin and undergo water-rock interaction during its travels making it increasingly difficult to decipher its origins.

According to White (1986), subsurface waters can be classified as follows based on their origin: meteoric water, which circulates or has recently been circulating in the atmosphere, co-existing with near-surface, uncemented sediments, can circulate in subsurface rocks and dissolve constituents; ocean water, which is partly evaporated products of meteoric water; evolved connate water, which forms in young marine sediments; metamorphic water, which is contained in or driven from rocks undergoing metamorphic dehydration reactions; magmatic water is derived from oceanic and evolved connate waters subducted along with oceanic crust into the mantle, and; juvenile water, which is classified as water that has never circulated in the atmosphere.

Ellis and Mahon (1978) classified geothermal water into four categories based on major ions: (i) Alkali-chloride water which has a pH 4-11, least common in young rocks. These are mostly sodium and potassium chloride waters although in brines Ca concentration is often significant; (ii) Acid sulphate waters which arise from the oxidation $H_2S \rightarrow SO_4$ near the surface and most of its constituents are dissolved from surface rock. Thus such water is generally not useful for prediction of subsurface properties; (iii) Acid sulphate-chloride water which may be a mixture of alkali chloride water and acid sulphate water, or it can arise from the oxidation $H_2S \rightarrow SO_4$ in alkali-chloride water or dissolution of S from rock followed by oxidation. Sulphate-chloride waters need not be very acid and may then reflect' subsurface equilibria and be used for prediction of subsurface properties; (iv) Bicarbonate water which may derive from CO_2 rich steam condensing or mixing with water, it is quite common in old geothermal waters or on the peripheries of geothermal areas in outflows. They are commonly at equilibrium and may be used to predict subsurface properties. A good way of distinguishing between the differences between the different types of geothermal water is the use of the chloride-sulphate-bicarbonate ternary diagram described by Giggenbach (1991).

As discussed by Ármannsson and Fridriksson (2009), it is possible to deduce the properties of subsurface water from the chemical composition of water collected at the earth's surface. The dissolved constituents of geothermal water to some degree originate in the original meteoric or oceanic water. However, water-rock interactions and sometimes additions of magmatic gases will further modify geothermal solutions. The dissolved components are divided into rock forming constituents, e.g. Si, Al, Na, K, Ca, Mg, Fe, Mn and incompatible constituents, e.g. Cl, B, Br. Products of geothermal alteration are controlled by temperature, pressure, chemical composition of water (e.g. CO_2, H_2S), original composition of rock, reaction time, rate of water and steam flow, permeability and type of permeability and these products in turn control the chemical composition of the fluid.

Some of the effects are that the silica concentration depends on the solubility of quartz/chalcedony, temperature dependent Al-silicate ion-exchange equilibria control Na/K, Na/Rb ratios, pH is controlled by salinity and Al-silicate equilibria involving hydrogen and alkali ions, Ca^{+2} and HCO_3 - concentrations depend on pH and CO_2 concentration because of equilibrium between the fluid and calcite, F^- and SO_4^{-2} concentrations are related to that of Ca^{+2}, limited by solubility of fluorite and anhydrite and temperature and salinity dependent silicate equilibria control a very low Mg^{+2} concentration. The results of alteration studies show that the chemical composition of geothermal fluids originates in controlled reactions dependent on temperature, pressure and rock composition.

4. SAMPLING AND ANALYSIS OF GEOTHERMAL FLUIDS

4.1 Sampling of hot springs

Obtaining information on the distribution of the geothermal manifestations in the area as well as on the temperatures and flow rates of the springs and fumaroles is very useful step during sampling of geothermal fluids from a particular field. The variability of surface activity between and within geothermal fields is highly intense. Although it may not be practical to sample all springs in a particular field, specific representative sites need to be selected for sampling. The criteria used to select hot springs for sampling include temperature, flow rate, geographic distribution, whether the

water issues from soil or directly from the bedrock and any hydro-geological observations that might indicate mixing of the geothermal water with surficial water (Arnórsson, 2006).

In essence, the most favourable sites are springs with the highest temperature, the highest flow rate, the smallest aperture and minimum contact with any soil. In addition to springs, sampling and analysis of ground and surface waters is important for evaluation of possible mixing of the geothermal water with such shallow water in upflow zones.

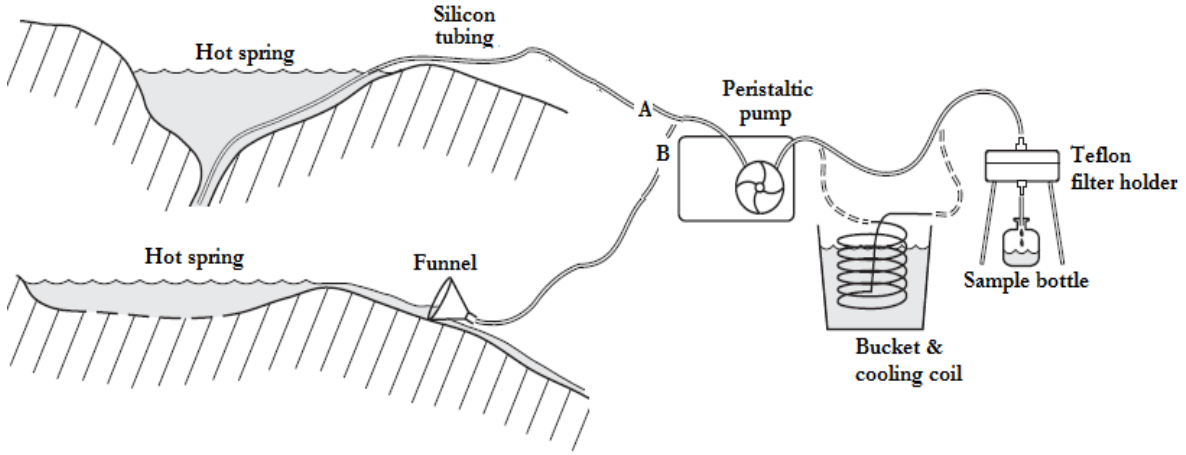

FIGURE 2: The layout of the apparatus for sampling a hot spring waters (modified from Arnórsson, 2006)

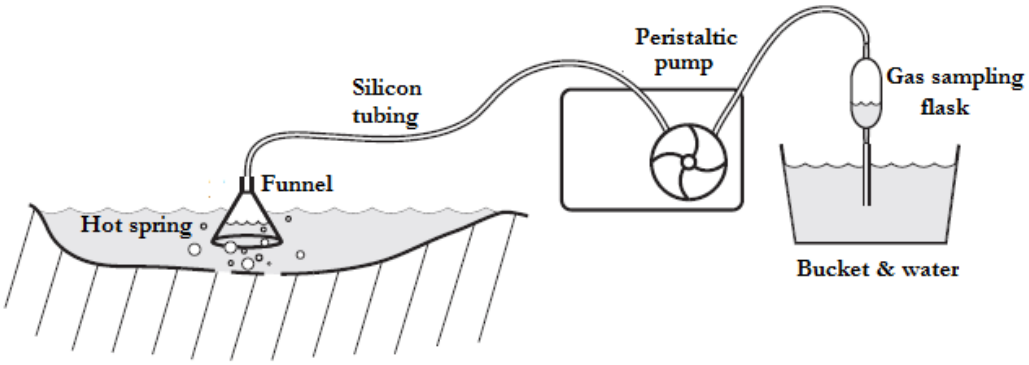

FIGURE 3: The layout of the apparatus for sampling gases bubbling from hot spring waters (modified from Arnórsson, 2006)

The layout of sampling apparatus is presented in Figure 2. If the water temperature is below 30–40°C, a cooling coil is not necessary as thermal contraction of water is not significant when cooled from this temperature to room temperature. If the water in the well is under pressure, the peristaltic pump is not needed to push the sample through the filtering apparatus. Contact of the water to be sampled with the atmosphere should be minimal, certainly for those components which may undergo changes in their concentration upon exposure to air. This can be done by immersing tubing into the hot springs well below the surface, if the surface area of the hot spring is sufficiently large and deep and withdrawing water through the tubing with a peristaltic pump and pushing it through the cooling coil and the filtering apparatus. If the aperture is small and on a slope, it is convenient to place a funnel just below the aperture and let the water flow by gravity into the tubing to the peristaltic pump.

4.2 Sampling of fumaroles

Selecting fumaroles for sampling is not as simple as that of hot springs. It is generally best to sample small outlets, which discharge steam at considerable velocity. The gas phase discharged from such

thermal manifestations tends to be low in H_2S compared with that of adjacent fumaroles because of its oxidation by oxygen dissolved in the surface water through which the steam passes (Arnórsson, 1987). Sampling fumarole steam provides information on individual gas concentrations in the steam and is for this reason also preferred to the sampling of gases bubbling through steam-heated or hot-spring water. The latter only provide information on the relative amounts of the gases in the gas phase and not their absolute concentrations in the steam. In addition, it is useful to measure the temperature when collecting samples from fumaroles so as to eliminate any uncertainty about the nature of the discharge.

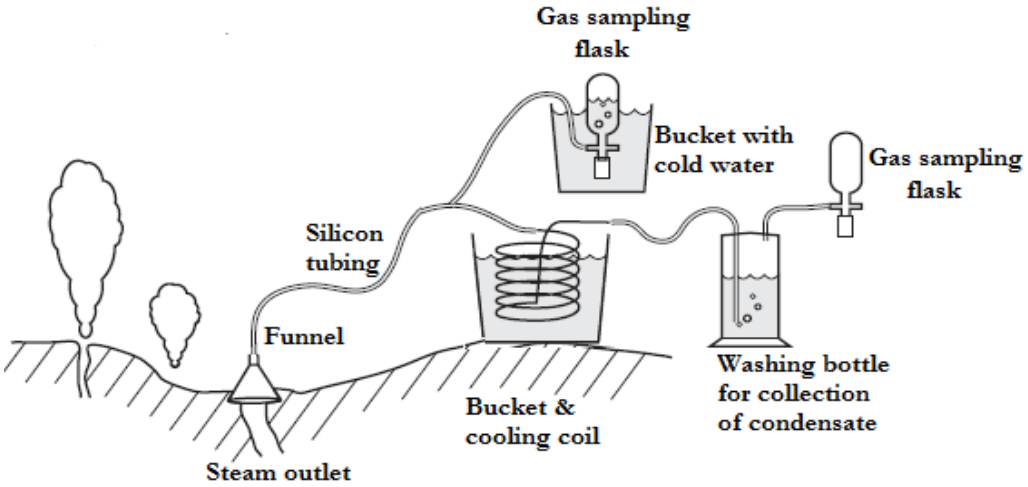

FIGURE 4: The layout of the apparatus for sampling fumarole steam (modified from Arnórsson, 2006)

The types of fumarole steam samples to be collected depend on which chemical and isotopic constituents are to be analysed. Chemical analyses for applied studies of geothermal systems routinely include CO_2, H_2S, NH_3, H_2, CH_4, O_2, N_2 and Ar. Analysis may also include the noble gases, CO, Rn and the heavier hydrocarbons. Isotopes routinely determined in steam include δ^2H and $\delta^{18}O$ and occasionally δ^3He and $\delta^{20}Ne$. Sometimes isotope ratios are also determined in individual gas components. They include δ^2H in CH_4 and H_2, and $\delta^{13}C$ in CO_2 and CH_4.

Three types of gas samples can be collected from fumaroles and hot springs (Figure 3 & 4). One is a sample of the total discharge of a fumarole, the second type is the gas fraction in the fumarole discharge and the third type consists of gas bubbles emerging from hot springs. No analysis or sample treatment is required on site for these steam and gas samples. Before collecting a sample, it is necessary to allow steam to pass through the tubing and the sample ports of the gas sampling bulb, and through the wash bottle when used, to displace any air in the system.

The sampling methods depicted in the diagram assume that the sampling bulb to have been evacuated in the laboratory before going into the field. For sampling of gas from hot springs, the gas sampling bulb, which must have a stopcock at both ends, should not be evacuated. After immersing the funnel upside-down into the spring water over the rising gas bubbles, the peristaltic pump is used to suck up water to displace any air in the whole system, including the sampling bulb. Gas is then allowed to accumulate under the funnel, and is subsequently pumped into the sampling bulb.

Some studies focus on analysing dissolved gases in water, such as the noble gases, including Rn. Because of its short half-life (3.8 days), Rn must be analysed soon after collection. Sampling methods for such studies are those used to sample hot springs and hot-water wells. Samples for He analysis must be collected into vessels which are not permeable to this gas, such as copper tubing or special Al-silicate glass.

As discussed by Arnórsson (2006), the gas phase in geothermal steam is most often largely CO_2 and H_2S (> 90% by volume). In order to obtain better analytical results for the less abundant major gases (H_2, CH_4, N_2, O_2, Ar), the most common practice is to collect samples into evacuated bulbs containing a solution of either NaOH or KOH. The CO_2 and H_2S present in the steam dissolve quantitatively in the alkaline solution, thus concentrating the remaining gases in the head space above the solution and allowing their more precise determination by gas chromatography.

When sampling fumarole steam the main concern is usually to avoid air contamination of the sample. Generally, the presence of oxygen in geothermal steam is taken as evidence for atmospheric contamination during sampling. However, oxygen in fumarole steam may have originated from degassing of near-surface steam-heated water and could truly be present in the steam.

In the discharges of dry and wet-steam wells, on the other hand, the presence of oxygen in gas samples can safely be considered to be a measure of atmospheric contamination during sampling. Atmospheric contamination reduces the value of data on N_2, Ar and other atmospheric gases. It also tends to yield low values for H_2S, which is easily oxidized by atmospheric oxygen in alkaline solution. The best samples are generally obtained from fumaroles discharging from ground highly altered by acid surface leaching. The funnel should be placed upside down over the steam vent and covered with compacted clay using a shovel.

5. DETERMINATION OF SOIL GAS CONCENTRATIONS/FLUXES

Several studies have shown that globally significant amounts of CO_2 are released to the atmosphere by quiescent degassing of volcanoes and soil diffuse degassing from volcanic geothermal systems. It has been demonstrated that soil diffuse degassing on flanks of volcanoes is sensitive to changes in magmatic activity, thus providing a potential, relatively safe method for volcano monitoring. Soil diffuse CO_2 degassing has also been shown to be a good indicator of the energetic state of geothermal systems. This is because CO_2 gas reaches the surface more easily than steam that can condense in the subsurface where groundwater flow can transport the resulting thermal energy laterally out of the systems (Chiodini et al., 2001). The study of diffuse degassing is one of the recent methodologies that have contributed in the monitoring of gases in soils and fumaroles. In Kenya, it has been part of the geochemical activities for monitoring fumaroles and for further exploration of geothermal areas. Gas studies confirm possible permeable zones, geologic structures and faults and the chemical and thermal evolution of hydrothermal areas.

5.1 Soil gas concentration (CO_2, Rn and Hg)

CO_2 gas concentration can be effectively measured using an Orsat apparatus. Radon radioactivity levels can be determined by a portable radon detector (emanometer) and mercury by mercury analyzer. The Orsat apparatus consist of absorption vessels, which measure about 100 mls and contain a 40% KOH solution for absorbing the acidic CO_2. The corresponding volume changes in the absorption vessel represent the corresponding amounts of the gases in volumes given as percent of the total gas as a percentage.

The soil gas is passed into the emanometer where Rn-222 and Rn-220 readings are recorded in counts per minute (cpm). Three background counts are recorded at three-minute interval prior to introduction of the sample into the emanometer. Upon introducing the sample, three more readings are taken at the same intervals to give the total radon counts. The CO_2 and Rn-222 obtained in the survey is corrected and used to construct concentrations contour maps. A ratio of CO_2/Rn-222 is used to eliminate other sources of CO_2 other than magmatic.

5.2 Soil gas flux (CO_2)

The CO_2 flux can be measured directly using a survey chamber CO_2 flux meter equipped with a non-dispersive infrared gas analyzer. The flux measurement is based on the rate of CO_2 increase in the chamber. The Survey chamber allows rapid measurements to be made at many sites and it is has carefully designed pressure vents to prevent pressure gradients and wind incursion from outside the chamber. The chamber closes automatically, minimizing mechanical disturbances during the measurement.

6. DATA INTERPRETATION

Application of chemical techniques has become an integral part of any geothermal exploration programme. Waters and gases discharged at the surface generally carry imprints of their deeper histories with them. The constituents encountered in these fluids has been subdivided into non-reactive or tracers (Cl, B, Li, Rb, Cs, N_2, He & Ar) and reactive or geoindicators (Na, K, Mg, Ca, H_2, H_2S, CH_4, CO_2 and SiO_2) (Giggenbach, 1991). The most important processes affecting geothermal fluid compositions include the overall irreversible dissolution of primary rock minerals and precipitation of secondary minerals. The dissolution process leads to increased concentrations of the aqueous components, including conservative Cl, Br and B. Other components, brought into solution by primary rock mineral dissolution, are removed again by precipitation of secondary or hydrothermal minerals.

As a result, the relative proportions of components in geothermal waters differ very much from those in common rock types. Components that largely reprecipitate include Al, Mg and Fe, whereas Li, Rb and Cs reprecipitate to a small extent. Chlorine and boron, together with many others, exist as fugitive components – chlorine as HCl, boron as borates, sulphur as SO_2, carbon as CO_2, and a lesser extent, as CO, fluorine as HF, and hydrogen as H_2O and H_2. The fugitive compounds tend to leave the magma by the process of degassing depending on the rate of ascent of magma, initial concentration, external pressure, its viscosity and rate of solidification.

In spite of being affected to some degree by secondary chemical processes, the above five constituents Li, Rb, Cs, B and Cl provide very useful markers for the identification of, and tracers to the origins of geothermal fluids, however, constituents Na, Mg, Ca and SiO_2, are chemically more reactive and form the basis for a number of valuable geoindicators.

6.1 Relative Cl, SO_4 & HCO_3 contents

Using the relative Cl, SO_4 and HCO_3 contents, waters can be characterized as steam-heated, mature, peripheral or volcanic waters (see Figure 5). Volcanic and steam-heated waters formed by the absorption of high temperature, HCl-containing volcanic, or lower temperature, H_2S-containing "geothermal" vapours, into groundwater. Most geochemical techniques are not suitable for application to these generally quite acid waters.

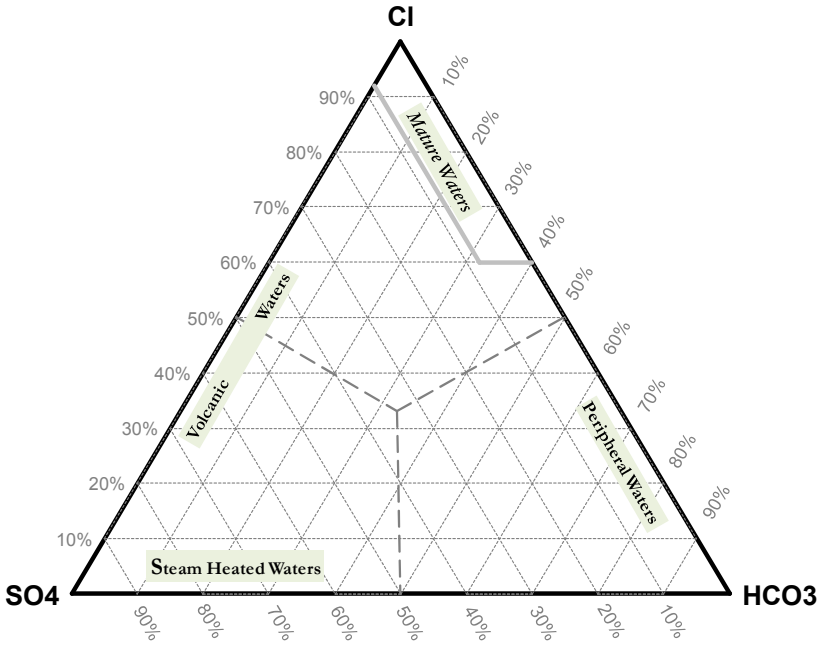

FIGURE 5: Relative Cl-SO_4-HCO_3 contents

The group best suited comprises the neutral, low sulphate, high chloride "geothermal" waters along the Cl-HCO_3 axis, close to the Cl corner. The relationship of these constituents allows the weeding out of unsuitable waters, but may already provide initial indication of mixing relationships or geographic groupings. High SO_4 steam-heated waters are usually encountered over the more elevated parts of a field. The degree of separation between data points for high chloride and bicarbonate waters gives already an idea of the relative degrees of interaction of the CO_2 charged fluids at lower temperatures, and of the HCO_3 contents increasing with time and distance travelled underground.

6.2 Relative Li, Rb and Cs contents

The relationship of Li, Rb and Cs stresses differences among waters, largely brought by comparatively shallow processes. An indication of the existence of a common origin, or of common, deep processes shaping the composition of surface water discharges, is provided by use of less reactive, "conservative" components, added at depth, but not affected by shallow processes, such as the rare alkalies Li, Rb and Cs. In the application of this triangular plot (Figure 6), advantage is taken of its insensitivity to dilution by little mineralized ground water or steam loss due to boiling of the rising fluids. As a result, data points for deep and shallow waters, having undergone any amount of dilution or steam-loss, plot on the same position. However, Rb closely parallels K in that it is readily taken up at quite high temperatures (> 300°C) in most K-containing alteration products, such as illite. Cs is incorporated into secondary zeolites, especially at temperatures < 250°C. Li is to minor degree incorporated into secondary quartz and chlorite.

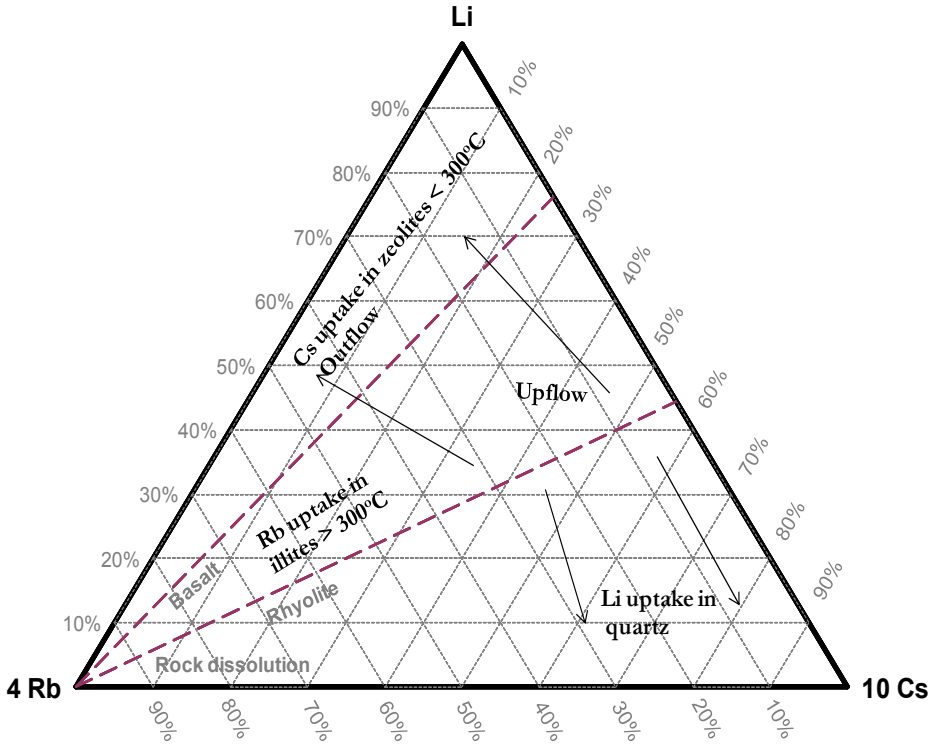

FIGURE 6: Relative Li-Rb-Cs contents

6.3 Relative Cl, Li and B contents

The alkali metal probably least affected by secondary process is Li, and therefore can be used as a "tracer" for the initial deep rock dissolution process and as reference to evaluate the possible origin of the other two important "conservative" constituents of thermal waters, Cl and B. Once Li is added into waters in hydrothermal systems it remains largely in solution since there is no obvious major sink for this element in hydrothermal systems. The B content of thermal fluids is likely to reflect to some degree the maturity of a geothermal system. Because of their volatility, constituents such as B, As, Sb

and Hg are likely to be expelled during the early heating up stages, and therefore, fluids from "older" hydrothermal systems can be expected to be depleted in these elements.

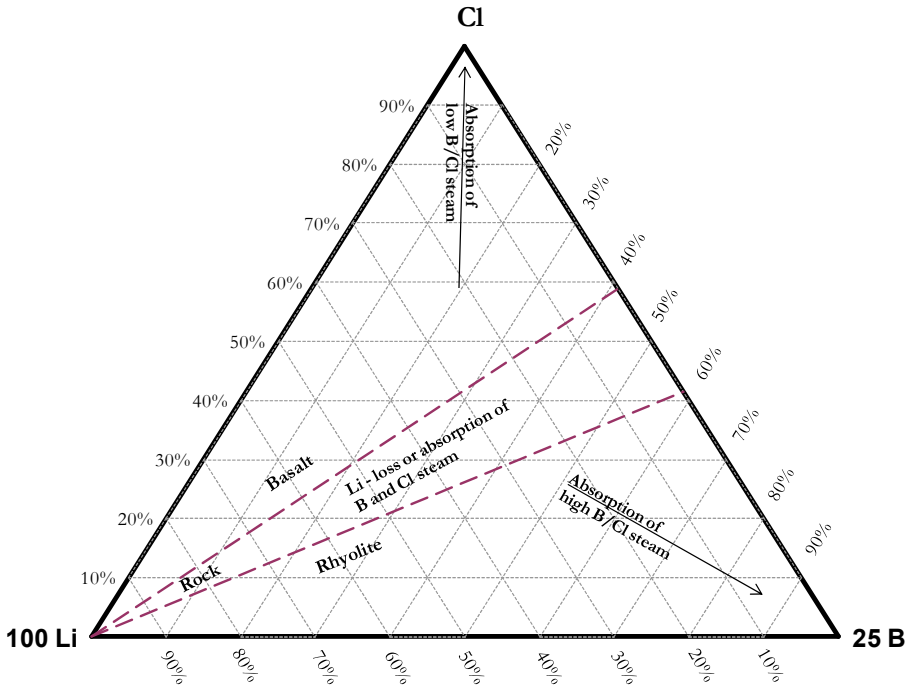

FIGURE 7: Relative Cl-Li-B contents

6.4 The Relative Na-K-Mg contents

The Na-K-Mg-geothermometers is a 'self-policing' technique that gives an automatic indication as to the suitability of given water for the application of ionic solute geoindicators (Giggenbach 1988). It characterizes waters to immature, partial equilibrated and fully equilibrated. Immature waters are not suitable for K-Na- and K-Mg-geothermometers and care should be taken while interpreting such temperatures.

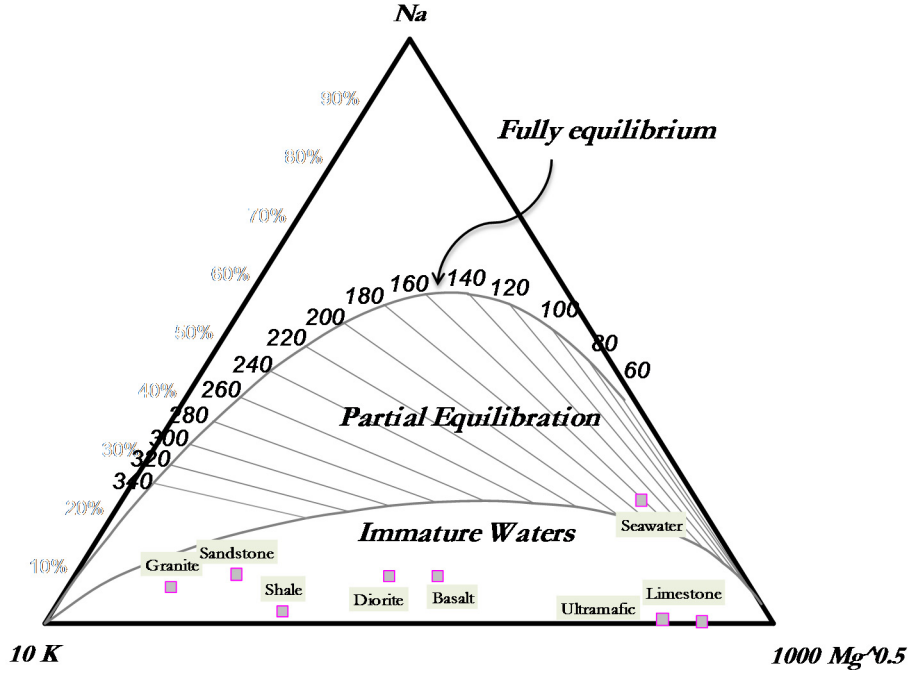

FIGURE 8: Relative Na-K-Mg contents

7. GEOTHERMOMETRY

Applications of geothermometry constitute one of the major tools for the exploration and development of geothermal resources. Geothermometry is simply the estimation of the reservoir (subsurface) temperatures using the chemical and isotopic composition of surface discharges from wells and/or natural springs/fumaroles. When employing geothermometry, a basic assumption is usually made that temperature dependent chemical and isotopic equilibria prevail in the source aquifer. Since the fluids may travel long from the source aquifer to the surface for collection, an approximation is made that chemical and isotopic reactions do not significantly modify the composition of the fluid during its ascent.

Geothermometers are classified into two groups: Chemical Geothermometers and Isotopic Geothermometers. The former utilizes the chemical composition (essentially the silica and major cation contents of water discharges, and the gas concentrations or relative abundances of gaseous components in steam discharges), whereas the latter is based on isotope exchange reactions between various phases (water, gas, mineral) in geothermal systems.

Chemical geothermometers are developed on the basis of temperature-dependent chemical equilibrium between water and minerals under deep reservoir conditions. The use of chemical geothermometers basically relies upon chemical species (solutes, gases, isotopes) reaching a state of reaction equilibrium in the reservoir, then leaving the reservoir and appearing at wells/springs/fumaroles before significant re-equilibration can occur.

8. SOIL GAS SURVEY

Early geochemical studies on diffuse soil degassing have been carried out in a number of geothermal areas. CO_2 soil gas investigations have been conducted in volcanic areas to examine unexpected rise in CO_2 flux (e.g. Farrar *et al.* 1995; McGee and Gerlach 1998; Gerlach *et al.* 1998), estimate total volcanic flux from volcanic vents and diffuse flank emissions (e.g. Allard *et al.* 1991; Chiodini *et al.* 1996), and to classify tectonic structures related to volcanic degassing (e.g. Giammanco *et al.* 1997; Bergfeld 1998).

The term volcanic gas defines a gas exsolved from a magmatic source of an active volcano whereas hydrothermal gas defines a gas exsolved from the envelope of hot water that surrounds the magmatic environment. Volcanic gases have composition different from the hydrothermal gases; the first is richest in SO_2 and the second in H_2S. CO_2 occurs in both magmatic and hydrothermal gases and is the most abundant gas after water vapor. The deep-seated faults in the crust tap magmatic CO_2, which is transmitted to the surface where it is naturally lost through the soil. Carbon dioxide (CO_2) of magmatic origin is normally channelled through deep-seated tectonic structures close to the surface of the earth and then seeps out of the ground through the soil. CO_2 may also originate from other sources like organic matter, or localized like in the rift valley, which are likely to give false impressions of a geothermal source.

Thoron gas (Rn220) is a short lived isotope of radon produced by the thorium (Th-232) decay series with a half-life of 55 seconds (Lopez *et al.* 2004). Due to its short half-life, thoron's transportation is limited to a few centimetres either by diffusive or convective flows, as compared to Rn222 (t ½ = 3.8 days) (Hutter 1993). As a result, the high concentrations of thoron are more likely to be due to convective movement of gases rather than diffusive processes and therefore it is difficult to achieve an exact quantitative measurement of its concentration. If we measure the disintegration of thoron, it shows a decrease during the first three minutes after collection of the sample, as opposed to the radon that presents a half-life of almost 4 days (Magana *et al.* 2002). High thoron values could be suggestive of enhanced permeability, as it may as well depend on other factors such as the degree of rock fracture and the ability of groundwater to circulate and remove thoron.

8.1 Soil gas survey of Silali geothermal prospect (case example)

Silali geothermal prospect is located in the axis of the northern Kenya rift. The northern segment of the Kenya Rift is a unique petrographic province composed of six Quaternary to Recent volcanic complexes namely Korosi, Paka, Silali, Emuruangogolak, Namarunu, and Barrier from south to north(Figure 1.1). Silali is the largest caldera volcano in the axis of the northern Kenya rift. It is characterized by a large caldera volcano, situated on the floor of the northern Kenya rift. Previous studies of the volcano and the surrounding area indicated occurrence of a hydrothermal system, signifying probable occurrence of a high temperature geothermal resource.

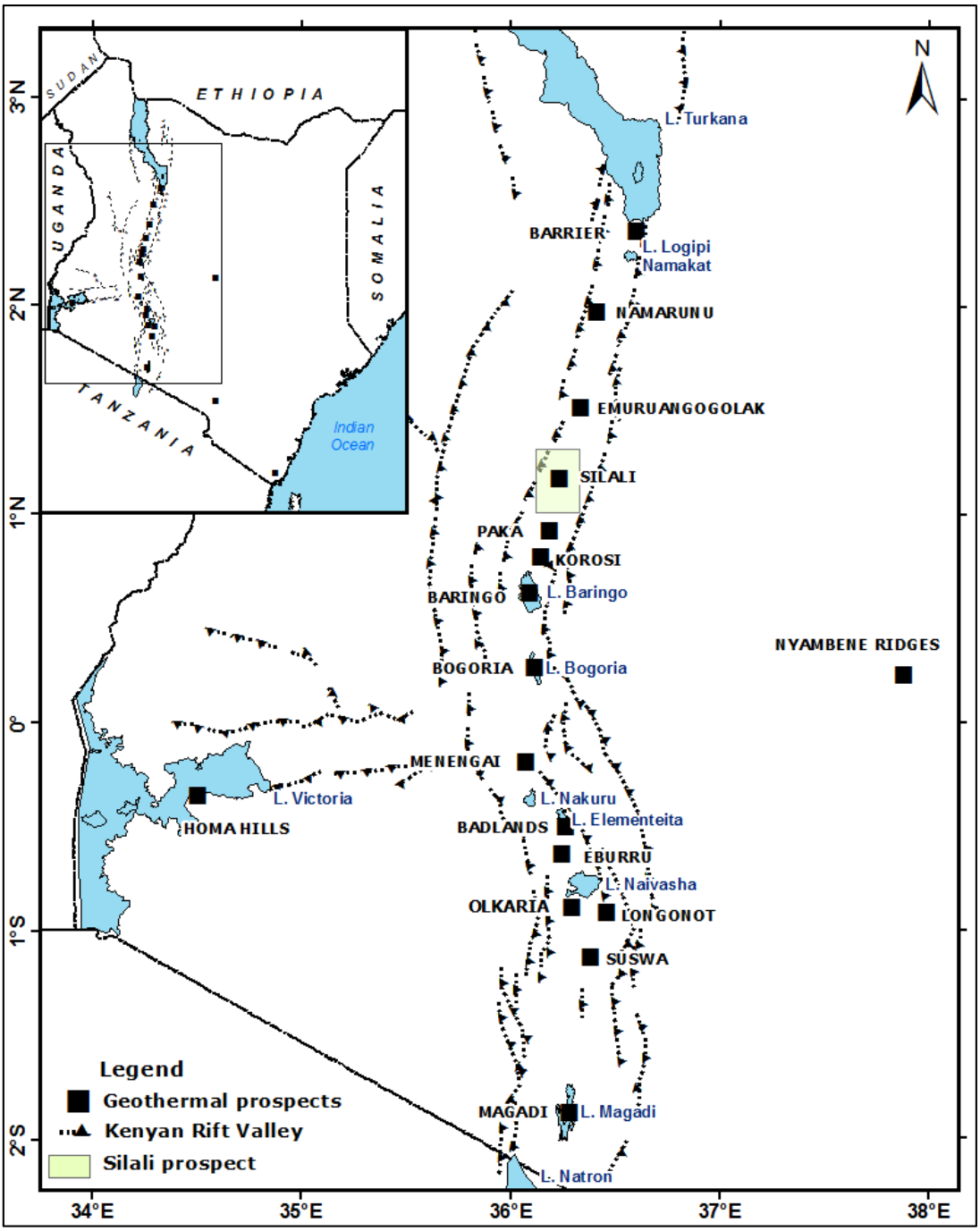

FIGURE 9**:** Map of the Kenya rift showing the location of Silali geothermal prospect (GDC, 2011)

Detailed geo-scientific exploration was carried out in 2010 to determine its geothermal potential. Soil gas measurements of CO_2 and radon was part of the survey carried out. The soil gas survey anomalies are depicted in Figures 10 and 11 below.

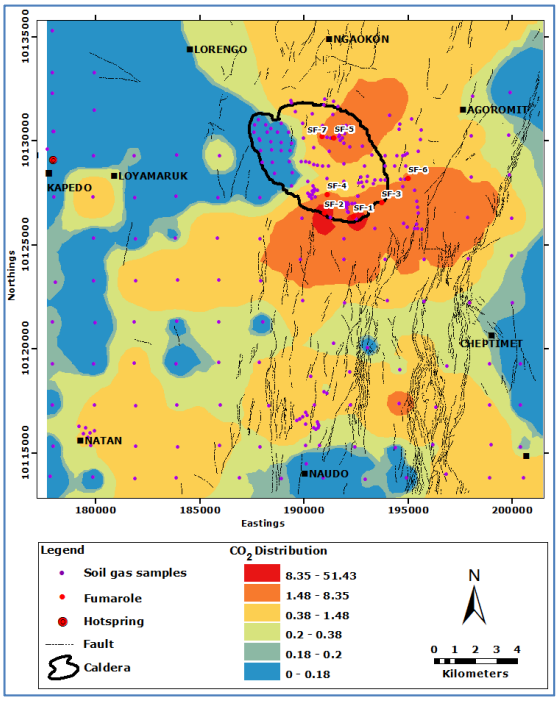

FIGURE 10: CO_2 distribution in the Silali prospect

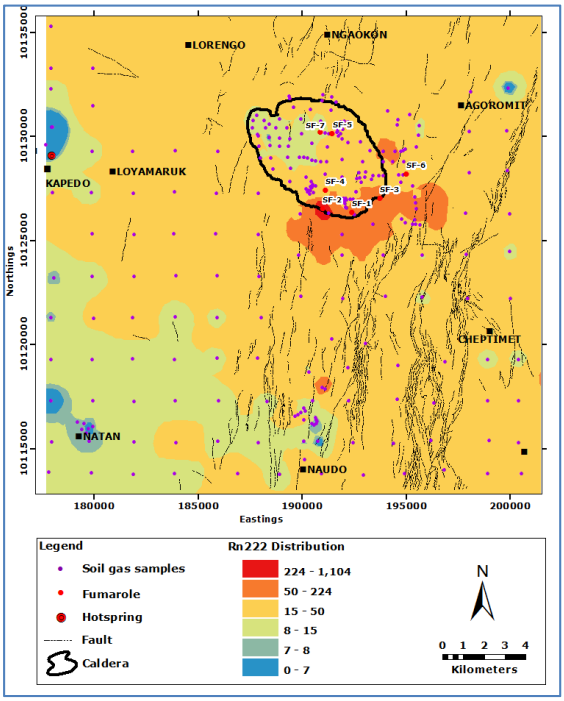

FIGURE 11: Rn-222 distribution

The CO_2 and Rn-222 anomalies observed on the maps are indicative of gas leakages through fluid transporting structures. This is because a big percentage of the gases are transported convectively. The elevated values of CO_2 and radon are useful in delineating areas with enhanced subsurface permeability which are good targets for siting exploration wells. The results should be correlated well with geological and geophysical findings.

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GEOTHERMAL MAPPING USING TEMPERATURE MEASUREMENTS

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ABSTRACT

Shallow temperature gradient holes are reliable in mapping geothermal prospects with heat loss features as surface manifestation. The sun least affects ground temperatures at 1 m depth and temperatures in the North rift are least affected by seasonal changes. Over 10,736 MWt is lost naturally from Menengai to Paka along the Kenyan rift. Most of the geothermal surface manifestations associated with the heat loss are oriented in the NW-SE with a few located in the NE-SW direction. Estimated down-hole temperature at I km depth is over 200°C. Fluid flow in the prospects from Lake Baringo to Paka is from East to West with an outflow to the north.

1. INTRODUCTION

Kenya is located in East Africa where the Great African Rift virtually splits the landmass into two. 14 geothermal prospects have been identified within the Kenyan Rift Valley starting from Barrier in the north to Lake Magadi in the south with a potential of over 3,000 MWe (Figure 1). The rift is a graben and during the formation of the prospects, hot rocks were brought closer to the surface and with intensive faulting and presence of water, the geothermal systems were formed as shown in the model in Figure 2.

Faults form areas of leakage resulting in the formation of surface manifestations related to the geothermal system below. Surface manifestations include hot grounds, hot springs, geysers, altered grounds and fumaroles. These features continuously transport mass and heat from the geothermal system underground to the atmosphere. This heat is referred to as natural heat loss of the system. The heat is lost by conduction, convection and very little by radiation. Ground temperatures can be used to map prospect areas with heat loss features. Areas with geothermal system are also associated with high local heat fluxes and high temperature gradients, which is above the normal geothermal gradient of 30°C/km.

During surface exploration, heat loss survey done is aimed at assessing the amount of heat being lost naturally from a prospect and is used to conceptualize the amount of energy that could be concealed and the relationship between the geological structures and the discharging features. Heat loss method is used indirectly to determine the size of the reservoir as large heat loss mirrors a large reservoir. Results from heat loss survey are an important input in numerical simulation of the prospect if the reservoir is proven.

About 130MWe is generated from Olkaria. Kenya has almost exhausted its hydro potential and to accelerate geothermal development the Government of Kenya (GOK) and KenGen have implemented Geothermal Resource Assessment program (GRA). Since 2004 surface exploration has been done in seven prospects in the north rift. During this study temperature measurements were used to map the prospect areas. Results obtained and the method used is the subject of this paper.

2. METHODOLOGY

Most of the heat loss features encountered in the seven prospects already explored were hot grounds, fumaroles and altered grounds. Hot springs and geysers were mostly in Lake Bogoria prospect therefore most of the heat is lost through conduction and convection.

2.1 Conductive heat transfer in solids due to periodic surface temperature variations.

Problems on heat conduction in solids with periodic surface temperature are of great practical importance. They arise in:

- The study of temperature fluctuations of the earth's surface crust due to periodic heating by the sun.
- In various experimental arrangements for determination of thermal diffusivity.
- In studying thermal stresses occurring in the cylinder walls of steam or internal combustion engines.
- In the theory of automatic temperature control systems.

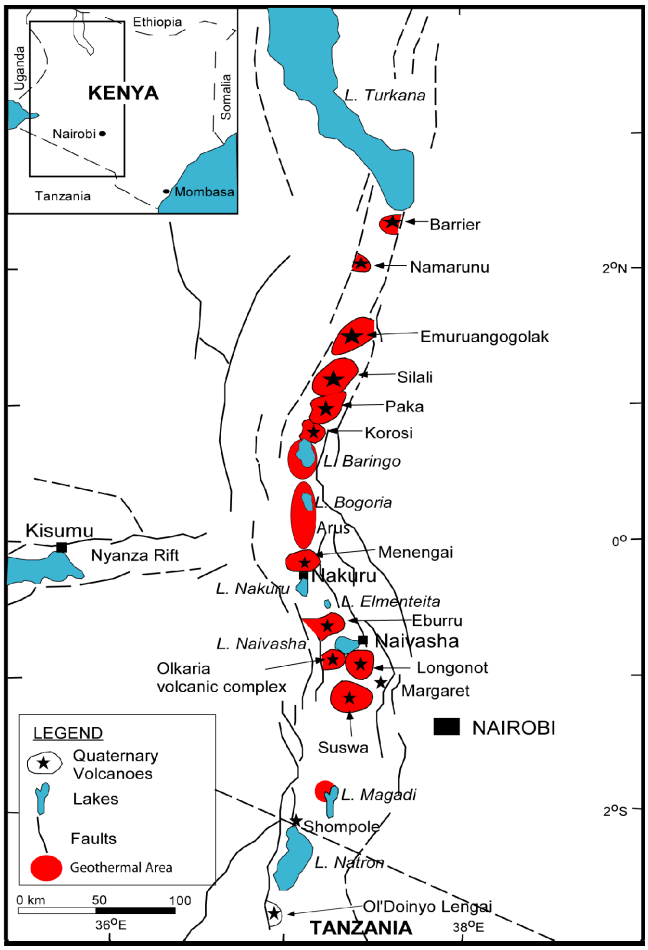

FIGURE 1: Geothermal prospects in the Kenya rift

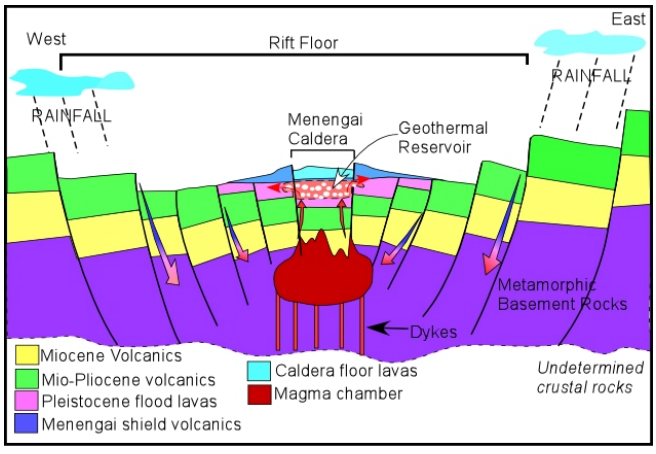

FIGURE 2: Model of a geothermal prospect in the Kenyan rift

It can be shown that temperature fluctuations due to periodic heating can be computed from the formula:

$$T = e^{-\varepsilon} Cos(\omega t - \varepsilon), \text{ where } \varepsilon = x(\omega / 2\kappa)^{\frac{1}{2}} \quad (1)$$

where T is temperature, ω is angular velocity, ε is phase angle. κ is the thermal diffusivity of the material and *t* is the time.

Differentiating the above equation with respect to distance *x* and multiplying it by thermal conductivity *(K)* of the material yields the heat flux at any time *(t)*.

$$q = \mathrm{K}\frac{\partial T}{\partial x} \tag{2}$$

The conduction equation assumes a homogeneous and isotropic solid with heat flow in one-dimension. No heat is lost from the surface (Carslaw and Jaeger, 1959).

2.1 Conductive heat loss measurements

Natural heat loss by conduction was estimated by obtaining temperature gradients from shallow 1 m depth holes drilled manually using 1-inch diameter spike. Temperatures were measured at the surface, at 50 cm and at 100 cm depths. Location of these holes was read from a portable Global Positioning System (GPS). Thermally active area was later estimated from 40ºC isotherm at 1 m depth. The holes were drilled at an interval of 100 m – 1 km in areas of high thermal activity and 1 - 4 km in areas of low activity. Area of the hot ground and average temperature gradient is then computed. The following one dimensional heat conduction equation is used to compute the heat flow assuming that the soil's thermal conductivity is constant at 2 W/m °C.

$$Q = Ak\frac{dT}{dy} \tag{3}$$

where Q is conductive heat flow (watts), A is surface area of hot ground (m^2), k = 2 is thermal conductivity of rock (W/m°C), T is temperature (°C) and y is depth (m).

2.2 Convective heat loss measurements

Natural convective heat loss from a geothermal system occurs from hot springs, geysers, fumaroles and steaming grounds. The convective component of the total heat loss was estimated by measuring steam flow velocities from fumaroles by use of a venturimeter and water manometer. To achieve this inverted plastic trough of known diameter was used and the venturimeter placed on a conveniently drilled hole at the back of the trough. To seal for any leakages, wet mud was used. With flow velocity and temperature and steam properties known at source temperature, mass and heat flow is calculated. The following equations were used to calculate steam flow rates and heat flow from fumaroles.

$$V = C_d A_t \sqrt{\frac{2g\Delta H(\frac{\rho_w}{\rho_s} - 1)}{(1 - \frac{d_t^{\,2}}{d^2})}} \tag{4}$$

where V is volumetric flow rate (m^3/s), C_d is coefficient of discharge (assumed to be 0.96), g is acceleration due to gravity (9.81 m/s^2), d_t is venturimeter throat diameter, d is venturimeter diameter at the high pressure tapping (m), ΔH is differential height at the manometer (m), ρ is density (kg/m^3), A_t is throat area (m^2) and the subscripts w and s refer to water and steam respectively.

$$Q_c = V\rho_s(h_s - h_w) \tag{5}$$

where Q_c is convective heat flow (watts) and h_s is enthalpy of steam in (J/kg) and h_w is enthalpy of water at ambient temperature.

Flow from hot springs and geysers was measured by use of a 90° V-notch weir or Pitot Static pressure method. For the V-notch weir, mass flow rate was computed using the formula:

$$\dot{m} = 0.01333h^{2.5} \tag{6}$$

where h is weir height in (cm) and $\dot{m}$ is mass flow rate in (kg/s). Heat flow Q_c in kilowatts was computed from the formula;

$$Q_c = \dot{m}(h_{sp} - h_s) \tag{7}$$

where h_{sp} is enthalpy at the source temperature while h_s is water enthalpy at the mean surface temperature in (kJ/kg).

For high flow rates average flow velocities of the resulting hot water was computed using Pitot static pressure method across the river from the formula:

$$v = C_d\sqrt{2gH} \tag{8}$$

where v is velocity in (m/s), H is static pressure head in (m) and C_d is coefficient of discharge (assumed to be 0.96). For cross sectional area of flow A (m^2) and water density (ρ_w) at the source temperature, the mass flow rate can be computed from the formula:

$$\dot{m} = vA\rho_w \tag{9}$$

Heat flow was then computed using Equation (7).

2.3 Reliability check

Temperature measurements were taken at different times of the day. Since ground surface temperatures in the north rift can reach 40°C, it was therefore prudent to check the data obtained for temperature variation due to day and night. Also control points were made in active and less active areas to check temperature variation due to seasonal change.

Equation (1) was used to check a random sample of field data for temperature variation at the surface, 50 cm and 100 cm depth due to effects of the sun. Heat flux from below is assumed constant. Formation penetrated by shallow gradient holes was assumed to be a mixture of granite and soil with average thermal diffusivity of 0.008 m^2/s. Variation in temperature over a 24 hour cycle was then computed assuming 12 hours of light and 12 hours of darkness in a day. Percentage deviation for the three temperature readings is plotted on Figure 3.

The highest deviation was 4% on surface temperature in areas of low thermal activity and 0.1% for anomalous areas. At 100 cm depth, the

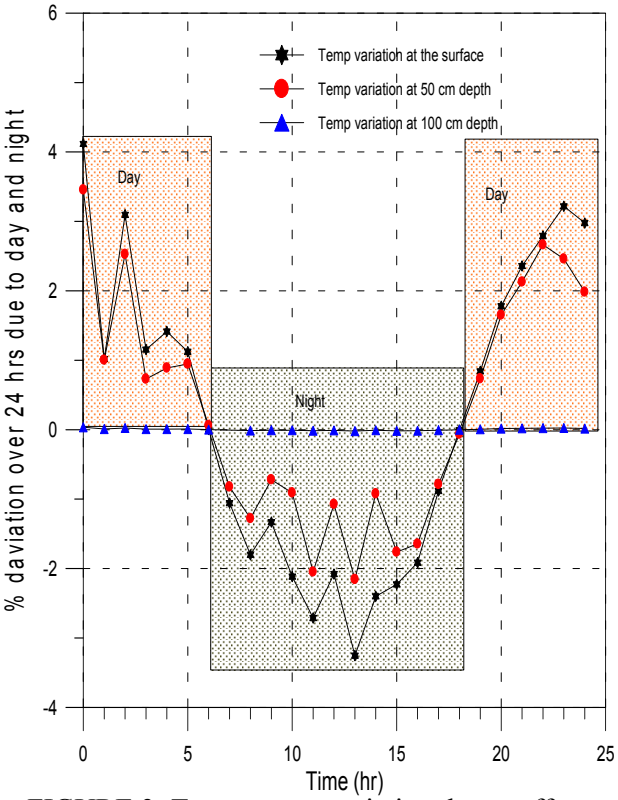

FIGURE 3: Temperature variation due to effect of daytime heating and cooling at night

deviation was 0.35% for cold areas and 0.1% for thermally active areas. This indicates negligible sun effect on temperature readings at 1-meter depth hence the method is reliable for delineating hot grounds.

2.4 Down-hole temperature and pressure measurements in boreholes

Boreholes drilled within prospect areas can serve as very good gradient holes for temperature gradient computation. Results obtained can be used to estimate temperatures likely to be encountered at depth. Pressure measurements in these boreholes can be used to model the hydrological picture of the area and hence give an indication of possible recharge and outflow zones. Mechanical Kuster down-hole tools were used for these measurements.

3. RESULTS FROM MENENNGAI TO PAKA GEOTHERMAL PROSPECTS

Under the ongoing GRA program surface studies have been conducted from Menengai geothermal prospect in the south to Paka in the north. The studies involved geology, geophysics, geochemistry, heat flow measurements and environmental baseline data collection. Obtained heat flow results and down-hole temperature and pressure measurements are as discussed below.

3.1 Menengai geothermal prospect

Menengai is a large Caldera covering an area of 90 km^2 on the rift floor near Nakuru town and also one of the most promising prospects in Kenya. It has extensive young lava flows and boreholes drilled to 300 m depths have recorded temperatures of 40-60 °C. The GoK and KenGen carried out exploration studies from February to May 2004 in an area of about 900 km^2. Heat loss features encountered are hot grounds and fumaroles. No hot springs were encountered.

Figure 4 shows the prospect hot area mapped using shallow gradient holes. It is demarcated by the 40°C isotherm. Areas of possible drills sites for further exploration through deep drilling have been suggested.

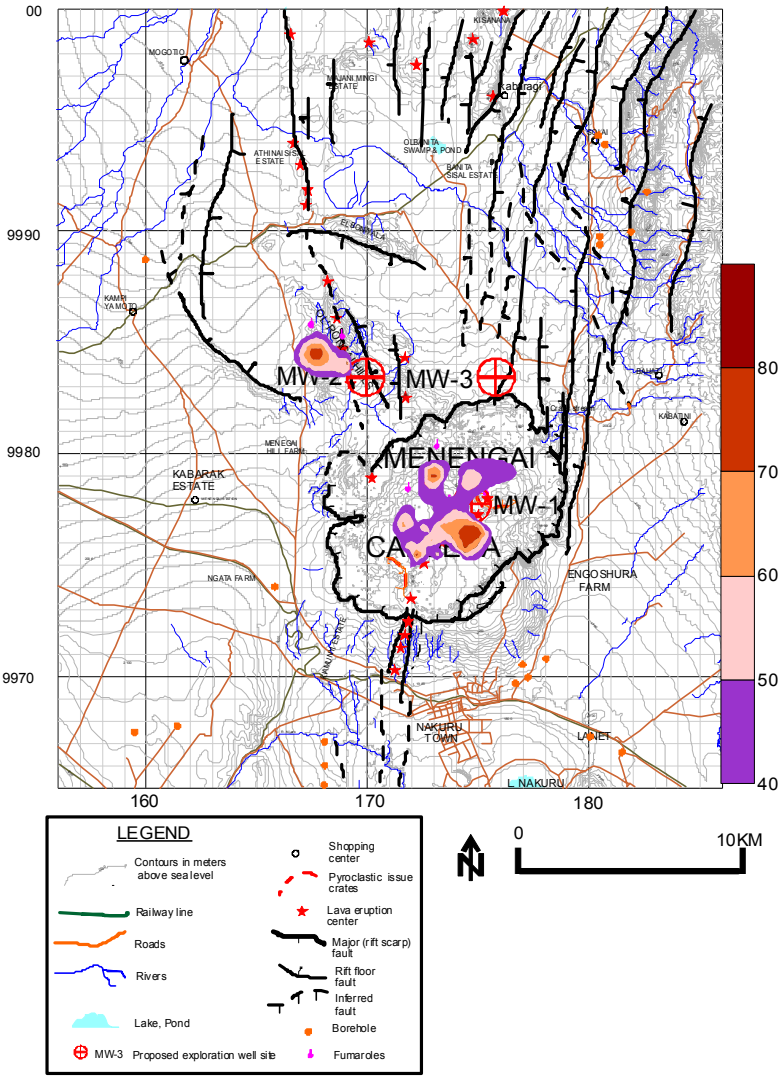

FIGURE 4: Heat loss results from Menengai prospect

3.1.1 Discussion

It was difficult to make holes in areas with fresh lava flow cover. Because of this, temperature gradients and areal extent in certain zones have been

extrapolated from temperature contours. For all practical purposes, this is considered well enough for field measurements.

Control points indicated no significant changes in ground temperature at 1 m depth due to seasonal variation.
Orientation of the high temperature areas is in a NNW-SSE direction and suggests that a major fault/fracture zone could be in this direction and allows deep hot fluids to travel close to the surface causing localised heating. Another possible structure seems to occur in NE-SW direction as can be observed from the orientation of the high temperature areas in the caldera.
Total heat loss estimated from the Caldera alone is in excess of 2,690 MWt indicating possibly a big hot body underneath which can be explored further for production of steam.

Areas around Olongai and Banita have low heat flow possibly because the geothermal system in this area is older.

It could be of interest to drill deep exploration wells in the Menengai Caldera and in Olongai/Banita areas with priority being in the Menengai Caldera (Ofwona 2004). Estimated power potential is over 700 MWe (Mungania et al, 2004).

3.1.2 Conclusions

Over 3,536 MWt of natural heat loss occurs in the Menengai/Olbanita geothermal prospect. 2,690 MWt is lost from the Menengai Caldera out of which 2,440 MWt is by convection through fumaroles.

This large heat loss could be an indicator of a huge heat source underneath this prospect.

3.2 Arus and Bogoria geothermal prospects

Arus and Lake Bogoria prospects are located to the north of Menengai and are not associated with any central volcano. Heat loss survey was done from 14th February to 8th July 2005 in an area of about 2,000 km^2. Earlier work at Lake Bogoria prospect was done in 1973-1974 under the sponsorship of United Nations covering an area of 31 Km^2. This study was regional starting from Turkana in the north to Lake Natron in the south. Other fields incorporated in the survey included Eburru, Olkaria and Lake Magadi. Infrared aerial photographs were taken over the named prospects. At Bogoria, the survey was localized around the lake where numerous geothermal surface manifestations are located. 40^{o}C isotherm was used to delineate the thermally active area resulting in a total heat flow of 353 MW$_t$ (Crane and O'Connell, 1982).

3.2.1 Discussion

Natural heat loss at Arus and Lake Bogoria prospects is by conduction through the soil and convection through hot springs, geysers and fumaroles (steaming grounds) located inside and on the shore of Lake Bogoria.

Figure 5 shows distribution of temperatures at 1 m depth in Lake Bogoria and Arus geothermal prospects. Anomalous areas are enclosed by the 40°C isotherm. Heat loss features are located on the southern shore of the lake. Some springs are submerged in the lake; therefore it is possible that anomalous temperatures at shallow depth can be obtained below the lake. Heat loss features at Lake Bogoria are more active when compared to those at Menengai possibly due to better recharge or poor capping.

3.2.2 Conclusions

At Arus prospect, the hot areas are inclined in the NE-SW direction possibly along a fault that may finally intersect the one controlling the Lake Bogoria system.

1,199 MW_t is naturally lost from Lake Bogoria prospect out of is 437 MWt is by convection. 467 MW_t is lost from Arus out of which 0.03 MWt is by convection.

Lake Bogoria prospect could be controlled by a NW-SE fault zone whereas the Arus prospect appears to be at the intersection of the NW-SE and the NE-SW fault zones
The prospects are better recharged and possibly more fractured or poorly capped than Menengai (Mwawongo, 2005).

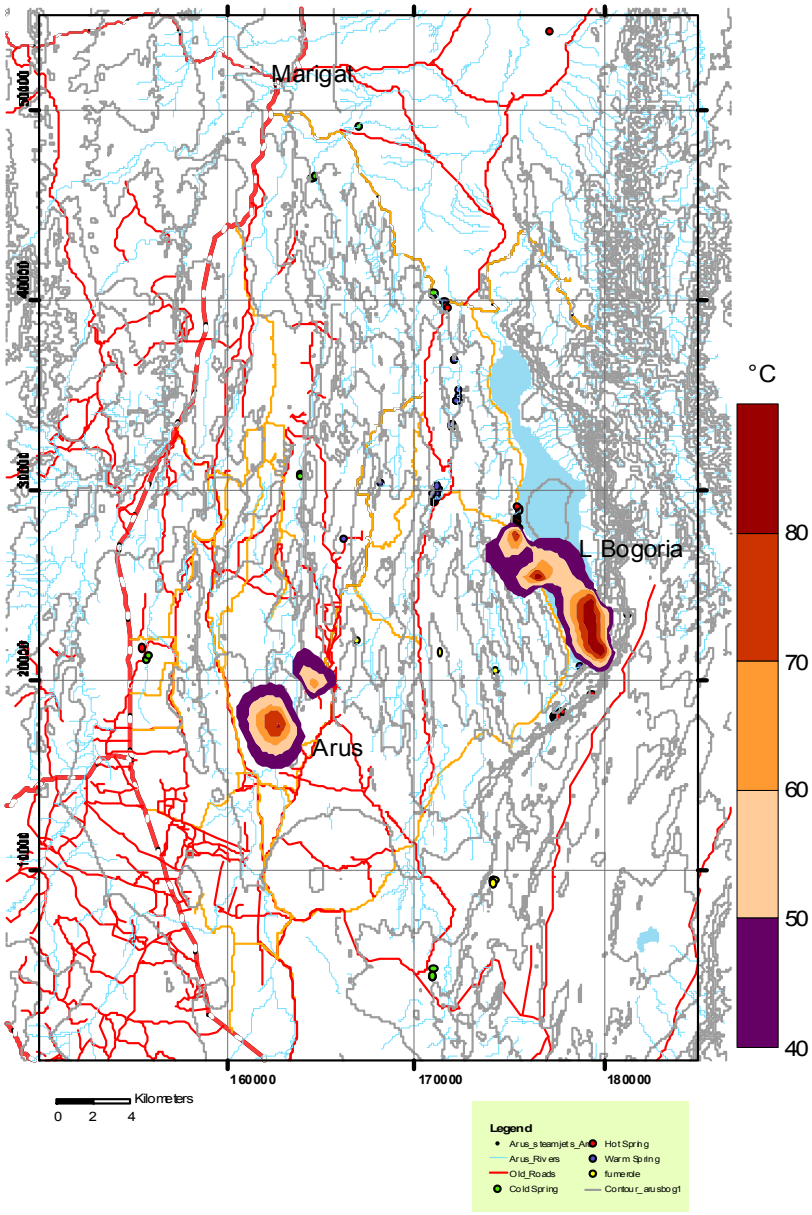

FIGURE 5: Temperature contours at 1 m depth

3.3 Lake Baringo geothermal prospect

Lake Baringo covers a large part of this prospect reducing the effective area substantially. There is no central volcano. Silt covers the low lands while highlands are covered with hard rock. Surface manifestations include hot grounds and anomalous boreholes.

3.3.1 Discussions

Figure 6 shows ground temperature contours at Baringo. The area is generally inactive as strong fumaroles and hot grounds were encountered only, in Kokwa Island and north of Kampi Samaki.
Hard rock covering the high lands and silt deposits in the low lands make it difficult to make temperature measure-ments. Silt cover lowers the natural heat loss as it acts as an insulator. Area covered by the lake could also be absorbing the natural heat flow underneath.

3.3.2 Conclusion

Natural heat loss at Lake Baringo geothermal prospect is by conduction through soil and convection through fumaroles (steaming grounds) and hot springs (encountered in Kokwa Island).

Total heat loss from the prospect is in excess of 1,049 MWt of which 941 MWt is by conduction and 108 MWt by convection. Of the total heat lost by convection, 105 MWt is lost in Kokwa Island. Heat loss features occur along NW-SE fault zones. Compared to Menengai, this heat loss is relatively low probably because the system could be older. There are indications (from alterations and old lavas) that it was once very active and has since cooled down. The prospect could be lowly ranked when compared to Menengai but nevertheless, could be explored further by deep drilling to estimate its power potential (Ofwona, 2004).

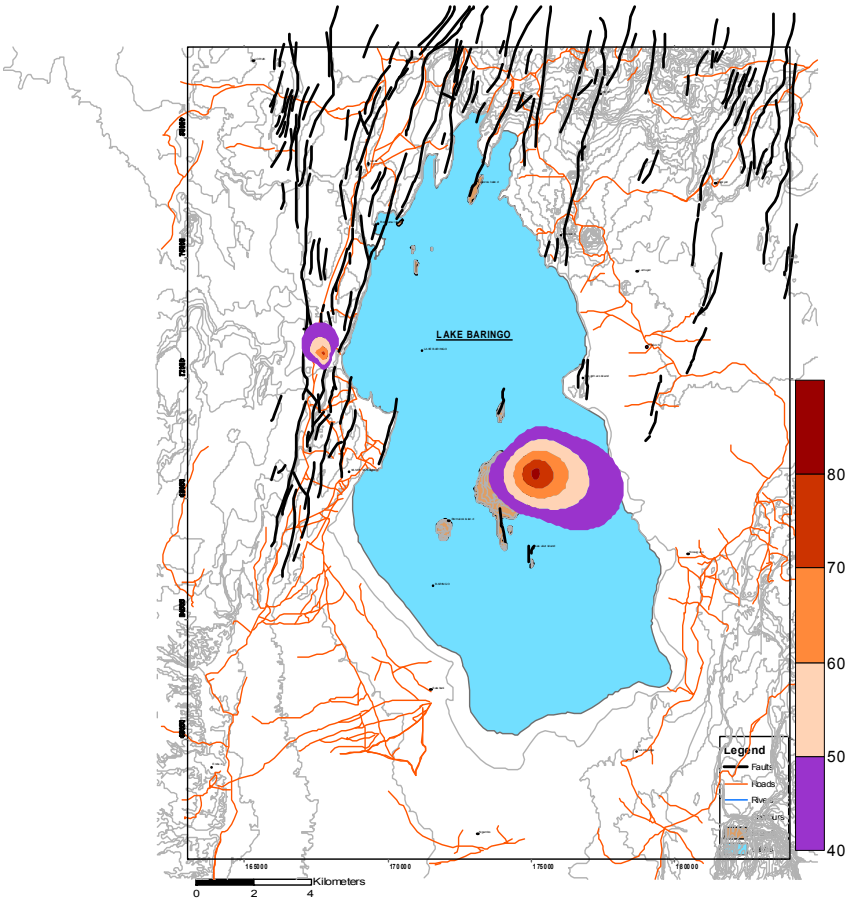

FIGURE 6: Temperature contours at Lake Baringo prospect

3.4 Korosi and Chepchuk

Surface exploration was done in these geothermal prospects from 11th October, 2005 to 24th March 2006 covering an area of about 900 km^2. Earlier work at Korosi by British Geological Survey in 1993 identified geothermal surface manifestations as being hot grounds (altered grounds), steaming grounds and fumaroles covering an area of 33 Km^2. A maximum surface temperature of 95^{o}C was recorded. At Chepchuk the area covered by similar thermal features was estimated at 2.3 km^2 and a maximum surface temperature of 90^{o}C was recorded (Dunkley et al, 1993).

3.4.1 Discussion

Figure 7 shows results obtained from the heat loss survey. For the area demarcated by the 40^{o}C isotherm, both Korosi and Chepchuk prospects have high temperature gradients at shallow depths. Temperatures recorded at 1 m depth ranged from 27^{o}C in the coldest region to 97^{o}C in the hottest part.

Korosi has a total heat loss of 2,135 MW_t with a negligible convective component of 0.4 kWt. Chepchuk has a heat loss of 546 MWt. Fumaroles at Chepchuk are weak.

At Chepchuk, hot grounds cover about 5 km^2. Maximum temperature recorded at the top of a highly altered hill is 95^{o}C (Figure 7).

3.4.2 Conclusions

Natural heat loss at Korosi and Chepchuk geothermal prospects is mainly by conduction through soil and very little by convection through weak fumaroles or steaming grounds. These features are located along fault lines in both prospects.

At Korosi heat loss features display a NE-SW and NW-SE trend while at Chepchuk the trend is not well defined (Mwawongo, 2005).

Estimated power potential at the two prospects is over 750 MWe (Ofwona C.O. et al, 2007)

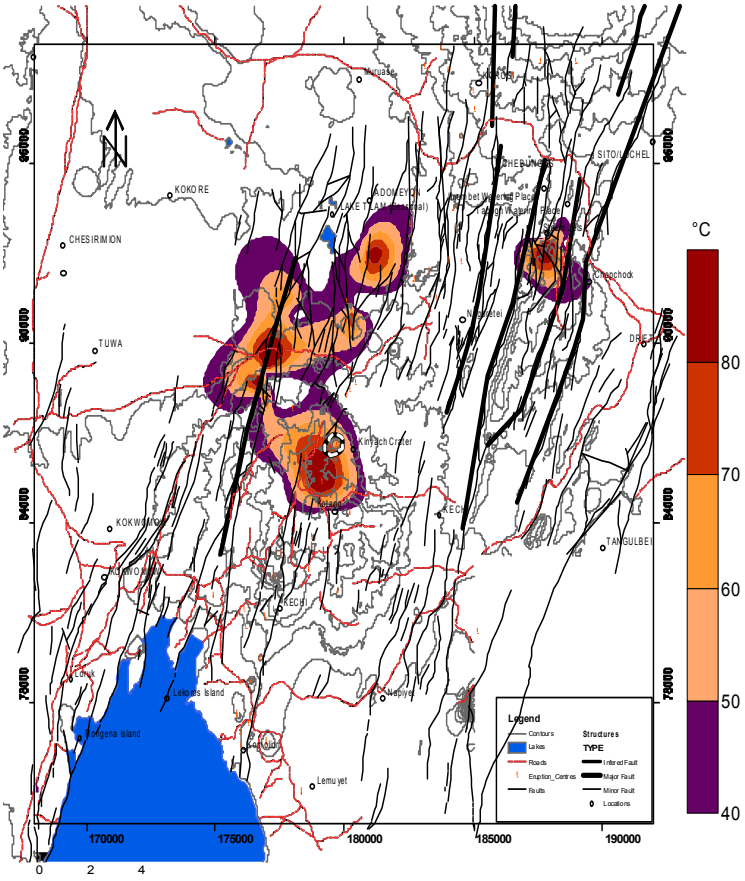

FIGURE 7: Temperature contours at Korosi & Chepchuk

3.5 Paka

Paka is a volcano built by trachyte, basalt lavas and pyroclastic deposits. Surface exploration was done from 18th September 2006 to 30th March 2007 covering an area of about 500 km^2. Earlier work at Paka by British Geological Survey between 1988 and 1993 identified geothermal manifestations as being hot grounds (altered grounds), steaming grounds and fumaroles covering approximately an area of 32 Km^2. Ground temperatures recorded ranged from 50.2 to 94.5^{o}C while fumarole temperatures ranged from 74 to 97.8^{o}C in the caldera (Dunkley et al, 1993).

3.5.1 Discussion

Heat loss features in Paka (Figure 8) especially the fumaroles in the crater are bigger and more active when compared to those found at Korosi and Chepchuk prospects. This suggests better fluid recharge and less sealing of the flow paths at Paka.

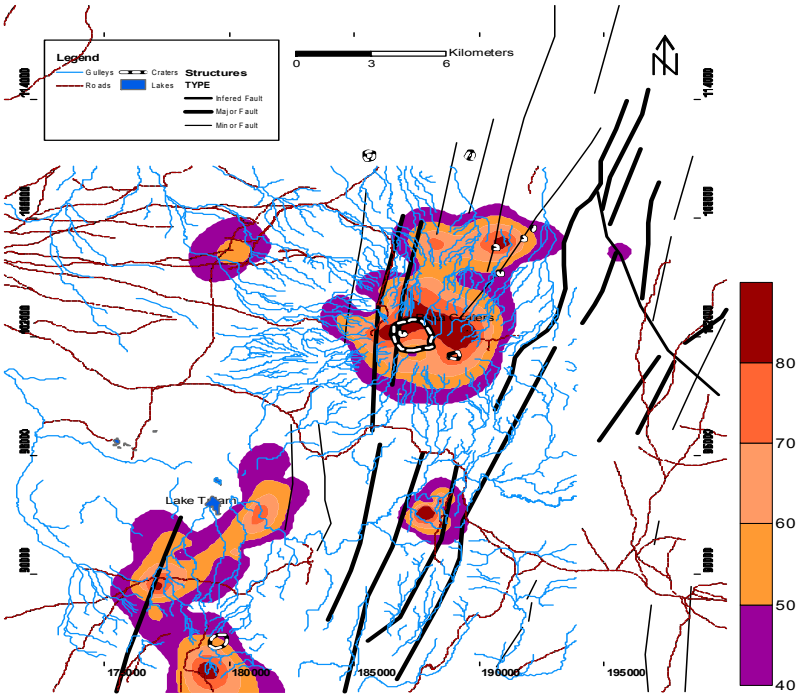

FIGURE 8: Temperature contours at Paka, Chepchuk & Korosi

The actual convective heat loss may be slightly higher than the computed values because some flows were too low to meter and it was also not possible to seal all the steam leakage from the trough.

Paka prospect is mainly related to the NE-SW fault zone as indicated by the heat loss features.

Control points indicated negligible temperature variation due to seasonal change. Percentage deviation varied from 0.1% in active areas to 2.27% in cold zones for temperature at 1 m depth.

Percentage deviation computed from equation (1) varied from 0.1% to 0.35%. This compares well with the actual values obtained from the control points.

Errors resulting in high temperature gradient could occur where holes were drilled in hard rock leading to additional heating due to friction between the tool and the rock. Low gradients could be due to colder shallow soil falling into the hole where the ground was unstable or a hole drilled in silted plains and affected by shallow water seepages.

3.5.2 Conclusions

Heat loss features at Paka are controlled by fault zones oriented in a NE-SW and NW-SE direction. About 2,855 MW_t is naturally lost at Paka with most of it being conductive and about 10 MWt being convective (Mwawongo, 2007). Estimated power potential is over 700 MWe (Mungania J. et al, 2007).

4. DOWN-HOLE TEMPERATURE AND PRESSURE MEASUREMENTS FROM BARINGO TO PAKA

Boreholes drilled in the prospect area can serve as very good gradient holes for heat flow estimation. A regional heat flow in the Kenya rift was done in 1992. Several selected deep wells and boreholes were probed and temperature gradients as well as rock conductivities in both rift flanks and the floor estimated. Average rock conductivity in the rift floor was found to be 1.4 w/mK. Temperature gradients computed from selected boreholes varied from 20 to 199 ^oC/km (Wheildon et al, 1992). Another survey done by Williamson in 1975 covered western Kenya, the rift flanks and the floor and an area north of Lamu near the Kenya-Somali border. Borehole depth ranged from 66 m to 226 m deep. Terrestrial temperature gradient computed ranged from 0.01 to 0.08^oC/m (Williamson, 1975).

Figure 9 shows borehole locations and mapped ground temperature at 1 m depth from Lake Baringo to Paka prospect. Temperature gradient from shallow boreholes is indicated red contours while blue contours indicate piezometric levels. Figures 10 and 11 show obtained down-hole temperature and pressure measurements.

4.1 Discussion and conclusions

Area covering Paka geothermal prospect has a low mean temperature gradient except for parts that are affected by geothermal heat. This is supported by low temperature gradients, which are in the terrestrial range in areas like Chepkalacha and Silangwa of 0.02^oC/m. High temperature gradients encountered at Korosi close to the foot of mount Paka suggest a possible interconnection of the two prospects at depth. Besides the distance separating the thermally active zones of Paka and Korosi of 6 km is very short hence further supporting the interconnection.

Near surface temperature varied from 24 $^{\circ}C$ to about 44 $^{\circ}C$ while bottom-hole temperature varied from 26 to 60^oC. Borehole depth varied from 54 m to 152 m. Water rest level varied from 28 m to 116 m from the surface

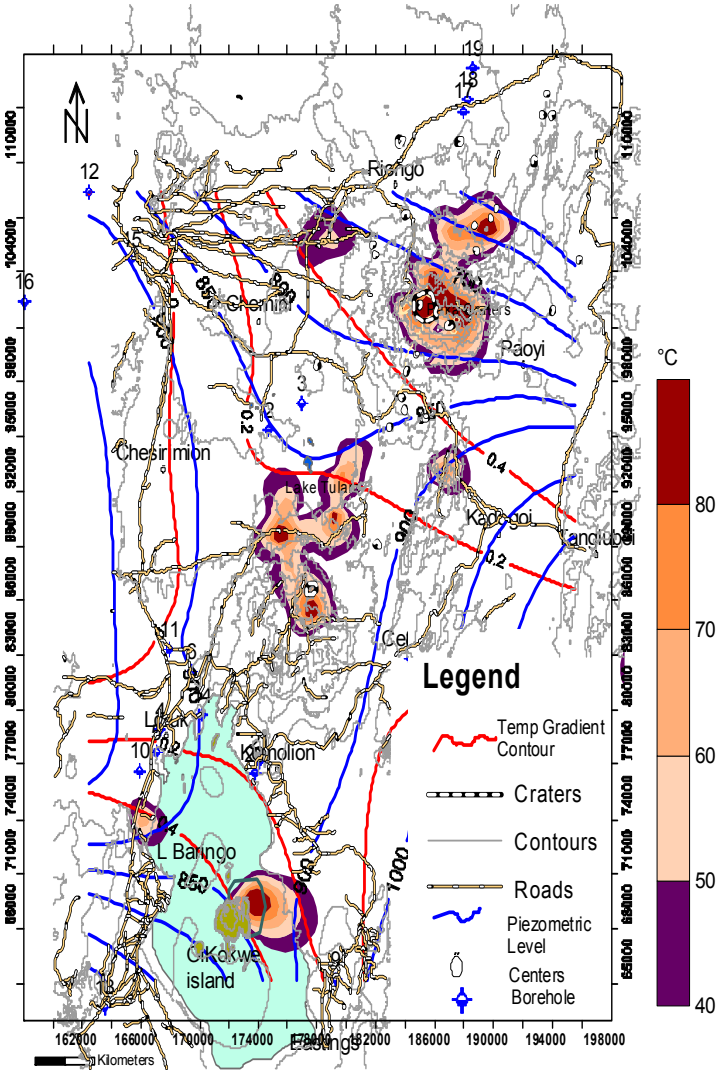

FIGURE 9: Temperature gradient & piezometric levels

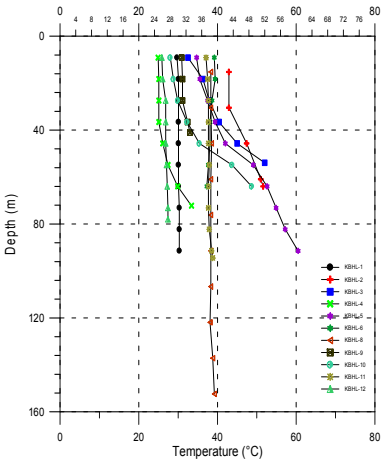

FIGURE 10: Down-hole temperature profiles

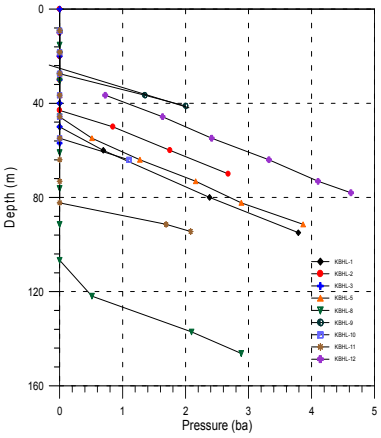

FIGURE 11: Down-hole pressure profiles

Looking at Chepchuk in relation to Paka, a possible NW-SE trend of thermal features is evident suggesting occurrence of intersection of the NE-SW and NW-SE fault zones either under the Paka caldera or between Paka and Korosi.

Paka prospect is close to the Eastern flanks of the rift hence it is possible that the deep flank faults control the E-W movement of fluids. The S-N flow at the rift floor is possibly by shallow N-S trending faults.

Boreholes at Korosi indicate temperature gradient of 0.230°C/m near the thermally active zone hence estimating temperatures of about 230°C at 1 km depth. Similar gradients are encountered at Loruk near the active zone of Lake Baringo prospect. Recharge to the prospect area is from east to west with an outflow to the north.

Estimated reservoir temperature at 1 km depth for Lake Baringo, Korosi, Chepchuk and Paka is over 200°C. Recharge to these prospects is from east to west and outflow from the same is to the north.

5. RANKING OF THE EXPLORED FIELDS BASED ON HEAT LOSS

Figure 12 shows the mapped areas of already explored fields from Menengai to Paka. Active areas are oriented in NW-SE at Menengai, Lake Bogoria and Lake Baringo while NE-SW is evident at Korosi and Paka. Table 1 indicates so far Menengai has the highest heat loss while Arus has the least. However the value is still high compared to those obtained for Olkaria of 400 MWt (Mahon 1989) and 187 at Olkaria Domes (Kagiri, 1994).

TABLE 1: Ranking based on heat loss survey

Prospect	**Heat loss**		**Total heat loss (MWt)**
	Conductive (MWt)	**Convective (MWt)**	
Menengai	1095	2440	3536
Paka	2845	10	2855
Korosi	2135	0.4	2135
Bogoria	762	437	1199
Baringo	941	108	1049
Chepchuk	546	Negligible	546
Arus	467	.03	467
Olkaria			400
Domes			187

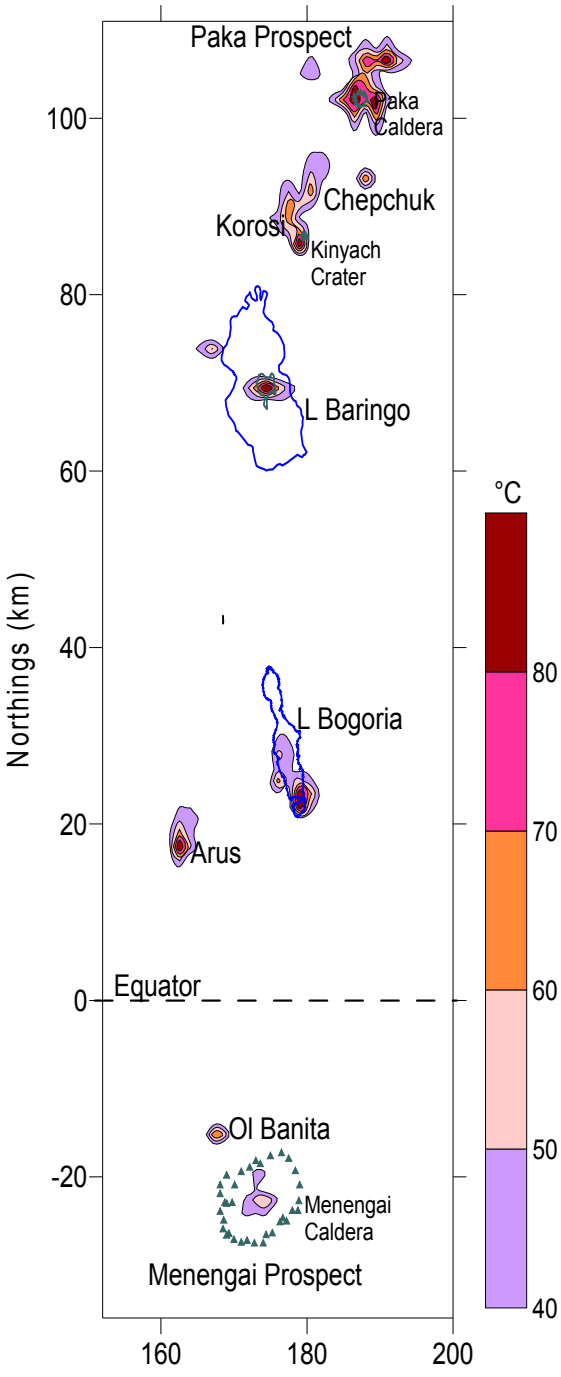

FIGURE 12: Explored prospects in the North rift

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ENVIRONMENTAL BASELINE STUDIES FOR GEOTHERMAL DEVELOPMENTS

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ABSTRACT

Environmental Baseline Study (EBS) is vital in predicting and evaluating potential environmental impacts of geothermal developments prior to any development. An EBS helps to understand existing environmental conditions thus defining the focus of the environmental impact analysis and resources that need protection through appropriate and viable mitigation measures. A number of national and international environmental policies and multilateral lending agencies regulations require description of existing environment that might be affected by potential development. The study process entails a scoping exercise by multi-disciplinary group of experienced specialists for the key environmental issues. Based on the valued ecosystem components, the study scope should cover, but not limited to issues such as climatic conditions, drainage and water resources, soils, flora, fauna, air quality, noise, land use, land tenure and socioeconomic aspects. Baseline environmental information is assembled through collection and analysis of existing data; carrying out specific field studies and community consultation programmes. Impacts arising from geothermal development could be physical, chemical, biological and socio-economic impacts. With such potential impacts, impact prediction process becomes relevant in both EBS and Environmental Impact Assessment Studies. Techniques used in impact prediction include: Checklists, Matrices, Networks and Flowcharts, Mathematical/Statistical Models, Maps and Geographical Information System (GIS) and Environmental Risk Assessment (ERA). With impacted predicted, mitigation measures should be in place to help avoid and minimize the potential impacts. Baseline monitoring is also required to provide effective feedback for specific environmental aspects. After the study the final EBS document need to be comprehensive, precise and accurate with uncertainties clearly stated.

1. INTRODUCTION

In order to predict and evaluate environmental impacts of geothermal development, it is critical to understand the baseline environmental conditions prior to development. This is achieved by carrying out Environmental Baseline Studies (EBS) during geothermal exploration. Understanding the existing environment serves to define the focus of the environmental impact analysis and resources that need protection through mitigation. Early collection of baseline data can help to guide the definition of the proposed geothermal project, including location of facilities. Significant impacts and development

costs can be avoided if the location and nature of the sensitive resources are identified early in the geothermal development process. Best environmental management practices have also revealed that avoiding impacts through careful siting and project design is more desirable and cost effective than mitigating adverse environment impacts.

1.1 Environmental policies and regulatory requirements for EBS

A review of country and institutional environmental policies and regulatory frameworks indicate that all national regulations and multilateral financial institutions guidelines require an understanding of the existing environment that might be affected directly or indirectly by a proposed energy project (Hietter, 1995). The regulations and guidelines require that a description of the environmental baseline conditions should be included in the environmental impact assessment report to expedite project approvals for licensing and funding.

The following are examples of policies and regulations specific to geothermal developments:

- In USA, both the National Environmental Policy Act (NEPA, 1969) environmental review regulations and the Geothermal Resources Orders (GRO) No. 5, require baseline data collection for one year to describe existing conditions and to predict, monitor and evaluate environmental impacts of implementation of a proposed geothermal project.
- In Kenya, the Environmental Management and Coordination Act (EMCA) of 1999 and Environmental Impact Assessment and Audit Regulations (2003) require inclusion of a description of the environmental baseline conditions in an environmental impact study report.
- The World Bank OP 4.01- Guideline on Environmental Assessment: requires environmental baseline information as part of the Environmental Assessment report for energy projects, geothermal included, proposed for funding by the World Bank.

1.2 Definitions

The "environment" is broadly defined to include the natural, cultural, social and economic systems and their interrelations.

The term "baseline" refers to conditions existing before development against which subsequent changes can be referenced.

"Environmental Baseline Studies" generally include an entire range of pre-project studies and are carried out to:

- Identify key environmental factors, which may influence project design decisions (site lay-out, etc);
- Identify sensitive issues or areas requiring mitigation or compensation;
- Provide input data to impact prediction models; and
- Provide baseline data against which the results of future monitoring programs can be compared.

1.3 Objective

The main objective of EBS is to outline the existing environmental conditions to understand changes that may occur as a result of proposed geothermal development.

2. THE ENVIRONMENTAL BASELINE STUDY PROCESS

2.1 Scoping

The early EBS process starts with a scoping exercise for the key environmental issues. A multi-disciplinary group of experienced specialists (Meteorologist/Air Pollution Specialist, Geologist/Soil Engineer, Chemist/Water Pollution Specialist, Forester/Ecologist, and Social Scientist/Geographer) define a) the key environmental factors b) baselines for the key factors, and c) project alternatives, including "no project" option. Inputs from consultations with other public stakeholders and statutory institutions e.g. The Ministry of Energy, National Environmental Management Authority (NEMA) in Kenya, are also incorporated in the final scoping document. Based on the valued ecosystem components, the EBS scope should cover, but not limited to the following:

- **Climatic conditions** – Information on local meteorological conditions is important in future for assessing the dispersion of gaseous emissions from sources associated with the geothermal development. This entails review of data on wind, temperature, humidity, rainfall and evaporation.
- **Drainage and water resources** – This entails description of major water bodies (lakes), rivers, springs and swamps. These can be further categorized into surface (lakes, rivers, dams, water pans, swamps) and groundwater sources (boreholes).
- **Soils**- Data collection on sol physical properties which is very useful in explaining the prevalence of erosion and the principles of its control. The chemical properties of the soil are vital in determining the potential impacts on soil fertility associated with geothermal development.
- **Flora** – Description of existing vegetation of the area. This involves use of ecological checklists that will show the distribution of plant species over the proposed geothermal prospect area. It also involves characterization of vegetation and description of the major vegetation types, composition and associations.
- **Faunal studies** - This entail description of the fauna in the area. Acquisition of quantitative data and information with an aim of identifying unique and important habitats together with the spatial and temporal patterns of habitat use by the animals.
- **Air quality issues** – involves identification of matters, which are important in assessing the air quality impacts arising from the proposed geothermal development. Assessing the existing air quality by determination of ambient concentration of the main geothermal gas (hydrogen sulphide) from surface manifestations such as fumaroles.
- **Noise quality** – the potential for a noise to annoy depends on the loudness of the noise relative to the existing noise levels. Thus to undertake an impact assessment it is necessary to determine the existing noise environment in the absence of noise emissions from the proposed geothermal developments. Data on background noise levels are important from the point of view of noise impact assessment because it is the difference between the background noise and the proposed geothermal development related noise that most closely correlates with the perceived annoyance of noise.
- **Land use and Tenure systems** – It is the use of a stretch of land and involves interaction between the land and its user, which encompasses the relationship between biophysical features (geology, topography, soil, climate, flora and fauna) and socio-economic issues (land tenure, culture, community organization, income etc). Thus land use in any give area is always dynamic in any given time. Land tenure is the type of ownership i.e. freehold (individuals with title deeds), leasehold (for a given period of time usually 99 years) and communal ownership (community ownership).
- **Socio economic aspects** – administrative boundaries, demography (population estimate & projections), economic structure and labour, commercial sector, agriculture, tourism, community infrastructure (education & training, health services, housing, recreational facilities, security), transport, perceptions of local over the project, aesthetic/historical,

cultural & archaeological sites, energy sources, natural resources (economic minerals) and utilities (power, communication, water supply & quality etc).

A comprehensive work plan is then drawn outlining details of the key environmental aspects to be considered, methods to be used for baseline data collection, the various stakeholders to be consulted, estimated human and financial resources required and time allocation for the various components of the EBS.

2.2 Methods of baseline data collection

Baseline environmental information is assembled using 3 methods during energy development (Ontario Energy Consortium, 1992), geothermal exploration included:

- Collection and analysis of existing data;
- Carrying out specific field studies to acquire supplementary data to help in prediction of impacts of the proposed geothermal project and its alternatives, and to identify potential trade-offs in an Environmental Impact Assessment studies; and
- Community consultation programmes.

2.2.1 Review of existing data and sources

Before embarking on an extensive and costly field studies, maximum effort should be directed at determining the numerical and spatial data that already exist and can be used in describing the baseline environmental conditions in the proposed geothermal project area.

Existing data sources include:

- Government databases and routine monitoring programs – review scope and extent of these programs and re-focus studies to include areas and parameters relevant to EBS.
- Historical environmental studies in the area – review all available scientific and technical literature including unpublished information from academic and NGO groups active in the area of study for use in the EBS.
- Experience gained from similar geothermal projects – useful in focusing baseline studies on key issues of concern.
- Aerial photographs and satellite images – useful in determining the historical land use changes, which have occurred in the area and prediction of additional cumulative impacts of the proposed geothermal project development on various features of the landscape.
- Traditional knowledge – local communities possess profound and refined knowledge of the spatial and temporal distribution of wildlife and their ecological relations often lacking in scientific literature. This is useful in understanding social-cultural impacts of geothermal developments, which affect the subsistence economy and continuous relationship of the indigenous people to land.

2.2.2 Field studies

Field studies are required to fill in data gaps realized from review of the existing information or to provide more focused information for the EBS.

Field sampling programs for baseline studies is designed with an aim of providing sufficient information to assist in impact predictions and developing a reference base to guide and test future geothermal project monitoring programs. The level of detail and scope are tailored to meet the needs of the proposed geothermal project.

2.2.3 Community consultation programmes

The community consultation programs are aimed at creating awareness and ensuring early involvement and active participation of the local communities living in the precincts of the proposed geothermal project area and other stakeholders, which may be directly affected on implementation of the proposed geothermal project.

The consultations between community leaders and representatives of the geothermal project proponent should be confined to key issues of concern. The local people including administration, elders, women and the youth, should be consulted and given a chance to articulate their concerns, fears and offer environmental solutions for consideration in geothermal project planning, design, and implementation. An appropriate feedback mechanism on issues raised should be established and maintained to avoid suspicions and ensure smooth implementation of the proposed project.

Utilizing services of a Community Liaison person has proved successful during implementation of KenGen Hydroelectric projects and is recommended for geothermal developments.

2.3 Impact prediction

2.3.1 Impacts types

The potential impacts of geothermal developments fall in broad categories that include: physical, chemical, biological, and social economic impacts. The physical impacts may vary from soil erosion due to civil works, noise emissions, visual quality impairment, etc. The Chemical impacts may arise from the chemical discharges from waste brine (B, As, Hg), and Non condensable Gases (H_2S, CO_2, CH_4). The biological impacts may include loss of sensitive habitats and interference with animal migration routes. The socio-economic issues may range from provision of employment opportunities and constraints on available social amenities.

Impact prediction is therefore fundamental to EBS as well as Environmental Impact Assessments (EIAs) and should consider *direct or primary impacts* as a result of the geothermal project implementation*, indirect or secondary impacts*, which are knock-on effects in the same project location or other adjacent areas, *cumulative impacts* that accrue over time and space from many developments, and possible *impact interactions* between different impacts of a proposed project. In general, impacts may be *positive (beneficial) or negative (adverse)*, short-term or long-term, reversible or irreversible, permanent or temporary.

To be able to make logical impact predictions, a good understanding of the nature of the proposed geothermal project, similar projects including effectiveness of impact mitigation measures, and other projects that may cause interactive or cumulative impacts, is required. For example, the experience gained in Olkaria I geothermal field has been used widely as a model case while carrying out EBS, EIAs, monitoring and evaluation of impacts of geothermal developments in other fields located in the Greater Olkaria Geothermal Area, and prospects outside Olkaria.

2.3.2 Methods of impact prediction and significance evaluation

Impact prediction is not an exact science irrespective of the method used. The uncertainties should therefore be clearly stated in the final EBS document. Direct impacts are often easy to predict unlike indirect or cumulative impacts.

Several standard techniques to aid in impact predictions are available and include: *Checklists, Matrices, Networks and Flowcharts, Mathematical/Statistical Models, Maps and Geographical Information System (GIS) and Environmental Risk Assessment (ERA)*. *Checklists and Matrices* are commonly used for most of the EBS conducted during geothermal exploration.

Statistical weightings of *impact magnitude, sensitivity and recoverability of relevant receptor* are used to quantitatively derive *impact significance*.

2.4 Mitigation and baseline monitoring

The mitigation measures are to avoid, minimize, remedy or compensate for the predicted impacts.

Examples:

- Alternative production techniques e.g. binary technology based on organic ranking process in place of conventional geothermal steam condensing systems, and site locations away from sensitive ecosystems (wetlands, habitats), etc.;
- Changes in construction time and methods e.g. avoiding night operations to minimize disturbances due to traffic and noise emissions;
- Changes in project design (few drill pads with 5-7 wells, wastewater re-injection systems, dispersion of NCGs through Cooling Towers), site boundaries, landscaping with local vegetation to maintain integrity of the existing ecological system, etc.;
- Off-site disposal of construction and operational waste (waste oil) to minimize both construction and operational impacts;
- Compensation for irreversible or permanent losses e.g., land, sensitive habitats; and
- Enhancement of positive impacts.

Baseline monitoring is necessary for effective feedback for specific environmental aspects e.g. faunal population and floral distribution. The monitoring program often lasts for many years to be able to establish the natural dynamic variations and not only "snapshots" of the environmental conditions at a particular moment in time.

2.5 Presentation of EBS Report and findings

The EBS report should be comprehensive, precise and accurate with uncertainties clearly stated. Impact predictions are critical and should include both potential negative and positive impacts of proposed geothermal development. Emphasis needs to be given to positive environmental impacts and ways of enhancement. Use of graphics in presentations is recommended.

Presentation on a selected case study: *Environmental Baseline Study of Arus-Bogoria Geothermal Prospects, Kenya.*

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ENVIRONMENTAL BASELINE STUDY FOR GEOTHERMAL DEVELOPMENTS: CASE STUDY ARUS-BOGORIA GEOTHERMAL PROSPECTS, KENYA

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ABSTRACT

Arus and Lake Bogoria geothermal prospects are located North of Menengai and South of Lake Baringo within the Kenya Rift. Geothermal phenomena in form of fumaroles, hot pings, steam jets, geysers, sulphur deposits and high geothermal gradient expressed by anomalously hot ground and groundwater water characterized by temperatures above ambient in the area. As an effort to explore the geothermal potential areas in the north rift, the Kenya Government, through the MoE and KenGen carried out surface investigations in the area to determine its geothermal resource potential. The survey was conducted from the 14th February 2005 to 8th July 2005 and was co-funded by the Kenya Government and KenGen. An environmental survey to collect and compile baseline data was undertaken to ensure that any possible environmental concerns that can arise could be predicted well in advance. Results of the study indicate that anticipated environmental impacts could be significant within LBNR. However, social impacts are insignificant in magnitude. The impacts, however, could be effectively mitigated during civil works, drilling and testing of geothermal wells and power plant construction and operation

1. INTRODUCTION

1.1 Study objective and scope

The study objective and scope of the environmental baseline study included surveys on the following environmental and social aspects of Arus-Bogoria geothermal prospect:

- Socio-economic issues such as land use and tenure systems, population, natural resources, infrastructure, public services, transportation, historical sites of social significance, energy usage and demand.
- Flora and fauna of the prospect area including any rare or endangered species for conservation purposes; and
- Water resources, their quality and general drainage trends; and
- Climate and ambient air quality

1.2 Justification

The study objective was mainly to collate and analyse existing socio-economic and environmental baseline data for Arus-Bogoria geothermal prospect.

In addition, the baseline information would be used during full-fledged Environmental Impact Assessment (EIA) for the subsequent geothermal energy utilization. This would ensure that any developments undertaken are environmentally sound and socially acceptable as stipulated in the Environmental Management and Coordination Act, EMCA (1999), and operational guidelines issued by geothermal energy development partners.

1.3 Study methodology

The social and environmental baseline data for the prospect area was acquired through site assessments and consultations with public officers, representatives of Non-Governmental Organizations (NGOs) and local community leaders.

2. BIOPHYSICAL ENVIRONMENT

2.1 Climate

Baringo and Koibatek Districts are arid and semi-arid. Two seasons of rainfall are experienced. The long rains start at the end of March to the beginning of July, and the short rains from the end of September to November (Figure 1). The rainfall is about 50% reliable. The rainfall varies from 300-750 mm in the Rift Valley floor near Lake Bogoria to 1200 mm in the highlands near Eldama Ravine town. The monthly rainfall recorded at Loboi station near Lake Bogoria as shown in Figure 1.

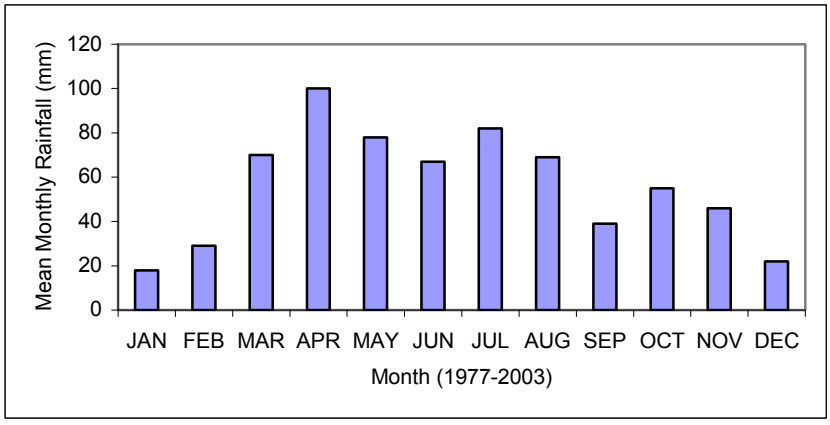

FIGURE 1: Lake Bogoria mean monthly Rainfall at Loboi Station from 1977-2003

Temperature varies from 15ºC to 35ºC and follows the rainfall pattern. The temperature is relatively cool from June to October and hot from December to March. The average temperature is about 28ºC for the most part of the year. The temperature and rainfall regimes in the vicinity of Lake Bogoria National Reserve combine to give Lake Bogoria a hot, arid to semi-arid climate. The evaporation in the area varies from 1,800 mm to more than 2,200 mm per year. The mean annual evaporation is estimated at 2,020 mm per year (JICA/MOARD, 1999).

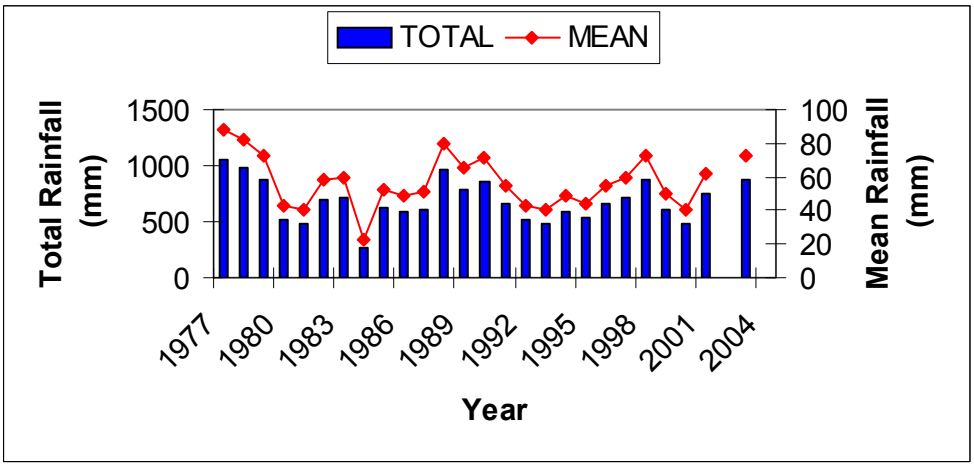

FIGURE 2: Lake Bogoria total and mean annual Rainfall at Loboi Station from 1977-2003

2.2 Soils

The soil types and distribution in the prospect area have been influenced by the topography. The steep slopes and rolling hills have soils developed from volcanic rocks, which are well drained varying from deep to shallow depths. Soils in these low-lying area (lowlands) have developed on volcanic rocks and alluvial. In most areas the bedrock is basaltic and some pyroclastics. This has weathered over time under dry climatic conditions to give rise to sandy loam soils in texture. They are well drained, moderately deep to very deep, brown to dark loams, sandy loams or clay loams and very erosive (Figure 3).

FIGURE 3: Erosive nature of soils around Mugurin

Mogotio and Kisanana areas, soils are very shallow and at times extremely gravely to extremely stony. The soils vary in colour from mainly brownish to reddish brown depending on the mineral contents. Sandstones and conglomerates are common in Simotwet, Kamar and Koibos locations making them to be rich in sand. There are pockets of sedimentary rocks mainly shale and silt in depressions especially where streams enter swampy areas. Around Mugurin and Molo Sirwe, soils have low water holding capacity, very shallow and extremely gravely clay-loams. At the escarpments soils have moderate water holding capacity, shallow depth, stony, gravely clay loams. Thick clay loam of alluvial origin is found around Marigat.

2.3 Land use

The prospect area supports both crop and livestock production. The semi arid zones of the prospect area are mainly used for livestock production (Figure 4). Large livestock numbers can cause threats like, land degradation and loss of biodiversity due to over grazing if not checked. Such practices are however gradually declining as more people settle down permanently around water points and arable land. There are pockets of irrigation agriculture along rivers like Perkerra, Molo, Wasseges and Loboi (Figure 5).

FIGURE 4: Livestock production within the prospect area

FIGURE 5: Sections of irrigation agriculture around Loboi

2.4 Water resources

The surface water resources in prospect area are scanty. The largest water body in the prospect area is Lake Bogoria which about 33 km^2 and highly saline. The main river that feeds this lake is Wasseges. It collects most of its stream flow from tributaries on Laikipia escarpment. In dry periods, the river dries up near Sandai before reaching the lake. From western side the lake is fed by some hot springs and seasonal tributaries including Emsos.

The surface water quality of selected streams in prospect area is good (Table 1). Surface water resources have also been developed by construction of Dams and Pans to provide water for domestic use and livestock watering. The largest operational scheme is found in Marigat (Perkerra Irrigation Scheme) and the Sandai scheme, located northeast of Loboi. There are many small irrigation schemes towards Lake Bogoria. It is only in the streams, which are fed by Hot Springs, increased fluoride concentrations are found.

TABLE 1: Water quality of selected streams/rivers in the prospect area (mg/L except for pH)

Item	**River Emsos**	**River Ararae**	**River Molo**	**River Narosura**	**Canadian Drinking water quality guidelines**
pH	8.2	7.6	7.9	7.1	6.5-8.5
Mn			0.439	0.425	0.05
Ca	4	7.2	8.8	5.6	200
Mg	1.92	14.59	Nil	Nil	50
Cl-	14	11	12	8	<251
F-	1.26	0.83			1.5
NO^-_3	0.06	0.1	1.9	2.9	45
SO^{2-}_4			6.0	7.0	500
TDS	260	180	113	74	<500

There are several water supplies and boreholes in the prospect area (Table 2). Unfortunately, most of the boreholes produce water of low drinking quality due to high levels of fluoride and sometimes manganese (Table 3).

TABLE 2: Water supplies and boreholes within prospect area

Division	**No. of W/supplies**	**Type of water (gravity/pumping)**	**Source of water (surface/borehole)**	**Remarks**
Mogotio	5	4 are pumping, 1 is gravity	4 boreholes, 1 river source	4 are community managed & 1 is GoK run
Kisanana	12	All pumping	All are boreholes	All are community managed
Emining	9	All pumping	7 boreholes, 1 river	All are community managed
Marigat	-	Pumping	17 boreholes, 1 river source	-
Mochongoi	-	Pumping	8 boreholes, 6 productive	-

TABLE 3: Water quality of selected bore holes (mg/L except for pH)

	Koitebes Borehole	**Kures Borehole**	**Rosaga Sch. Borehole**	**Nyalibuch Borehole**	**Nguberetti Borehole**	**Canadian drinking water quality guidelines**
pH	6.0	6.8	8.0	7.9	7.55	6.5-8.5
SiO_2	25.0	20.0		25.0	40.0	-
Mn	3.7	1.2	1.2	1.0	0.1	0.05
Na	101.8	101.8		24.9	137.5	200
K	32.8	37.7		17.0	16.8	-
Fe	0.2	0.03	0.13	Nil	0.05	0.3
Ca	18.0	24.0	58.4	20.0	76.0	200
Mg	16.8	19.0	14.88	5.2	23.0	50
Cl-	8.0	15.0	15	4.0	54.0	<251
F-	4.0	5.0		0.6	0.6	1.5
NO^-_3	Nil	1.1	3.0	Nil	Nil	45
SO^{2-}_4	30.0	10.0		0.8	112.5	500
TDS	450	450	450	175	670.0	<500

2.5 Floral composition

Natural vegetation comprises of several species of acacia and grasses characteristic of a dry savannah. The areas comprising Radat, Kimose, Saos, Molo Sirwe, Emining, Mukuyuni, Wassegese and Maji Moto vegetation is deciduous and semi deciduous bushland (Figure 6). Around Mugurin, Ngendalel, Mogotio, Kisanana and around Lake Bogoria vegetation is a combination of evergreen (Figure 7), deciduous and semi deciduous bushland. The area around Loboi, Sandai and Logumgum vegetation is a combination of deciduous Shrubland (Figure 8), deciduous shrub grassland (Figure 9), seasonally flooded grassland (Figure 10) and acacia woodland (Figure 11). Common tree species include: *Acacia tortilis, A. seyal, A. nilotica, A. brevispica, A. mellifera and other Acacia species*. Other species include *Balanites aegyptica, Tarconanthus comphratus and Terminalia. Grasses include Cynodon, Digitaria, Hyperhenia and Cenchrus sp.*

FIGURE 6: Deciduous and semi deciduous bushland

FIGURE 7: Deciduous shrub-grassland

FIGURE 8: Evergreen bushland

FIGURE 9: Seasonally flooded grasslands

FIGURE 10: Deciduous Shrub land

FIGURE 11: Woodland

The only endangered plant species in the area is Aloe Vera plant species (Figure 12), which is currently being overexploited because of its medicinal value. Funds have been secured from the European Union and plans are underway to construction a factory for sap extraction at Koriema (pers. comm. with residents involved in Aloe Vera project).

2.6 Fauna

Lake Bogoria and part of its catchment area is rich in fauna hence has been protected as Lake Bogoria National Reserve (LBNR) and covers an area of 107 km^2 (Figure 13). It was gazetted in 1973 and is currently managed by Baringo and Koibatek County Councils. Recently the LBNR was designated as a third Ramsar site after Lake Nakuru and Naivasha. The lake is saline and covers an area of 34 km^2. It is rich in biodiversity, hosting about half of the world's population of lesser flamingos (*Phoeniconaias minor*). It is also a habitat to other bird species including greater flamingos (*Phoeniconaias rubber*), black-necked grebe (*Podiceps nigricollis*), ostriches, fish eagles and several migratory species. Due to its avifauna richness, it has been designated as an Important Bird Area (IBA). The mammalian fauna in LBNR include zebras, gazelles, buffaloes, several primates and the only relatively accessible population of greater kudus. In addition to its rich biodiversity, Lake Bogoria has numerous hot springs.

FIGURE 12: Aloe Vera project at Sandai primary school

FIGURE 13: Flamingos in Lake Bogoria National Reserve

2.7 Biodiversity value of Lake Bogoria

Microorganisms

A bacterial population of over 10^6 bacteria/ml of the Lake Bogoria water has been recorded. Numerous bacteria have been isolated from this lake but are yet to be characterized. In a recent study, a new novel genus of *actinomycetes*, *Bogoriella caseilytica* has been described. The phytoplankton community is dominated by a cyanobacterium, *Spirulina platensis*, yet on occasions this species has almost been absent.

The hot springs environment is characterized by thick green or orange algal mats which are the primary producers of a quite complex micro-ecosystem. Some of the green-orange algal mats are known to be *Chloflexus-synechococcus* association but many other are still undetermined in terms of species composition. The zooplankton community is relatively abundant with *Brachionus plicatilis* and the benthos mainly consists of chironomid larvae.

Macrophytes

The Waseges-Sandai River enters the lake through a large freshwater wetland, the Kesubo Swamp, dominated by cattail, *Typha domingensis*. The Greater Loboi Swamp to the north of the lake is dominated by papyrus, *Cyperus papyrus*, and cattail (a marsh plant), *Typha domingensis*. There are no submerged macrophytes in the lake. The open shore, often littered with lava boulders is dominated by the salt-tolerant grass species, *Sporobolus spicatus* together with the sedge *Cyperus laevigatus* around the hot springs.

Terrestrial vegetation

The terrestrial vegetation is mainly thorny bushland dominated by the species of *Acacia*, *Balanites* and *Commiphora* with patches of riverine woodland containing *Ficus capensis*, *Acacia xanthophloea* and *Acacia tortilis*. In the lower slopes of the Siricho Escarpment, *Combretum* and *Grewia* thickets dominate. The areal coverage of the different vegetation types in the Lake Bogoria catchment is shown in the Table 4.

TABLE 4: Vegetation types in Lake Bogoria catchments

Vegetation types	Area (km^2)
Acacia mixed	62.054
Acacia mixed (A. mellifera, dominant sp.)	8.369
Acacia mixed (dense)	8.122
Aloe Euphorbia	19.501
Ficus forest	1.502
Swamps	0.053
Mixed bushland	293.410
Scrubland	26.911
Open ground	2.667

Source: Njuguna, 1999.

Herpetofauna and fish

Lake Bogoria has no fish, however, around the mouth of Wasages-Sandai River and in both Greater Loboi and Kesuba Swamps fish species of the genus *Protopterus* has been reported. Crocodiles and monitor lizards are found in the wetlands associated with Lake Bogoria.

Birdlife

Lake Bogoria is internationally important as a main feeding ground for a large percentage of the world's population of the lesser flamingo (*Phoeniconaias minor*). The high productivity of the blue-green algae, *Spirulina platensis*, coupled with the presence of freshwater at several places results in a concentration of the lesser flamingo in large numbers, at times over two million, to give the appearance of large shimmering pink sheets across the lake. Kenya holds between a third and a quarter of the total world population of the lesser flamingo.

Recently, Lake Bogoria was reported to have a flamingo population estimated at Two Million, believed to be the largest number of flamingos converging on a single water body at any one time. Lake Bogoria is recognized as one of the 60 Important Bird Areas (IBAs) in Kenya. It is also one of the 13 lakes listed for the internationally important number of migratory birds they hold (Nature Kenya, 1999). In July 1994, a ground count of flamingos yielded an estimate of 1,579,000 flamingos. The following year, in March 1995, the flamingos were estimated at 248,499 birds with the greater flamingos, *Phoeniconaias ruber*, (6,143) only making 2.3% Palearetic waders totalled 3,143 birds in 1995, the vast majority being the ruff, Philomachus pugnax (2,327). An impressive number of the black-necked grebe, Podiceps nigricollis (1,832) was recorded. One greater painted snipe, Rostratula benghalensis was also found. The lake is also important for other bird species, for example, the Steppe Eagle, African Fish Eagle, Tawny Eagle, and Marabou Stork. The lesser flamingos fall prey to Marabou Stork, baboons, monitor lizard and warthogs. Ostriches are also common in LBNR especially in the Sandai area to the north of the lake.

Mammals

There are no mammals inside Lake Bogoria but a small variety of animals exist in the adjacent areas. They include the rare Greater Kudu (*Tragelaphus strepsiceros*) and many other antelopes such as gazelles and impala. Other mammals found in LBNR are zebras and buffaloes. The Greater Kudu population is reported to be on the decline, as a result of the demand on their horns, which are used by

the locals for ritual purposes. The zebra population is reported to have increased tremendously in the recent past. There is an urgent need for an animal census.

3. SOCIO-ECONOMIC ISSUES

3.1 Administrative set of the prospect area

The prospect area is situated partly in Baringo District and partly in Koibatek District. It traverses Marigat and Mochongoi Divisions in Baringo District and Emining, Mogotio and Kisanana Divisions in Koibatek District (Table 5). This is a marginal agro-ecological zone IV-semi arid zone suitable for livestock production, wildlife habitat and dryland agriculture with little rainfall and high temperatures.

TABLE 5: Administrative units of Arus and Lake Bogoria geothermal prospect area

District	Division	Area (km^2)	Locations	Sub-Location
Koibatek	Mogotio	538.2	6	11
	Kisanana	236.4	7	25
	Emining	401.6	5	9
Baringo	Marigat	641	9	18
	Mochongoi	329	3	7

3.2 Land tenure system

In terms of land holding system, most of the lands in the prospect area are communal land (trust lands) but land adjudication is on going to facilitate private ownership. Land adjudication and surveying is on going and several land adjudication sections have been established and include Maji Ndege area (Loboi, Mbechot, and Kapkuikui villages), Maji Moto, Koitumet, Cheparandi (Emining) and Wasseges (Kisanana) adjudication sections. In Mogotio Division, much of the land is under sisal farming under private ownership. No livestock group ranches exist in the prospect area. Currently, no map regarding land ownership is in place as land registration is still in progress.

3.3 Population and demographic characteristic

The Arus and Lake Bogoria geothermal prospect area's population is projected to have increased from 76,708 people in 1999 with a population density as shown in Table 6 to **107,590** at the end of 2004.

TABLE 6: The 1999 population of Arus-Lake Bogoria by sex, households, area and density

Division	Male	Female	Total	Households	Area (km^2)	Density
Kisanana	3263	3435	6698	1262	236.4	28
Emining	6944	7122	14066	2818	401.6	35
Mogotio	9054	8876	17930	3613	538.3	33
Marigat	13285	13638	26923	6356	1224	44
Mochongoi	5745	5346	11091	2413	329	19

3.4 Agricultural activities

The prospect area is classified as lowland in terms of agro-ecological zones with little rainfall and high temperatures. The land is used for animal grazing and furrow irrigation agriculture. Pockets of rain-fed and irrigated crop production can be found especially along the river course and lowland.

Crop failure prevails in both rain-fed agricultural and irrigation areas because water is limited in this lowland. There are small-scale irrigation schemes in the area that are served by both permanent and seasonal rivers, streams and swamps. Reliable sources of rivers and streams include Perkerra River, Molo River, Wasseges and Loboi. Swamps include Loboi and Kapkuikui. Soil erosion in the area is also widespread. This has been aggravated by reduction in vegetation cover and by overstocking of livestock leading to land denudation and formation of large gullies.

Crop production statistics

There are pockets of crop producing area in this lowland. The main food crops are maize, millet, beans and Irish potatoes. The prospect area is a perennial food deficit. Despite the area producing a little food to feed her population, most of the food (60%) is sold for cash requirements thus occasioning frequent food shortages. The poverty level in the prospect area is more than 50% as much of the cultivated area is put under low value food crops.

Livestock production

Livestock keeping is one of the most important economic enterprises in the prospect area. Under the semi arid conditions that prevail, traditional raising of indigenous livestock breeds is managed under pastoral and nomadic systems. Livestock production is depressed due to lack of adequate water and insufficient pasture as a result of prolonged droughts, epidemic disease outbreaks and lack of breeding systems for better productivity.

3.5 Health and sanitation

The top ten diseases are as indicated in Table 7 with Malaria and URTI being the most prevalent diseases in the five Divisions of the prospect area. The high prevalence of these top diseases are attributed to factors such as presence of diseases vectors mostly mosquitoes; weather changes (for URTI); low latrine coverage (intestinal worms and diarrhoea); inadequate water supply; poor housing and unprotected sex.

HIV/Aids prevalence in Baringo District side of the prospect area is about 4 %, which is low compared to the current National prevalence level of 7%. Marigat area within Arus-Bogoria prospect in Baringo District, however, presents a unique scenario due to large numbers of casual workforce engaged at Perkerra Irrigation Scheme. The majority are low-income earners residing in a slum area within Marigat centre known as "Kampi Ya Turkana". Most of them are social refugees from Turkana ethnic group, hence the name "Kampi Ya Turkana". The group's inability to meet the basic social-economic needs forces them into sexual relationships with multiple partners and therefore vulnerable to HIV/ Aids infections. According to the Public Health Officer in-charge of HIV/Aids Programmes in Baringo District, 80% of people living with HIV/Aids (PLWHA) in Marigat Division are from "Kampi Ya Turkana" area.

For Koibatek side of the prospect area (Mogotio, Kisanana and Emining), data for the 4th quarter of 2004 indicate that HIV/Aids Antenatal clinic (ANC) and sexually transmitted diseases (STDs) prevalence was 7.7% and 18.2 % respectively. No HIV/Aids data was available for Voluntarily Counselling and Testing (VCT) Centres. The current health facilities within Arus-Bogoria geothermal prospect area is as indicated in the Table 8.

TABLE 7: Disease prevalence in 2004 by Divisions within the prospect area
(value in parenthesis is disease rank)

Disease	Divisions				
	Kisanana[1]	**Mogotio[2]**	**Emining[3]**	**Marigat[4]**	**Mochongoi[5]**
Upper Respiratory Tract Infection (URTI)	1427 (1)	3156 (1)	4932 (2)	10263 (2)	5847 (1)
Malaria	828 (2)	2832 (2)	5760 (1)	12745 (1)	2083 (2)
Diarrhoea	567 (3)	480 (3)	960 (3)	244 (9)	684 (5)
Intestinal worms	383 (4)	218 (5)	111(4)	849 (4)	365 (9)
Skin diseases	-	333 (4)	-	2156 (3)	1094 (4)
Pneumonia	-	-	-	849 (4)	1299 (3)
Rheumatism	-	-	-	257 (8)	465 (6)
Accidents*	-	-	-	593 (5)	432 (7)
Urinary Tract Infection (UTI)	55 (5)	-	15 (8)		
Ear Infection	3	36 (6)	20 (7)	294 (7)	237 (10)
Gonorrhoea	40 (6)	2 (10)	3 (9)		
Malnutrition	20 (7)	-	-		
Eye Infection	-	33 (7)	31 (6)	414 (6)	400 (8)
Chickenpox	6 (9)	15 (9)	56 (5)		
Mumps	9 (8)	16 (8)	-		
Amoeabiasis	-	15 (9)	-		
Measles	3				

Source: Department of Public Health, Baringo District Hospital-Kabarnet & Koibatek District Hospital-Eldama Ravine. * Include injuries such as burns etc.[1]-Olkokwe dispensary & Kisanana Health Centre, [2]-Mugurin & Maji Moto dispensaries, [3]-Emining Health Centre, [4]-Marigat Sub-district Hospital,[5]-Mochongoi Health Centre

TABLE 8: Health facilities (hospitals, dispensaries and health centres) within the prospect area

Division	Mogotio	Emining	Kisanana	Marigat	Mochongoi
Health facilities	2	1	2	12	4

Source: Department of Public Health, Baringo District Hospital-Kabarnet & Koibatek District Hospital-Eldama Ravine.

3.6 Tourism

Tourists and visitors to the Reserve are stakeholders, in search of recreation, education and research. They include both local, national, and international tourists and visitors. According to records in the Lake Bogoria recording station, over 50,000 school children visit Lake Bogoria annually to understand and appreciate the unique physical geography of the Rift Valley (Figures 14 and 15), an important topic in the geography syllabus in Kenyan schools. Researchers who come to seek knowledge are among this group.

FIGURE 14: Lake Bogoria with its hot springs

FIGURE 15: Unique landscape of the Great Rift Valley

The number of visitors to LBNR fluctuates very much according to season with the peak being between the months of July and September (Figure 3) and the lowest between months of January and May.

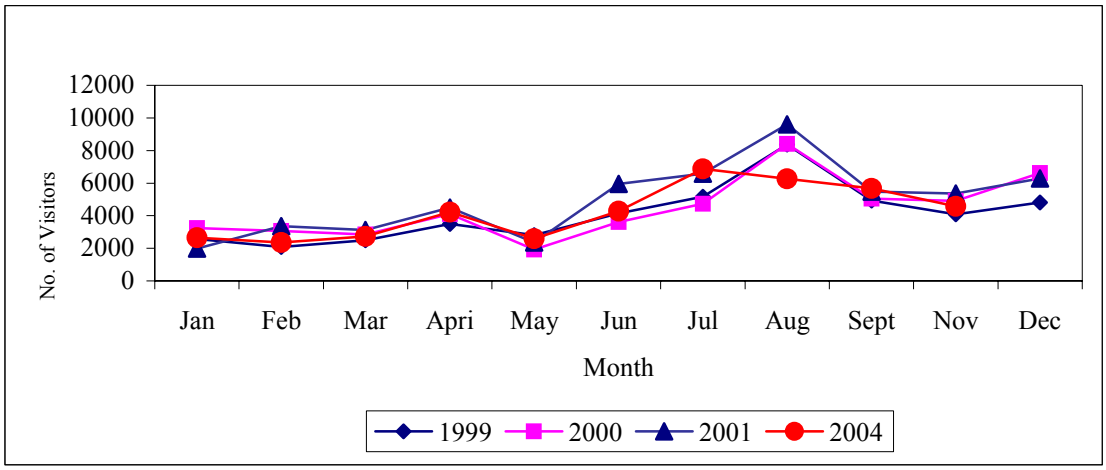

FIGURE 16: Visitors to Lake Bogoria National Reserve

3.7 Employment profile

In estimating employment, it is worthy noting that some people engage in multiple activities like farming, retailing while at the same time they could be employed in the public sector. The largest employer in the prospect area is the small farm sector (e.g. rain-fed and irrigated crop farming, and bee keeping) and livestock keeping. There is also migrant seasonal labour, rural self-employment and urban self-employment. Urban self-employment includes small-scale business (wholesale and retail trades, hotels) and informal sector enterprises (e.g. welding and carpentry) in urban and market centres. In general, most of the labour force within the prospect area is unskilled and semi skilled and is mainly engaged in small farm sector, livestock keeping and rural self-employment. Labour force in the public sector is skilled and is mostly from outside the prospect area. The main sources of casual employment are NGO's and Corporations that support various community-based projects.

3.8 Physical infrastructure

Roads

The area is criss-crossed by quite a number of all weather roads and motorable tracks, which can be classified as roads of Class B (National trunk roads), Class E (Special purpose and Minor roads) and a few unclassified roads. The classified roads include the D365 Mogotio Lake Bogoria road (58 km) and the E460/D365 Loboi-Makutan-Tangulbei road (80 km). The non classified roads include Molo Sirwe-Oteri road (25 km), Lake Bogoria/Maji Moto road (17 km) and the Marigat-Mochongoi road (57 km).

The Ministry of Public Works and Roads through its Roads Maintenance Department in the two districts, has endeavoured to keep most of the roads and tracks in motorable state including the ones within Lake Bogoria National Reserve. The Contractor that was awarded the contract of gravelling Marigat-Arabal-Mochongoi (C51) abandoned the Contract after logistical delays. There were also plans of constructing a new loop to connect Nakuru-Marigat-Mochongoi-Nakuru to improve communication in the area after completion of the Marigat-Arabal-Mochongoi road project.

Postal and telecommunication

There are post offices at Mogotio and Marigat and a sub post office at Emining. There are plans to extent services to areas not covered such as Mugurin and Maji Moto near Lake Bogoria.

The prospect area is relatively served with telephone lines with Mogotio division having more than 50 telephone lines. There are manual telephone exchange facilities located at Marigat, Kampi Ya Samaki, Kisanana and Emining. Areas lacking telephone facilities are Olkokwe and Mugurin. Marigat's total capacity of the telephone exchange facilities is 300 lines and only 90 lines are utilized. Therefore, there are 210 telephone lines for new customers around Marigat, Loboi, Kapkuikui, Loboi and Sandai locations at a cost of Ksh 8,200 per line. In addition to the above network, a wireless line has been extended from Kabarnet Exchange to Loboi and Mochongoi Centres through radio systems. Ms Celtel has also commissioned a base transmission station at Marigat. This has improved communication network in the area.

Power

Only a few areas within Arus-Bogoria prospect are connected to the electricity power grid. These are mainly the trading centres located along the power distribution grid. Main ones include Mogotio, Emining, Marigat, Loboi and Mochongoi. The power connection by KPLC has been limited only to the people who are able to pay. For example at Marigat the capacity of the Transformer installed is 1.5 MVA and the actual consumption by connected consumers is about 0.5 MVA. This leaves a surplus of 1.0 MVA for new connections around Marigat, Loboi and Kapkuikui among other locations in the vicinity of Marigat Centre.

3.9 Educational profile and facilities

Educational facilities in within Arus-Bogoria prospect are as shown in Table 9. Schools are few and lack basic requirements such as classrooms and desks and laboratories in comparison to the schools in highland areas. Similarly, enrolment in both primary (29,992) and secondary (2,076) schools is low. The hostile semi-arid environment, effects of disease outbreaks particularly malaria and URTI, cultural practices particularly early marriage and pastoral lifestyle and high poverty levels are among many other factors responsible for the low enrolment rates. However, interventions from World Food Programme (WFP) through World Vision ADP and the GoK through free school-feeding programs sustain enrolment of pupils in these lowland schools.

TABLE 9: Educational Profile and facilities in Arus-Bogoria prospect in 2005

Division	Pre-Units	Primary Schools	Secondary Schools	Enrolment in Pri. Schools	Enrolment in Sec. Schools
Mochongoi	27	27	1	6151	140
Marigat	33	33	4	9498	687
Emining		24	2	4948	583
Kisanana		13	1	2809	241
Mogotio		24	5	6586	425
Total		**121**	**13**	**29992**	**2076**

Source: Education Department, Baringo District-Kabarnet & Koibatek District, Eldama Ravine

3.10 Mineral resources

Ruby deposits have been discovered at Kaplengoi and Kurintoi in Mochongoi division. The current prospecting site is East of Lake Bogoria around Mbechot area and West of Marigat. Corby Company Ltd has been issued with prospecting licenses for three areas at Mbechot in Mochongoi Division. Trona deposits on the shores of L. Bogoria are mined on a small scale by pastoralist community for their livestock.

4. ANTICIPATED ENVIRONMENTAL AND SOCIAL IMPACTS AND MITIGATIONS

Environmental impacts arising from geothermal development in Arus-Bogoria prospect area will largely depend on a specific location where development will take place. The subsequent section is therefore a summary of generalized impacts that might be anticipated during development. The potential impacts have been modelled on similar projects that have been implemented else where e.g. Olkaria

4.1 Environmental impacts

Flora
The opening of the area for drilling will involve removal of the original vegetation for road construction and drill pad preparation.

Recommended mitigation
- Reduction of pad size to a minimum as far as practicable to ensure minimum disturbance of natural vegetation;
- Immediate seeding of the affected area with indigenous perennial grass species such as *Cynodon dactylon, Cenchrus ciliaris, Cymbopogon sp., Themeda triandra, Sporobolus ioclados, Chloris roxburghiana;*
- Re-injection of drilling effluents and waste brine to minimize impacts on flora in the surrounding environment;
- Vegetation monitoring programme to assess the possible potential long-term effects of effluents on natural vegetation is recommended.

Fauna
Major impacts could be realized if major developments will be undertaken closer to Lake Bogoria and its surroundings which is a key habitat both fauna and avifauna. Of importance to note is noise pollution during drilling and well testing which has been considered as a negative impact on avifauna because it is thought that it can make animals move away from preferred habitats. The LBNR being an Important Bird Area (IBA) and a designated ramsar site close developments need to be undertaken with caution.

Water resources
Drilling of geothermal wells and construction of geothermal utilities and operation require large amounts of water for both domestic consumption and industrial uses.

Recommended mitigation
- Consider alternative sources of water for geothermal well drilling like drilling new boreholes.
- Adopt modern drilling techniques using minimal amounts of water during drilling and with recycling capability.

Soil
Removal of vegetation and opening of ground during geothermal well drill pad preparation and construction of geothermal utilities may lead to soil degradation through wind or storm water induced erosion.

Recommended mitigation
- Rehabilitation of drill sites through planting of fast growing plant species such the indigenous perennial grass species like *Cynodon dactylon, Cenchrus ciliaris, Cymbopogon sp., Themeda triandra, Sporobolus ioclados, Chloris roxburghiana*; and
- Monitoring of soil quality to assess the magnitude of short and long-term impacts.

4.2 Socio-economic impacts

Land use
Land would be required for access roads, geothermal well drill pads and subsequent development. The land is held under trustee by Koibatek and Baringo County Councils.

Population and settlement
Development of geothermal resource would lead to an increase in population due to people coming to the area in search of employment. The main impact anticipated could be change in social stratification among the local inhabitants

Infrastructure and other public utilities
The anticipated social impacts from geothermal development activities in this Prospect area may include opening up of the area and improved road network through upgrading of existing roads.

Tourism
Lake Bogoria National Reserve (LBNR) is already attracting many local and foreign non-paying visitors. Therefore, the planned construction of geothermal utilities in the area is anticipated to attract both local and foreign people due to its unique feature as is the case with geothermal developments in Olkaria field within Hells' Gate National Park, which has become major attraction. The area's potential to generate revenue from visitors will increase especially with revenue that will accrue from accommodation facilities that are coming up.

Energy consumption and demand
Development of geothermal, which is a cheap, reliable and environmentally clean source of electric power in Arus-Bogoria Prospect area, will halt any further degradation of vegetation resources and enhanced public access to electric power thus improved living standards.

5. CONCLUSIONS

The anticipated environmental impacts could be significant within LBNR. However, social impacts are insignificant in magnitude. The impacts, however, could be effectively mitigated during civil works, drilling and testing of geothermal wells and power plant construction and operation.

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GEOTHERMAL ENERGY IN THE WORLD FROM ENERGY PERSPECTIVE

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ABSTRACT

An overview is given of the energy utilization in the world and the operations of the UNU Geothermal Training Programme in Iceland are presented, with emphasis on East Africa. Utilization of geothermal energy in Africa is reviewed and examples are presented from region, as well as from Iceland where geothermal energy plays a larger role than in any other country in the world.

Based on UN World Energy Assessment Report update on the status in 2001, the primary energy consumption in the world was assessed as 400 EJ, with about 80% coming from fossil fuels, and only 14% from renewable energy sources. The contribution of the renewables is discussed and their possibilities. The current share of the renewables in the energy production is mainly from biomass and hydro, but in a future envisioned through depleting resources of fossil fuels and environmentally acceptable energy sources, geothermal energy with its large technical potential is expected to play an important role.

High-temperature geothermal resources within the Great East African Rift Valley have the potential to provide East Africa with the some of the energy it needs for development, and even become one of the main resources for electricity production. Kenya is now producing about 2010 MWe of electricity from geothermal and has set itself a very ambitious goal of having reached 5000 MWe from geothermal resources on-line in the year 2030. This is an example for the other East African countries to follow.

1. INTRODUCTION

Geothermal energy is one of the renewable energy sources that can be expected to play an important role in an energy future where the emphasis is no longer on fossil fuels, but on energy resources that are at least semi-renewable and long-term environmentally acceptable, especially with regard to emission of greenhouse gases and other pollutants. For developing countries which are endowed with good geothermal resources, it is a reliable local energy source that can at least to some extent be used to replace energy production based on imported (usually) fossil fuels. The technology is proven and cost-effective. For developing countries that have good resources and have acquired the necessary local expertise it has become very important. A good example of this is Kenya, as well as the Philippines, El Salvador and Costa Rica, where geothermal energy has become one of the important energy sources providing for 10-20% of the electricity production. Iceland should also be mentioned as the only country where geothermal energy supplies more than 50% of the primary energy used, both through direct use for heating, bathing, etc., and through production of electricity.

Geothermal systems can be classified into a few different types but with reference to variable geological conditions each one is in principle unique, so that good knowledge is needed through exploration. Furthermore, development of a geothermal system for electrical production is a capital intensive undertaking, and thus requires financial strength, or at least access to good financing. Thus, for developing geothermal resources, good training and expertise are needed for the exploration and development work, and strong financial backup for the project.

Here, the role of geothermal energy in the world's energy mix is presented with some emphasis on E-Africa, and examples are given on its use in Africa and Iceland. But first the United Nations University Geothermal Training Programme is introduced.

2. THE UNU GEOTHERMAL TRAINING PROGRAMME

The United Nations University Geothermal Training Programme (UNU-GTP) has operated in Iceland since 1979 offering six month annual courses for professionals from developing countries. From being one of four geothermal schools established in the 1970s the UNU-GTP is now the only international graduate school offering specialized geothermal training. The aim is to assist developing countries, with geothermal potential, in capacity building in order to make the countries self sufficient in geothermal development. The trademark is to give university graduates engaged in geothermal work intensive on-the-job training. The training is conducted in English and tailor-made to suit the needs of the home country. UNU Fellows generally receive scholarships financed mainly by the Government of Iceland. Since 2000, cooperation between the UNU-GTP and the University of Iceland (UI) has opened up the possibility for a few UNU Fellows to extend their studies to MSc level, with the six months training adopted as an integral part (30 out of 120 ECTS). In 2008, the cooperation was expanded to include PhD studies, with two former UNU Fellows commencing PhD studies in the academic year 2008-2009. A similar cooperation agreement has now been signed with the Reykjavik University

As a contribution to the UN Millennium Development Goals and through the contribution of the Icelandic government, the UNU-GTP has expanded its activities by annual workshops/short courses in Africa (started in Kenya in 2005), Central America (started in El Salvador in 2006), and Asia (started in China in May 2008). The events are organised in cooperation with local energy agencies responsible for geothermal development. A part of the objective is to increase geothermal cooperation inside the region, and to reach out to countries with potential and interest in geothermal development who have not yet received quality training. This has made it possible for the UNU-GTP to reach out to an increasing number of geothermal scientists and engineers. More recently, this has also been one factor that has contributed to the UNU-GTP being able to offer customer-designed courses, lasting from one to 12 weeks, modelled to the demands of the paying customer. The first such courses were given in 2010. This has since become an important factor in the operations of UNU-GTP.

Africa has always been a major cooperating partner of the UNU-GTP. Amongst the 554 graduates of the UNU-GTP (1979-2013), 191 or 34% have come from thirteen African countries. Most of these come from the countries of East Africa. The largest numbers have come from Kenya (89), followed by Ethiopia (32) and Uganda (16). Former UNU Fellows lead the geothermal research and development in most of these countries. The political and economic situation in some of the countries has, however, delayed geothermal development, with some of its professionals trained at the UNU-GTP having left their jobs in the geothermal sector and even immigrated to other countries. Almost half or sixteen out of the thirty five UNU MSc-Fellows that have graduated from the MSc programme are from Africa, 9 from Kenya, 2 from Ethiopia and Eritrea and 1 from each of Uganda, Djibouti and Rwanda. Also, eight Africans are currently pursuing their MSc studies in Iceland, coming from Kenya (6), Rwanda and Tanzania. Finally, the first UNU PhD-Fellow to graduate was a Kenyan, defending her thesis in February 2013, with two additional Kenyans pursuing their studies. Figure 1 shows the group of UNU Fellows that attended 6 month training in Iceland in 2013.

FIGURE 1: The group of UNU Fellows that attended the 6 months training in Iceland in 2013, at Hjalteyri low-temperature field, Eyjafjördur, N-Iceland

For more information on UNU-GTP, see e.g. Fridleifsson (2008, 2010) and Georgsson, (2010, 2012) or its web page (www.unugtp.is).

3. THE ROLE AND POTENTIAL OF GEOTHERMAL ENERGY TODAY

Geothermal energy is a resource that has been used by mankind for washing and healing through its history. In the 20th century, geothermal gradually came on-line as an energy source for electricity production and to be used directly, besides bathing or washing, for heating of houses, greenhouse heating, aquaculture etc. According to energy reviews based on surveys for 2009, presented in combination with the World Geothermal Conference 2010, geothermal resources have been identified in over 90 countries while quantified utilization is recorded in 78 countries. Electricity is produced from geothermal energy in 24 countries. In 2009, the worldwide use of geothermal energy was estimated to be about 67 TWh/a of electricity (Bertani, 2010), and direct use 122 TWh/a (Lund et al., 2010).

In the modern world, access to clean energy at affordable prices is a key issue to improve the standard of living. However, at present, two billion people, a third of the world´s population, have no access to modern energy services, and in addition the world population is expected to double by the year 2100. Furthermore, the world energy consumption is expected to double in the new century. So the task in providing clean energy to people in the coming century is enormous (Fridleifsson, 2003).

Today´s energy consumption relies on fossil fuels. Table 1 shows the use of primary energy in 2001 based on the UN World Energy Assessment Report update (WEA, 2004). With rising oil prices and with environmental concerns expected to play a bigger role, through necessary reduction in emissions of greenhouse gasses, renewable energy sources are expected to play an increasingly bigger role in the 21st century. The technical potential of the renewable energy sources is certainly large enough (WEA, 2004).

TABLE 1: World primary energy consumption (WEA, 2004)

Energy source	Primary energy EJ	%
Fossil fuels	**332**	**79**
Oil	147	35
Natural gas	91	22
Coal	94	22
Renewables	**57**	**14**
Traditional biomass	39	9
Hydro, geothermal, wind, solar, tidal	18	5
Nuclear	**29**	**7**

The use of geothermal energy has increased steadily during the last few decades, and until the start of this century it was seated as number three of the renewables with regards to electricity production. However, more recently wind energy has surpassed geothermal, pushing it into fourth place. The total electricity production from renewable energy sources (Table 2) was assessed as 3188 TWh in 2005 (WEA 2007). Of this 89% came from hydropower, 5.7% from biomass, 3.3% from wind, 1.8% from geothermal while solar and other sources contributed to 0.2%. With its huge technical potential, geothermal energy is definitely one of the energy resources contributing to a greener future.

A comparison of cost of energy between countries is difficult, because of differences in taxation and subsidies. But the survey discussed here proves that the renewables are definitely competitive (WEA 2004), showing the electrical energy cost to be 2-10 UScents/kWh for geothermal and hydro, 4-8 UScents/kWh for wind, 3-12 UScents/kWh for biomass, but higher for solar energy. The investment cost is also assessed to be quite similar for the different energy sources, 1000-3500 USD/kW for hydro, 500-6000 USD/kW for biomass, 800-3000 USD/kW for geothermal and 850-1700 USD/kW for wind. The advantage of geothermal energy compared to other renewables is the high capacity factor, being independent of weather conditions contrary to solar energy, wind energy, or hydropower. The reliability of geothermal plants means that usually they can be operated at capacity factors in excess of 90%. This is partly illustrated in Table 2 that shows data on electricity production from the renewable energy resources in 2005 (WEC, 2007).

TABLE 2: Electricity produced from renewable energy resources in 2005 compiled from data in WEC (2007)

	Installed capacity		Production per year		Capacity factor
	GWe	**%**	**TWh/y**	**%**	**%**
Hydro	778	87.5	2,837	89	42
Biomass	40^{+}	4.5	183	5.7	52^{+}
Wind	59	6.6	106	3.3	21
Geothermal	8.9	1.0	57	1.8	73
Solar	4	0.4	5	0.2	14
Total	890	100	3,188	100	41

In 2009, electricity was produced from geothermal energy in 24 countries, increasing by 18% from 2004 to 2009 (Bertani, 2010). Table 3 lists the top ten countries producing geothermal electricity in the world in 2009, and those employing direct use of geothermal energy (in GWh/year). The largest electricity producer is the USA, with almost 16,600 GWh/a, but this still amounts only to half a percent of their total electricity production. It is different for most of the other countries listed there, with geothermal playing an important role in their electricity production. That certainly applies to the second country on the list, The Philippines, where the production of more than 10,000 GWh/a means that geothermal supplied 17% of the electricity produced. Same applies to Kenya, the total production

of 1430 GWh/a only put the country in 9th place with regard to total production but it still amounted to 17% of the total production. The highest value is though seen for Iceland where a production of 4597 GWh/a means that geothermal supplied about 25% of the produced electricity. For direct use (Lund et al., 2010), China heads the list with USA and Sweden in second and third place through rapidly increasing use of ground source heat pumps, followed by Turkey, Japan, Norway (new on the list, also through use of ground source heat pumps) and Iceland. With direct use of geothermal energy still insignificant in Africa it is not surprising that no African country is seen among the top ten countries with direct use of geothermal energy.

TABLE 3: Top ten countries in electricity production from geothermal energy in 2009 (Bertani, 2010), and those with direct use (Lund et al., 2010)

Geothermal electricity production			**Geothermal direct use**	
Country	**GWh/a**	**% nat. produc.**	**Country**	**GWh/a**
USA	16,603	0.5?	China	20,932
Philippines	10,311	17	USA	15,710
Indonesia	9,600	3?	Sweden	12,585
Mexico	7,047	3	Turkey	10,247
Italy	5,520	2	Japan	7,139
Iceland	4,597	25	Norway	7,001
New Zealand	4,055	10	Iceland	6,768
Japan	3,064	0.3?	France	3,592
Kenya	1,430	17	Germany	3,546
El Salvador	1,422	25	Netherlands	2,972

Focussing on energy use in the East African region, Tables 4-6 show interesting numbers, still valid despite the data not being quite new. They are based on statistics from the IEA, published in 2005. Table 4 shows the primary energy consumption in four of the East African countries in 2004. It shows well how important biomass and waste are in the region, accounting for 70-90% of the total consumption in the respective countries, and how small the share of the other renewable energy sources is. Fossil fuel supplies energy for some of the electricity and of course the transport sector.

TABLE 4: Primary energy consumption in East Africa in 2004 (IEA statistics)

	Fossil	**Hydro**	**Geoth./ sol./wind**	**Waste/ biomass**
Kenya	16%	2%	2%	80%
Eritrea	29%			71%
Ethiopia	7%	1%		92%
Djibouti				
Tanzania	8%	2%		90%
Uganda				
Total	**10%**	**1%**	**1%**	**88%**

Table 5 shows the installed capacity for electricity production in East Africa in 2004. Here the renewable sources are well represented through hydro providing for 70% of the production capacity, with thermal plants supplying 26%. The Olkaria power plant in Kenya is largely responsible for the remaining 4%. Here a significant change will hopefully be seen in the coming decade.

TABLE 5: Electricity production in East Africa in 2004 – installed capacity in MW (IEA statistics)

	Thermal	**Hydro**	**Geoth.**	**Wind**	**Total**
Kenya	346	584	121	1	1052
Eritrea	130				130
Ethiopia	36	671	7		714
Djibouti	85				85
Tanzania	202	561			763
Uganda		300			300
Total	**799** **26%**	**2116** **70%**	**128** **4%**	**1** **0%**	**3044**

Finally, Table 6 demonstrates the huge difference in electricity production per capita between the East African countries, varying from 22 to 255 kWh/capita compared to the average value for the OECD countries, about 8000 kWh/capita. It certainly shows the need for improvement in the region, if life standards are to be improved significantly.

TABLE 6: Energy consumption in E-Africa, 2001-2003 in kWh/capita (IEA statistics)

	Population	**GNI $/capita**	**Energy kWh/capita**
Kenya	32 million	390	117
Eritrea	4.4 million	190	42
Ethiopia	69 million	90	22
Djibouti	0.7 million	910	255
Tanzania	36 million	290	59
Uganda	25 million	240	64
OECD			**8,056**

For a more thorough overview of the use of geothermal energy in the world and comparison with other energy resources, see e.g. Fridleifsson, 2003 and 2006.

4. UTILIZATION OF GEOTHERMAL ENERGY IN AFRICA

As seen in Section 3, the East African countries have similar energy production and consumption characteristics. Traditional biomass represents by far the largest category of energy produced (Table 4). The extensive use of combustible waste and biomass causes deforestation and contributes to environmental degradation. All the East African countries import petroleum products, mainly for transport and some for electricity production, which is not desirable in times of environmental awareness and high oil prices. Instead local renewable energy sources should be preferred, at least as far as conventional resources allow. For the countries surrounding the East African Rift System (EARS) (Figure 2) with its volcano-tectonic activity, high-temperature geothermal resources have the potential to play a much bigger role and even become one of the most important resources for electricity production. Currently, renewable energy sources (hydro, geothermal, wind, solar, etc.) represent only a small portion of the total primary energy production, averaging 2% for hydropower, geothermal and solar production combined (Teklemariam, 2008).

Geothermal can also be expected to play an important role in the countries of North Africa. However, the geothermal resources in this part of Africa are of the low-temperature type, and thus the practical utilization is mainly limited to direct uses, i.e. space heating, agriculture, aquaculture, recreation, etc., Electrical production through binary stations might though be possible at a few locations.

With the technology of today, East Africa has the potential to generate energy in the range 2,500-6,500 MWe from geothermal power (assessment by GEA, 1999). Despite that, Kenya is now the only country harnessing this resource to a significant extent. It has the richest potential, with geothermal potential recently having been evaluated to be able to supply more than 7000 MWe (Simiyu, 2010). Since the early 1980s, Kenya has slowly been increasing its total geothermal power generation from 15 MWe to 210 MWe at the Olkaria geothermal area in 2012 (Figure 3), with big increases scheduled in the near future. With Kenya's Vision 2030, geothermal is scheduled to become Kenya's main source of electricity, with plans for 5000 MWe on-line in the two next decades (Ngugi, 2012). It should also be mentioned that at Lake Naivasha, Kenya, geothermal water and carbon dioxide from geothermal fluids are used in an extensive complex of greenhouses for growing roses (Figure 4). Using geothermal heating to improve the quality of the products started in 2003. The Oserian farm is now (2010) the biggest geothermal greenhouse farm in the world, with 50 ha. of greenhouses being heated with geothermal to produce high quality cut flowers. Rose exports from this "geothermal" farm alone have totalled USD 300 million per year (Mwangi, 2005).

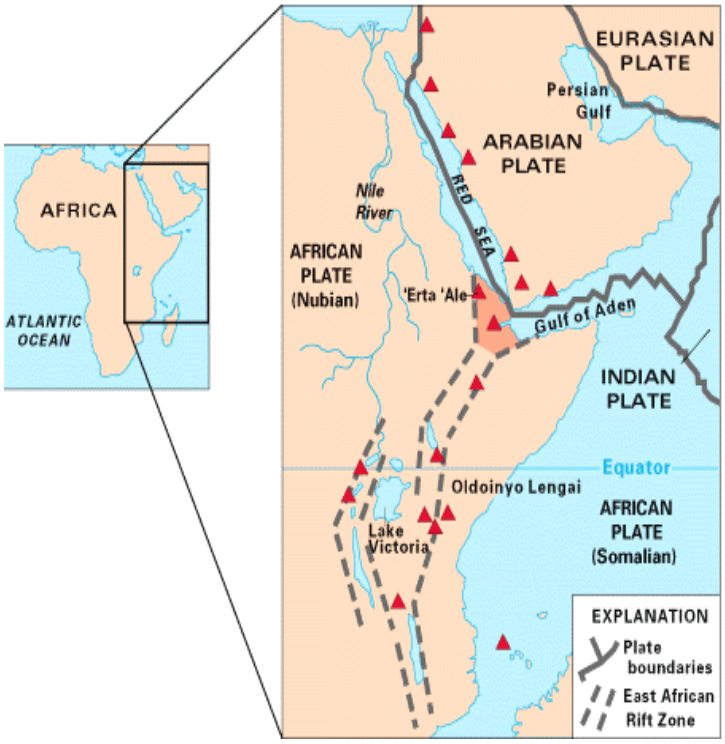

FIGURE 2: The Great East African Rift System (Teklemariam, 2008)

FIGURE 3: The Olkaria II power station in Kenya in 2010 with an installed capacity of 105 MWe

In Ethiopia, the Aluto-Langano pilot power plant, built in 1998 for producing 7.2 MWe on-line, has been only in partial operation since few months after its opening about 10 years ago, with mechanical problems in the plant and limited steam supply being difficult problems to overcome. This led to no or low production for long periods of time. After restoration, the plant is now producing 3 MWe (Teklemariam, 2008).

FIGURE 4: Roses grown in a greenhouse heated with geothermal at the Oserian farm, Kenya

Geothermal exploration and research have been undertaken in Djibouti, Eritrea, Uganda, Tanzania, Zambia, Malawi, and most recently in Rwanda. The potential to use geothermal energy for electricity production may be greatest in Kenya, Djibouti and Ethiopia, but countries like Eritrea, Uganda, Tanzania and probably also Rwanda should not be discounted here. Ambitious exploration projects, including in some cases exploration drilling, are now in the initial stages in Djibouti, Ethiopia and Rwanda in cooperation with foreign companies and/or investors, and Uganda and Eritrea may not be far behind. The Geological Survey of Germany (BGR) must be mentioned, having been very active in the area in recent years, promoting geothermal exploration through its Geotherm programme. This effort has got geothermal exploration going in some countries where not much had been done for a long period of time, such as in Tanzania, Rwanda and Yemen (which partially belongs to the EARS), not forgetting the BGR projects in e.g. Uganda and Ethiopia. The same can be said about the Icelandic Development Agency - ICEIDA with its project in Uganda and in Eritrea.

The status of exploration and utilization of geothermal energy resources in the East African region for the last three decades has been summarized by Teklemariam (2008):

- The region has a large untapped geothermal resource potential;
- The geothermal resources are an indigenous, reliable, environmentally clean and economically viable, renewable energy resource;
- Development of geothermal resources is constrained by
    i. the risks that are associated with resource exploration and development;
    ii. the financial risks that are associated with investment in power development projects; and
    iii. lack of appropriate investment and institutional settings in many East African countries;
- Diversified use of geothermal energy augments energy supply from hydropower plants and improves the generation mix. It avoids vulnerability to drought and oil price fluctuations.

To light up East Africa by geothermal electricity, investors and financial assistance from international agencies are necessary, and the human capacity to deal with the exploration and development needs to be built up further.

In North Africa, low-temperature waters for direct use have been utilized successfully in Tunisia where hot water intended for irrigation is cooled down in greenhouses thus allowing production of quality products, such as cucumbers and melons, mainly for export to Europe (Figure 5). In 2010, the total area heated in geothermal green-houses in Tunisia had reached 194 ha, making it one of the largest producers in the world from geothermally heated greenhouses. Extensive use of geothermal water for bathing can be added to this as an important cultural habit with roots stretching back some

thousands of years. Direct use of geothermal energy is also recorded for Algeria, and Morocco has been exploring for geothermal resources, but Tunisia provides the example for the other countries of North Africa to follow (Ben Mohamed, 2010).

FIGURE 5: A geothermal green house in Tunisia,
the hot water flows through plastic pipes at the ground surface

5. EXAMPLES OF USES OF GETHERMAL ENERGY IN ICELAND

Iceland is a unique country with regard to utilization of geothermal energy, with more than half (62%) of its primary energy consumption from geothermal energy. Direct use plays the most important role here with 89% of houses in the country heated by geothermal energy. Other uses include greenhouses, fish farming, industry, snow melting, swimming pools, etc., but even so only a fraction of the potential is used. Electrical production from geothermal power plants has increased rapidly in the last 5 years, amounting to about 26% of the total electrical production in 2009. At the end of 2009 the total installed capacity was about 575 MWe (Figure 6).

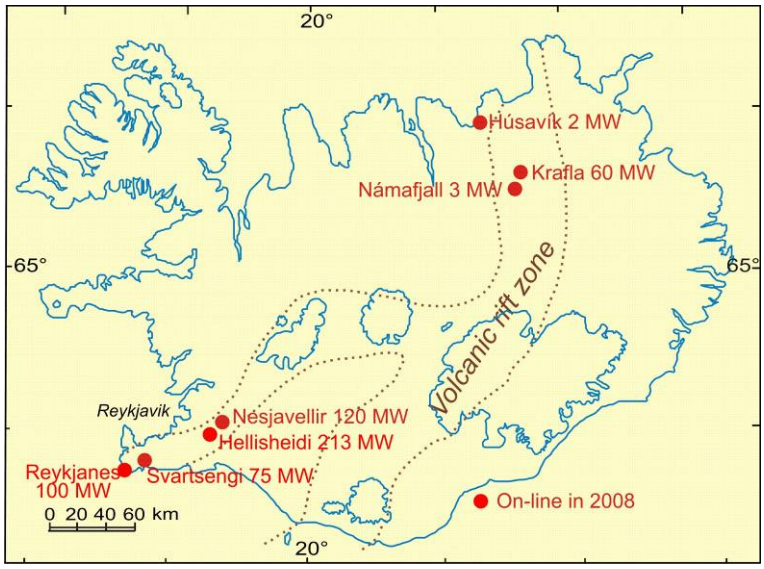

FIGURE 6: Geothermal power plants in Iceland in 2010

It can be said that geothermal energy is a way of life in Iceland. Reykjavik Energy supplies the capital, Reykjavik, and its surroundings, in total just over 200,000 people, with hot water for heating through 12 months of the year, making it the largest municipal heating service in the world. The geothermal swimming pools in Iceland are found in almost every village and small town. The most famous bathing place is, however, the Blue Lagoon (Figure 7), a byproduct of the Svartsengi power

plant and located in a hostile lava field, 5-10 km from the nearest towns. It has become a landmark for Iceland and a must for any tourist to visit.

To this can be added benefits such as snow-melting of pavements around houses, not forgetting the use of geothermal water for heating of greenhouses and for fish farming.

FIGURE 7: UNU Fellows bathing in the Blue Lagoon in 2003

6. THE GEOTHERMAL FUTURE

In a future where the emphasis is no longer on fossil fuels but on renewable and environmentally acceptable energy resources, geothermal energy is bound to have an important role. For developing countries which are endowed with good geothermal resources, it is a reliable local energy source that can, at least to some extent, be used to replace energy production based on imported (usually) fossil fuels. The technology is proven and cost-effective, and the technical potential is huge.

Geothermal energy is now on the threshold of becoming a major player in the energy market in East Africa. Kenya has set itself very ambitious goals to reach in the coming decade, by declaring that geothermal is to become their main source of additional electricity in the near future. From current production of about 202 MWe, the long-term plans are now to reach 2000 MWe on-line from geothermal by the year 2018, and 5000 MWe by the year 2030.

Other countries in the region are slowly following in Kenya's footsteps. Ethiopia, Djibouti, Eritrea, Uganda and Rwanda are taking significant steps through new projects, partially in cooperation with foreign companies or investors, in exploration and development of their geothermal sources. The time has, however, come to take it one step further, to the energy production. That should be the trademark of the next decade in East Africa.

The UNU-GTP looks forward to see geothermal turn on the lights in the East African countries, and is determined to provide the training opportunities which the region needs, both in Iceland and hopefully also through a future UNU-GTP training centre in Kenya in cooperation with the Geothermal Developing Company (GDC) and Kenya Electricity Generating Co. (KenGen).

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THE GEOLOGY AND GEOTHERMAL ACTIVITY OF THE EAST AFRICAN RIFT

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ABSTRACT

The East Africa Rift System is a classical continental rift system associated with the world-wide mid ocean rift systems. The rift extends from the Red Sea – Afar triple junction through Ethiopian highlands, Kenya, Tanzania and Malawi to Mozambique in the south. The western branch passes through Uganda, DRC and Rwanda while the nascent south-western branch runs through Luangwa and Kariba rifts in Zambia into Botswana. The volcanic and tectonic activity in the rift started about 30 million years ago and in the eastern branch the activity involved faulting and eruption of large volumes of mafic and silicic lavas and pyroclastics. The western branch, typified by paucity of volcanism, is younger and dominated by faulting that has created deep basins currently filled with lakes and sediments.

Geothermal activity in the rift is manifested by the occurrences of Quaternary volcanoes, hot springs, fumaroles, boiling pools, hot and steaming grounds, geysers and sulphur deposits. The manifestations are abundant and stronger in the eastern branch that encompasses Afar, Ethiopian and Kenya rifts while in the western branch, the activity is subdued and occurs largely as hot springs and fumaroles. Detailed and reconnaissance studies of geothermal potential in Eastern Africa indicates that the region has potential of over 15,000MW$_e$.

1. INTRODUCTION

The East African rift system is widely recognized as the classical example of a continental rift system which is part of the Afro Arabian rift system that extends from the Red Sea to Mozambique in the south. As the rift extends from the Ethiopian segment southwards it bifurcates at about 5°N into the Eastern and Western branches. The two branches of the rift skirts around the Tanzania craton and formed within the Late Proterozoic belts adjacent to the margins of the craton (Mosley, 1993 and Smith and Mosley, 1993). However, the Eastern Branch that comprises the Ethiopian and Kenya rifts is older and relatively more volcanically active than the western branch that comprises Albert–Tanganyika-Rukwa-Malawi rifts.

In the rift axis of the eastern branch occurs numerous central volcanoes of Quaternary age overlying products of Miocene and Pliocene volcanism. The shield volcanoes are built largely of intermediate lavas and the associated pyroclastics, thus indicating the presence of shallow hot bodies (magma chambers). In the Western Branch, there is paucity of volcanism along the entire length of the rift with the main volcanic areas being Virunga and Rungwe. The geothermal activity in the East African

rift occurs in the form of hot springs, fumaroles, hot and altered grounds is closely associated with Quaternary volcanoes in the axis of the rifts. The association is related to the shallow hot magma bodies under the massifs, which are the heat sources. In the Afar rift where the crust is as thin as 5km, extensive manifestations and high heat flux is due to a combination of mantle heat and magma bodies occurring at shallow depths. In the less magmatic western branch of the rift, heat sources could be combination of buried pluton and high heat flux associated with thinned crust.

Using today's technologies, Eastern Africa has the potential to generate over 15,000 MW of energy from geothermal power. Despite this potential, only Kenya and Ethiopia have active geothermal generation of 209 MW and 7.2 MW, respectively. Varying degrees of geothermal exploration and research have been undertaken in Djibouti, Eritrea, Uganda, Tanzania, Zambia and Malawi. The potential to use geothermal energy for grid-connected electrification is greatest in Kenya, Djibouti, Ethiopia, Uganda and Tanzania. In addition, all the countries have the potential to use geothermal energy for grid connected electrification.

2. GEOTHERMAL ACTIVITY

2.1 General

East African rift system (EARS) is a succession of rift valleys that extend from Beira in Mozambique in the south to Afar triangle in the north; a total distance of more than 4,000-km. The EARS is a continental branch of the worldwide mid ocean rift system that corresponds to the third arm of the Afar- Red Sea – Gulf of Aden triple junction. The rift is assumed to mark the incipient plate boundary between the Somali and Nubian micro-plates and linked to the Afar- Red Sea – Gulf of Aden rift systems (Figure 1). The EARS splits into two at about 5°N to form the Eastern and Western branches. The Eastern branch comprises the Afar, Ethiopian, Turkana and Kenya Rifts while the western branch comprises Albert, Kivu, Tanganyika, Rukwa and Malawi Rifts. The SW branch comprises Luangwa-Kariba-Okavango rifts.

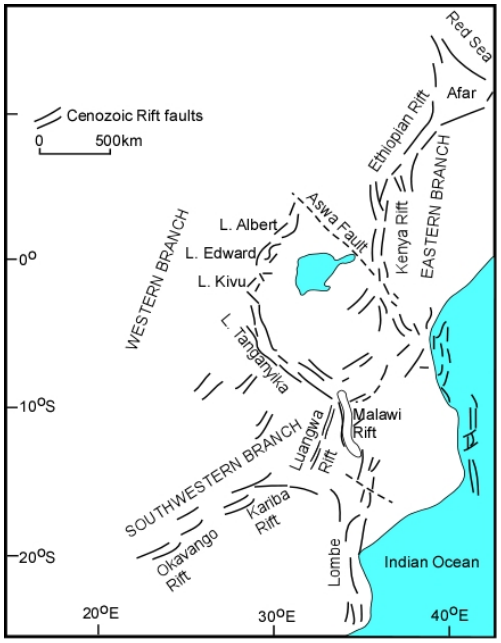

FIGURE 1: Structural map showing the East African Rift System (Modified from Atekwana et al., 2004)

The standard model for active rift formation involves lithospheric extension accompanied by upwelling of the underlying ashenospheric mantle (Figure 2). Decompression of the asthenosphere results in large volumes of magma generation. Further brittle extension of the crust results in down faulting and formation of the graben. In the case of the EARS, extensions is more active in the north being more than 2cm/year in the Red Sea – Gulf of Aden, 1 mm/year in the Main Ethiopian Rift, and further less than 1mm/year in the Kenya Rift and southwards. In response to the increased extension in the EARS, the Moho is at between 5 and 35 km along the axis of the rift.

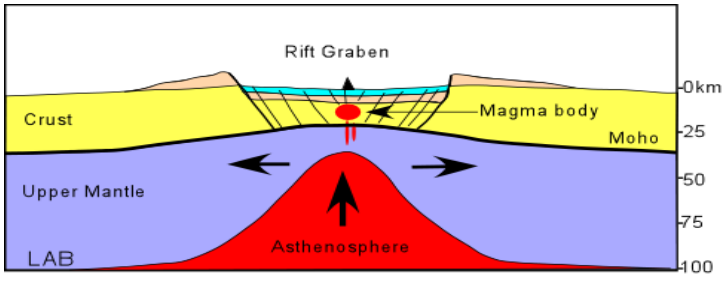

FIGURE 2: Generalized E-W section across a typical continental rift showing late stages of its formation

2.2 The Ethiopian Rift

The Main Ethiopian Rift (MER) and Afar Rift represent the northernmost part of the East African Rift (Figures 2 and 3). Volcanic activity in Ethiopia started about 30 million years ago with uplift followed by eruption of large volumes of basalts (Mohr and Zanettin, 1988). However, activity has reduced since the Miocene times with eruptions of bimodal suite of basalts and more alkaline silicic lavas concentrated within the rift zone. More recent activity in the axis of the rift consisted of rhyolite volcanoes and domes as well as ignimbrites and non-consolidated pyroclastics. Studies by Mohr (1992) indicate that over 90% of the eruptives are of silicic composition. In the axis of the rift occurs the Wonji fault belt, which is a region of Quaternary crustal extension. The fault zone if offset in several locations along its length and some of the large volcanoes including Aluto are located at the fault intersections (Figure 3).

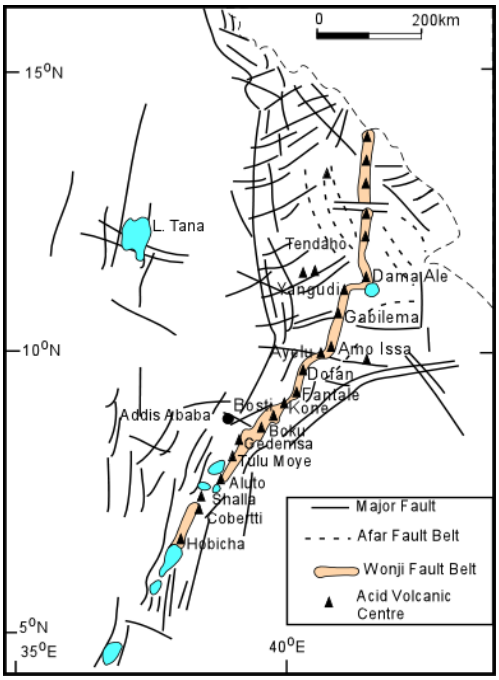

FIGURE 3: Structural map of the Ethiopian Rift showing locations of Quaternary volcanoes (From Abebe, 2000)

The Afar rift is the most active segment of the entire EARS with Erta Ale volcano being presently active. The Afar rift floor is dotted with a large number of rhyolitic volcanoes in the south and more basaltic centres in the north. The surface geology in the south is similar to that of the MER where ignimbrites are abundant while in the north basalt sheets of Quaternary age dominate. The volcanics overlie older sedimentary rocks in the Afar rift zone.

Geothermal manifestations occur as fumaroles, altered grounds, steaming grounds and hot springs in many locations, most of which are associated with young volcanic fields in the rift valley. Hot springs also occur on the flanks of the rift where they are associated with Tertiary faulting episodes. The manifestations are more pronounced and vigorous within the axis of the rifts than on the flanks due to the favourable hydrology and relatively shallow heat sources. The heat sources for the geothermal systems are related to (1) shallow magma chambers associated with the young rhyolite volcanoes that are common in the southern Afar and MER and (2) upper mantle intrusion/ upwelling associated with the thin crust in the area that averages between 5 and 20 km.

2.2.1 Djibouti

Djibouti lies at the Afar triple junction of three active, major coastal spreading centres: (a) the Eastern Africa Rift zone; (b) The Gulf of Aden Rift; and (c) and the Red sea Rift (Figures 1, 3 and 4). In Djibouti, areas of strong manifestations are located within the Asal and Hanle rifts in the Afar Depression (Mohamed, 2004). According to a recent study by the Geothermal Energy Association (GEA, 1999), the geothermal potential in Djibouti is between 230-860 MW_e from a number of prospects including: Lake Lake Asal, Abhe, Hanle, Gaggade, Arta, Tadjourah, Obock and Dorra.

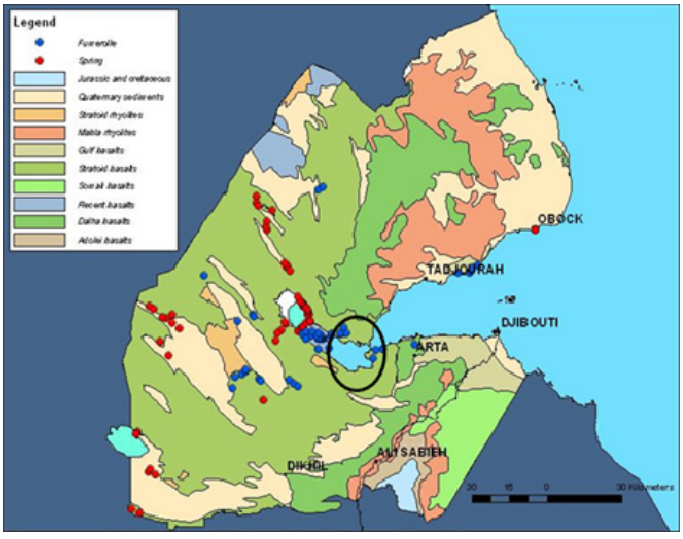

FIGURE 4: Map of Djibouti showing geothermal areas

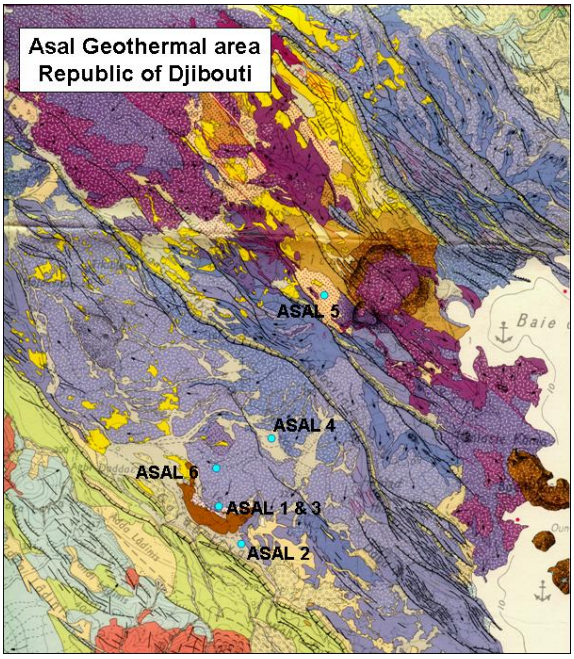

FIGURE 5: Map of Lake Asal geothermal field showing exploratory wells

Much effort has been expended in Djibouti since the 1970's, in view of the country being deficient of indigenous energy resources. Djibouti's current energy production is by fossil fuels. The first concerted effort to assess and explore Djibouti's geothermal resources took place in the Assal area from 1970-83 and funded by the French government. About six exploratory wells were drilled in the Assal geothermal fields (Figure 5). While a very high temperature system has been successfully located, problems related to high salinity of the discovered fluids, which is due to the close proximity of the field to the Gulf of Aden, has delayed resource development and exploitation (Teklemariam, 2005).

The other promising prospect is at Hanle which lies south-west of the country between Lake Abhé and Lake Asal. Several fumaroles and hot springs are identified in the area and detailed studies are planned in the future.

2.2.2 Eritrea

In 1973 the United Nations Development Programme (UNDP), identified a potentially significant exploitable geothermal resources in Eritrea. In 1995 with help of USGS, Eritrea identified the Alid geothermal prospect area for follow up detailed investigations. This area is located about 120km south of Massawa (Figure 6)

Alid Volcanic center is the better studied of all geothermal areas in Eritrea. The geothermal prospect lies within the Danakil Depression and is characterized by a rhyolitic domal intrusion which is considered to be the main heat source for the geothermal system. Manifestations occur in the form of boiling pools, hot springs, and fumaroles (Woldegiorgis et al., 2003). Detailed geoscientific investigations revealed a potential reservoir temperature of about 250°C. However, exploratory drilling is yet to be undertaken in the prospect.

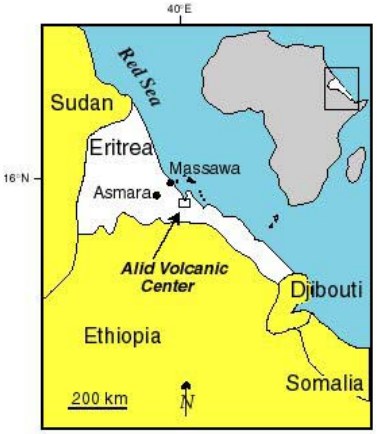

FIGURE 6: Map showing the location of Alid volcanic centre in Eritrea

2.2.3 Ethiopia

Ethiopia started a long-term geothermal exploration undertaking in 1969. Over the years a good inventory of the possible resource areas has been built up and a number of the more important sites have been explored in the Ethiopian Rift Valley. Of these areas, about sixteen are judged to have potential for high temperature steam suitable for conventional electricity generation (Figures 3 and 7).

Exploration work peaked during the early to mid-1980s when exploration drilling was carried out at the Aluto-Langano geothermal field, Lakes District Eight deep exploratory wells were drilled to a maximum depth of about 2500m, and four were found to be productive with a maximum geothermal reservoir temperature of about 350ºC.

During the early 1990s exploration drilling was also carried out at Tendaho (Northern Afar). Three deep (2100m) and three shallow wells (500m) confirmed the existence of, a high temperature (270ºC)

reservoir. The Aluto-Langano geothermal field was handed over to the Ethiopian Electric Power Company (EEPCo) for development in the year 1996 but utilization was delayed until 1998 when the first 7.2MW$_e$ pilot power plant was built.

Feasibility study for the expansion of the Aluto Langano Geothermal power has been recently completed with the Japanese Overseas Development Assistance. The study indicated expansion of the Aluto Geothermal power to additional 35MWe is feasible. Accordingly, as an initial step to develop the 35MWe, it is planned to drill four deep appraisal wells in 2011 with the Japanese technical assistance and the World Bank. By 2012 it is planned to generate 75 MWe of geothermal power from Aluto Langano and by 2018 it is anticipated to generate a total of 450 MWe from the other geothermal areas in the Rift.

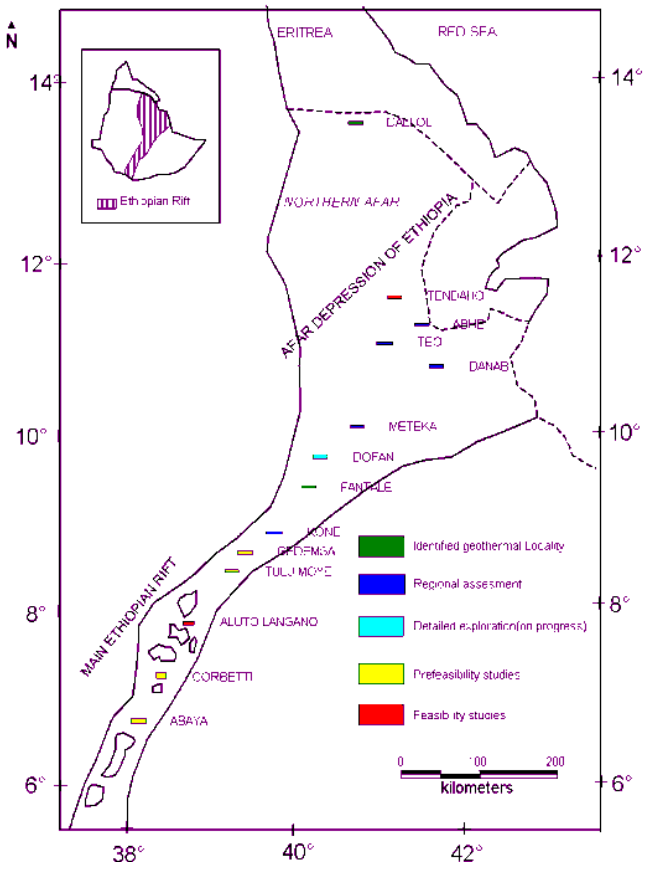

FIGURE 7: Location map of the geothermal areas in the Ethiopian Rift

2.3 The Kenya Rift

The Kenya rift is the segment that extends from Lake Turkana to northern Tanzania. The formation of the Kenya rift started about early Miocene in the north around Lake Turkana and migrated southwards being active from about middle to late Miocene in the central segment. The development of the rift occurred largely within the Late Proterozoic basement of Mozambique belt and close to the eastern margin of the Tanzania craton.

The formation of the rift started by up doming and volcanism on the crest of uplift and followed by faulting to form a half graben. The formation of a full graben occurred during the early Pleistocene, on the floor was erupted lava flows of basaltic and trachytic composition, and intercalated with tuffs. Subsequently, sheet trachytes were grid faulted with dominant north-south closely spaced faults. The Quaternary times saw the development of many large shield volcanoes of silicic composition in the axis of the rift.

Activity in the southern extreme of Kenya and northern Tanzania segment of the Kenya rift is dominated by alkaline and carbonatitic volcanism of which Ol'Doinyo Lengai is well known. Prevalence of the carbonatites in the region is attributed to deep source of the lavas occasioned by the thick cratonic crust in the region. Alkaline lavas are predominant in the areas around Kilimanjaro where micro- rift grabens occur near Arusha and further south.

The entire length of the Kenya rift from Lake Turkana in the north to northern Tanzania has young volcanoes dominantly of silicic composition in its axis. The youthfulness of the volcanoes attests to active magmatism under the rift. Similarly, geothermal manifestations are more abundant and stronger within the rift and in many cases they are associated with the young Quaternary volcanoes (Figure 8).

Geothermal manifestations in the Kenya rift include fumaroles, hot springs, spouting springs, hot and altered grounds and solfatara (sulphur deposits). Fumaroles commonly occur on the mountains while

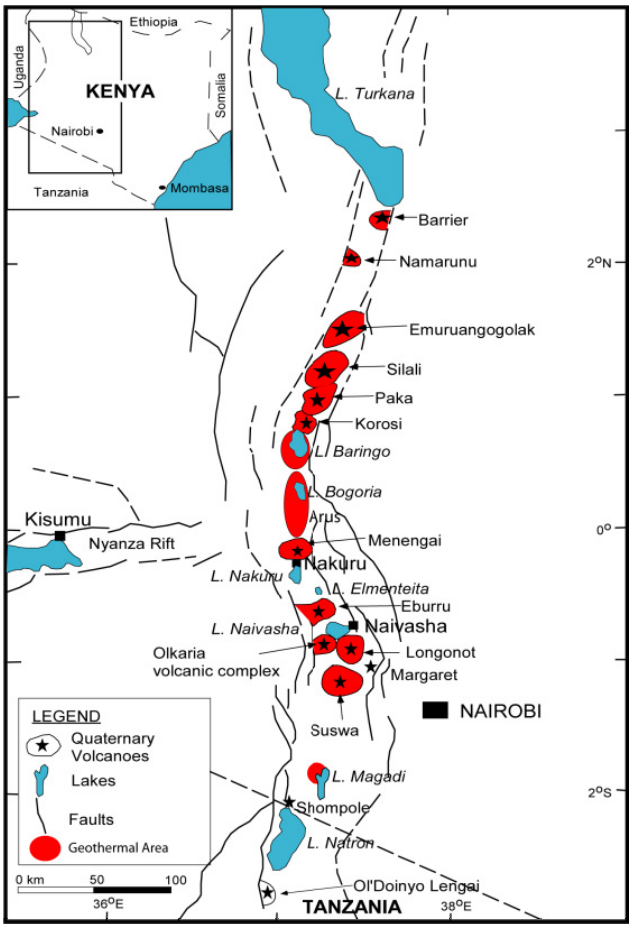

FIGURE 8: Map of the Kenya rift showing the locations of geothermal areas

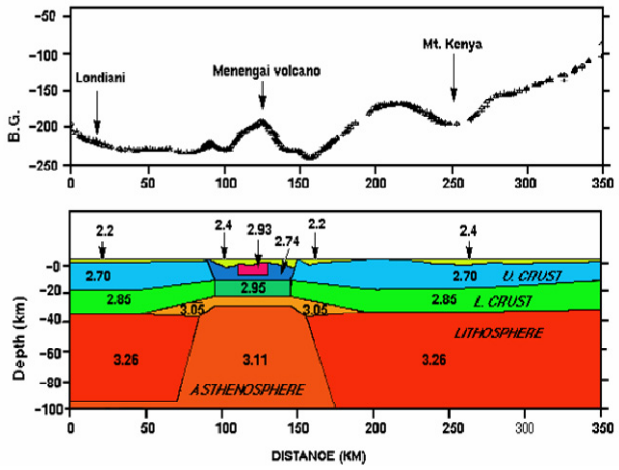

FIGURE 9: E-W Gravity model across Menengai Menengai volcano (After Simiyu, 1996)

hot springs and geysers are common on the lowlands. Sulphur deposits have been observed at several geothermal areas including Olkaria, Paka and Barrier volcanoes where it is indicative of the presence of a degassing magma body at depth. Extinct manifestations in the form of travertine deposits, silica veins and chloritized zones are common in the Lakes Baringo – Bogoria regions indicating long-lived geothermal activity in the rift.

Of these areas, Olkaria has been developed for electricity generation (209 MW_e) while a pilot plant is planned for Eburru (2.5 MW_e). Both the Olkaria and Eburru geothermal systems are volcano hosted resources and thus, the heat driving the systems are associated with hot intrusive bodies under the volcanic complexes. Gravity and seismic have imaged dense bodies under the volcanoes (Figure 9).

Detailed investigations recently concluded in Menengai, Korosi, Paka and Lakes Baringo and Bogoria geothermal prospects reveal the possible existence of geothermal systems. High temperatures systems possibly exist at Menengai, Paka and Korosi while low to medium temperatures resources could be associated with the systems around Lakes Baringo and Bogoria. Exploratory drilling is planned for Menengai prospect in 2011. It is estimated that over 7,000 MW_e can be generated from the geothermal systems in the Kenya rift. It is notable that in Kenya other than electricity production, geothermal water and carbon dioxide are used in an extensive complex of green houses for growing roses at Olkaria.

2.4 Western Branch

The western branch of the rift runs along the western side of Lake Victoria and along the edge of the East African plateau (Figure 10). The geography of the western branch is typically half grabens characterized by the high angle normal rift faults. The western branch of the rift is characterized by paucity of volcanism relative to the Kenyan and Ethiopian rifts. Whereas the volcanism and tectonic activity in eastern branch commenced about 30 million years ago in the eastern branch of the rift, volcanic activity in the western branch commenced about 12 Ma in the north near Lake Albert and about 7 Ma in the Tanganyika rift (Ebinger, 1989).

The northern zones of the rift comprise several basins that define the Albertine Graben near Lake Albert. The Lake Albert rift was initiated early Miocene and is dominated by thick sequence of sediments and is largely non magmatic except for the southern basins where volcanic products occur. The Albertine basin is also thought to have petroleum potential. The western branch is characterized by the abundance of potassic alkaline rocks that consists of carbonatites, ultrapotassic mafic rocks and potassic mafic-felsic lava. Volcanic activity is more intense in the Virunga volcanic field where Nyiragongo and Nyamuragira in the DR Congo are active with basaltic eruptives.

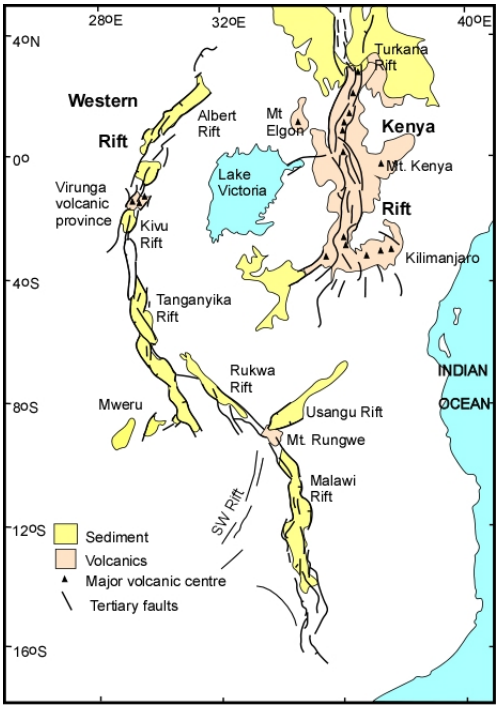

FIGURE 10: Map showing the structural relationship between the Eastern (Kenya) and Western branches of the EA Rift system

The Tanganyika–Rukwa-Malawi (TRM) segment of the western branch follows the fabric of the basement structures inherited from the Proterozoic period. The rift is characterized by normal boundary faults, which define half grabens, horsts and step faults with riftward tiled blocks and monoclinal structures. The Malawi segment extends south to the Urema and Lebombo grabens in southern Mozambique. Within the rifts occur lakes Tanganyika and Malawi, which are deep sedimentary basins. The rift segment is largely non-magmatic during the Quaternary times with volcanic fields being only at Rungwe between lakes Tanganyika and Rukwa. Late Cenozoic volcanism started about 9-7 Ma ago in the Rungwe volcanic province where the rift follows the NE-SW trend in line with the Kenya rift. The volcanic products include Quaternary mafic and felsic rocks.

Whereas there is paucity of recent volcanism in this segment of the rift, geothermal activity is still evident in many localities. The manifestations in the Tanganyika-Rukwa-Malawi Rift include hot springs and fumaroles at temperatures of up to 86°C which occur at Mbeya where they are closely associated with the Quaternary Rungwe volcanic field. The area is also characterized by high seismicity signifying that the area is still tectonically and magmatically active. Other hot springs occurring in Malawi, Zambia and Mozambique are fault controlled and are associated with the border faults. The hot springs are probably due to deep circulation of ground waters through the rift structures.

2.4.1 Tanzania

Geothermal exploration in Tanzania was carried out between 1976 and 1979 by SWECO, a Swedish consulting group, in collaboration with Virkir-Orkint (Iceland), with financial support from the Swedish International Development Authority (SIDA). Reconnaissance studies for surface exploration were carried out in the north (near Arusha, Lake Natron, Lake Manyara and Maji Moto) and in the south (Figure 11). Geothermal work in all locations in Tanzania is at the surface exploration stage.

Two potential target areas for geothermal exploration singled out so far are: (a) Arusha region near the Kenyan border in the North; and (b) Mbeya region between Lake Rukwa and Lake Nyasa in the southwest. Another potential area (Luhoi) was prospected during 1998-2002 by First Energy Company of Tanzania. It conducted important project definition and reconnaissance evaluation work. This area is located 160 km south of Dar es Salaam. The work conducted so far indicates the existence of a possible geothermal system with reservoir temperature greater than 200°C. In northern Tanzania, geothermal activity occurs mainly along the southern extension of the Kenya rift into L

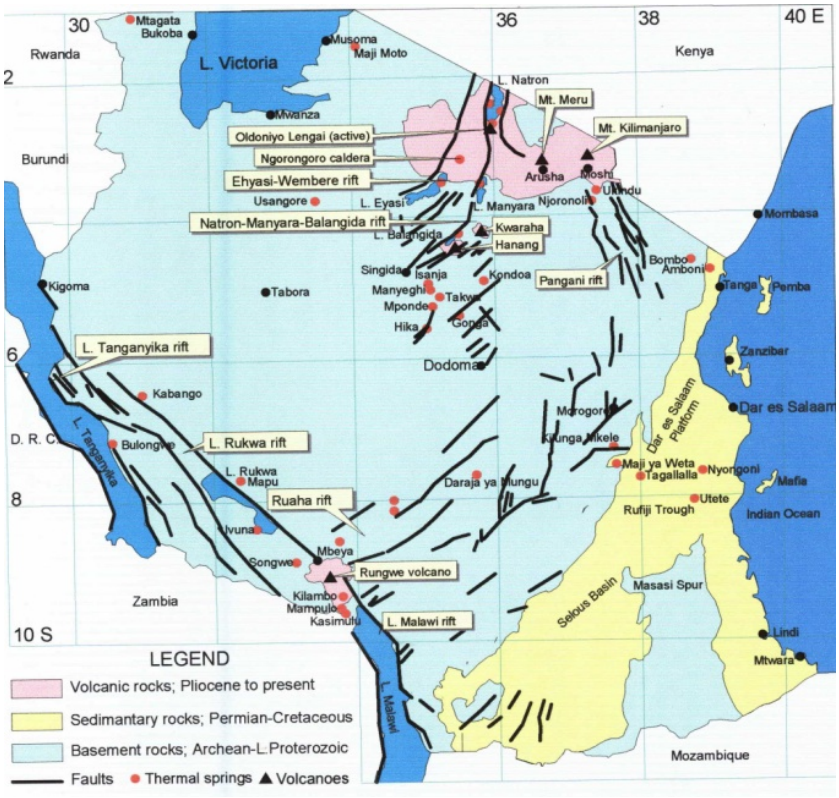

FIGURE 11: Map of Tanzania showing the location of geothermal areas

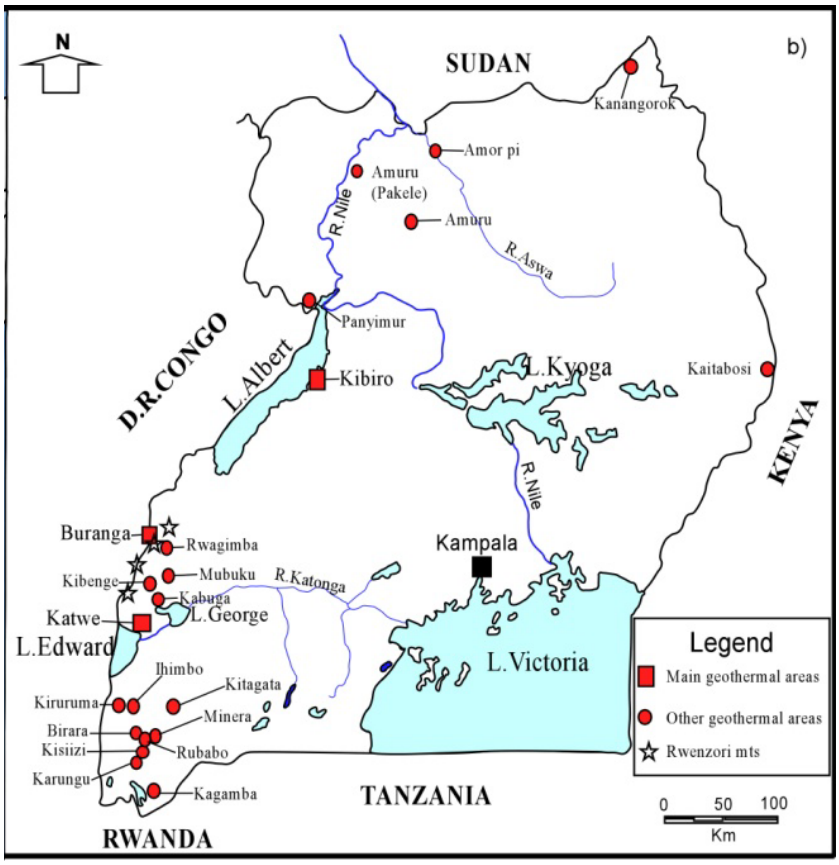

FIGURE 12: Map of Uganda showing the location of geothermal areas

Eyasi, Ngorongoro, L. Natron, Ol'Doinyo Lengai and Arusha areas. Other low temperature manifestations occur in central and south east Tanzania in Singida and Rufiji areas.

2.4.2 Uganda

Reconnaissance survey has been carried out on geothermal areas of Uganda since 1935 when the first documentation of hot springs was made (Bahati and Tuhumwire, 2002). The geothermal activity is restricted largely to the areas within the western rift valley. Geothermal manifestations in the form of fumaroles and hot springs occur along some of the border faults of the rift valley and within the volcanic fields. The main geothermal areas are Katwe-Kikorongo (Katwe), Buranga and Kibiro. They are all located in the Albertine graben that runs along the border of Uganda with the Democratic Republic of Congo (Figure 12). The Albertine graben is part of the western branch of the East African Rift System in Uganda, commonly known as the Western Rift Valley.

Fault controlled manifestations occur at Buranga at the foot of Ruwenzori massif as well as at Kibiro near Lake Albert. The manifestations at Buranga discharge at boiling point while travertine deposits have also been noted in several localities (Bahati, 2003).

Buranga has the most impressive surface geothermal manifestations

(hot springs) in the whole of the western branch of the East African Rift System with a wide areal coverage. They include hot springs, calcareous tufa and recent surveys have reported small-scale fumaroles at the Mumbuga spring area. The surface temperature is close to 98°C and the flow is approximately 10-15 l/s (Bahati, 2008). Geothermometry at Buranga prospect recorded temperatures of 120-150°C.

The geothermal surface manifestations in the Katwe prospect are hot springs located in the Lake Kitagata crater, and warm springs and travertine deposits that have built up tufas in the Lake Katwe crater, which is located 12 km southwest of Lake Kitagata. The maximum surface temperatures in the hot springs in Lake Kitagata crater is 70 C, while in Lake Katwe crater it is 32ºC (Bahati, 2008). At Katwe, fluid geothermometric temperatures of 160-200°C was estimated fom fluids.

The geothermal surface manifestations in the Kibiro geothermal prospect are mainly concentrated at Kibiro and Kachuru, west of the escarpment, on the shores of Lake Albert. They comprise hot and warm springs at Kibiro, and deposits of sulphur at Kachuru (Bahati, 2008). The hot springs at Kibiro are related to a secondary fault, oblique to the main Rift fault, and controlled by the intersection of the two (Bahati, 2008). The total flow measured from the hot springs is approximately 7 l/s and the maximum surface temperature is 86.4 C Kibiro prospect has a relatively simple geologic structure and waters indicative of subsurface temperatures of above 200°C.

Shallow Temperature gradient wells were drilled in Kibiro and Katwe prospects in 2008 to between 200 to 300m depth. Shallow geothermal reservoirs were not encountered by the wells. Uganda Government has planned to re evaluate the results of the temperature gradient and surface studies with a view to siting exploration wells in the most promising prospects.

2.4.3 Rwanda

Virunga geothermal prospect in Rwanda lies within the Virunga volcanic province within the western arm of the East African Rift System. The geography of the western branch is typically half graben characterized by high angle normal rift faults. The western branch of the rift in Rwanda is characterized by paucity of volcanism relative to the Kenyan and Ethiopian rifts.

Whereas the volcanism and tectonic activity in eastern branch commenced about 30 million years ago in the eastern branch of the rift, volcanic activity in the western branch commenced about 12 Ma in the north near Lake Albert and about 7 Ma in the Tanganyika rift (Ebinger, 1989).

The western branch is characterized by the abundance of potassic alkaline rocks that consists of K-basanites, leucitites, nephelinites, K-mugearites, K-benmoreiites and K-trachytes and other intermediate lavas in the Virunga area. Volcanic activity is also more intense in the Virunga volcanic field where Nyiragongo and Nyamuragira have erupted in the recent past. Quaternary volcanoes in the area include Karisimbi, Bisoke, Mikeno, Sabinyo, Gahinga and Muhabura in the northern part of the prospect (Figure 13). The western part of the prospect is dominated by mafic and intermediate lavas of Tertiary age that predominantly originated from Karisimbi and Nyiragongo volcanoes. These lavas flowed and partially filled the Lake Kivu and Kamatembe basins.

Paucity of volcanism in the western rift relative to the eastern branch is reflected in the low volumes of the eruptive products from the volcanoes in the region. It is therefore estimated that the thickness of the eruptives is less than 1-km in most areas in Virunga. The thin volcanic cover is underlain by Proterozoic metamorphic rocks.

In 2006, investigations were undertaken by the American company, Chevron, on the Mashyuza and Gisenyi prospects. Eighteen hydrothermal and mineralized springs were mapped and analysed analyzed. Geothermometers applied by BRGM and Chevron indicated reservoir temperatures of between 150°C – 210°C. From these investigations, three prospective sites (Karisimbi, Mashyuza and

Ntaresi) were identified for further detailed investigations with the first major focus on the areas south, southwest and southeast of the Karisimbi volcano within the Virunga volcanic province.

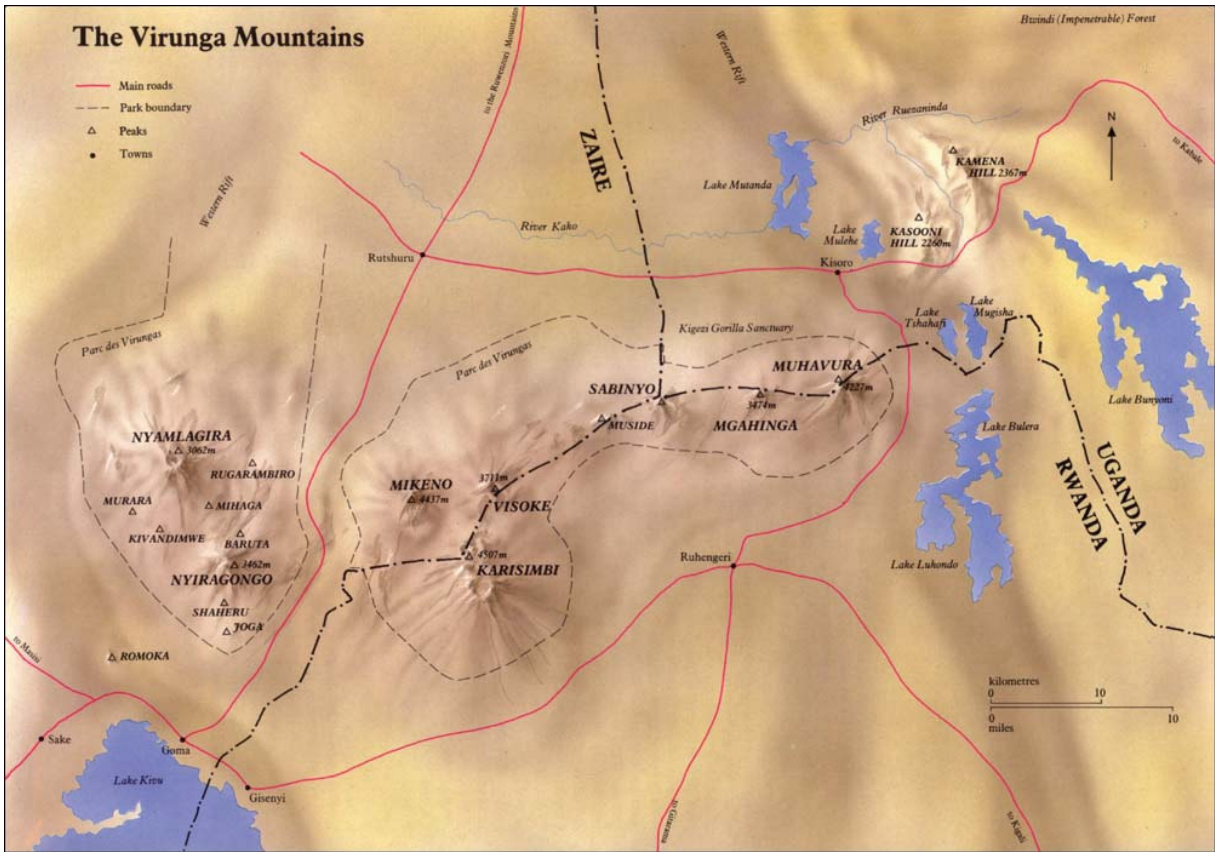

FIGURE 13: Map of Virunga Volcanic Complex prepared from satellite imagery (from http://volcano.oregonstate.edu/ volcanoes/volc_images /Africa/ karisimbi.html)

Geothermal manifestations are marked by warm and hot springs within the study area. The springs mainly occur within the basement formation and at the rift margin. The hottest spring with a temperature of about 75°C, is located at the NE shores of Lake Kivu and is classified as bicarbonate water. Studies by Newell et al. (2006) indicated that the reservoir temperature of the Gisenyi hot springs could be between 150°C and 210°C. The other hot spring (64°C) is at the vicinity of Lake Karago in the south-east of the study area. Several other warm and cold springs show evidence of gaseous emissions.

Preliminary MT results indicate a low resistivity anomaly, covering an area of about 50 km^2, at south of Karisimbi volcano (Fig. 14). The anomaly is interpreted to reflect the occurrence of a high temperature geothermal system on the southern slopes of Karisimbi volcano. The heat source is closely associated with the latest phases of trachytic magmatism at Karisimbi. The reservoir temperature is believed to be more than 210°C as discussed by Newell et al. (2006). It is also interpreted that a smaller, medium temperature geothermal systems exists along the NE trending accommodation zone west of Mukamira.

The Government of Rwanda intends to undertake further geological and geophysical measurements in Karisimbi with a view to undertaking exploratory drilling in 2011.

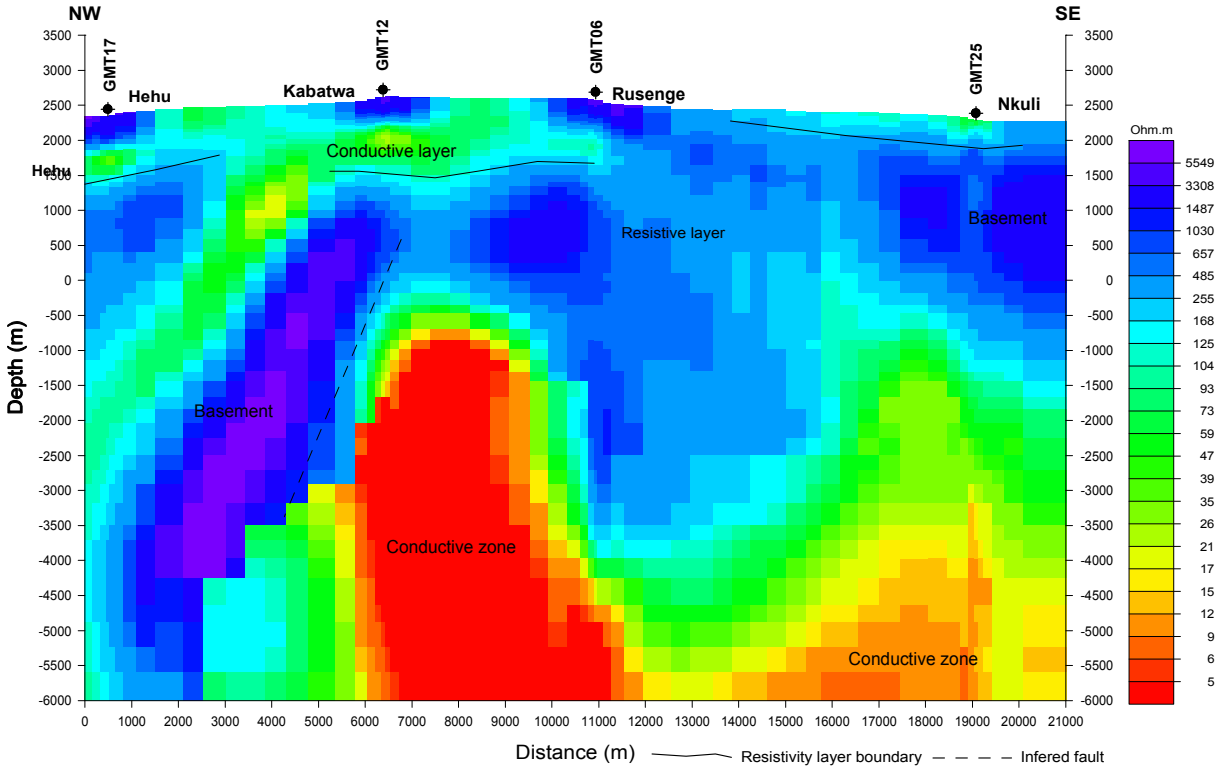

FIGURE 14: Geothermal model of Karisimbi volcano

2.4.3 DR Congo

Volcanism started 12 Ma at Virunga and has continued to the present time with Nyiragongo and Nyamulagira being some of the most active volcanoes in Africa. The Virunga complex covers a larger area in DR Congo than in Rwanda and Uganda as described in the earlier sections.

Geothermal manifestations occur in many areas within and near Virunga volcanic field. At Kiabukwa within the Upemba incipient rift, a 0.2MW$_e$ binary plant was installed in 1952. However, the plant stopped operation after only two years due to lack of proper maintenance.

2.5 South-western Branch

The south-western branch of the western rift follows geological structures along mobile belts from Lake Tanganyika into southern DR Congo and Zambia then south-westward into the Okavango rift system in northwest Botswana. The rift is non magmatic in its entire length, however, faults are evident along the entire length of the rift. However, rift structures in the Okavango have been identified only through geophysical techniques (Atekwana et al., 2004).

2.5.1 Zambia

Geothermal activity in Zambia and southern DR Congo occurs within the southwestern rift. The geothermal manifestations that include hot springs occur at Kapisya that discharge at 85^{o}C near Lake Tanganyika and also near Lake Mweru. Other springs occur at Chinyunyu (60^{o}C) near Lusaka (Figures 1 and 15).

FIGURE 15: Map of Zambia showing the location of Kapisya and Chinyunyu geothermal areas

The Italian government in 1987 funded a mini geothermal pilot power plant (200 KW) at Kapisya hot springs located at the shores of Lake Tanganyika. The plant was installed on the basis of limited exploration work, and it never became operational. ZESCO has signed an MOU with KenGen to assist in refurbishing and commissioning of the plant after being idle for 20 years. As part of the agreement, KenGen and ZESCO carried out detailed scientific investigations at Kapisya and Chinyunyu which revealed that the geothermal systems follow the fault plane model where the heat is due to deep circulation along the rift structures (Figure 13). It is estimated that each of the prospects can generate up to $2MW_e$ using binary technology (Omenda et al. 2007).

2.5.2 Malawi

Malawi is located in the western arm of the greater Eastern African system that extends from Afar triple junction to Beira in Mozambique. Much of Malawi is made up of igneous and metamorphic rocks of the Basement Complex of Precambrian age. Parts of the country are created by Karoo strata and by Cretaceous igneous and sedimentary rocks and alluvium occurs along Lake Malawi.

The Rumphi-Nkhata Bay area where Chiwondo, Chiweta, Mawira and Kasitu geothermal prospects are located is underlain by gneisses, schist and granites of the Malawi Basement Complex of Lower Palaeozoic age (Fig. 16). In the western and central portions, there are scattered outliers of Karoo sediments (Figure). Tertiary sediments occur on the lake shore plains and a general superficial cover of residual soils, particularly on the western plains.

Geothermal manifestations in Malawi occur in form of mainly warm springs, hot springs, *Fimbristylis exilis* "geothermal grass". Twenty one (21) major hot springs are reported in Malawi, in the Chitipa-Karonga area in the north to Chipudze in the southern region with the highest recorded temperature at 79.3°C. Discharge of gases is observed in some springs. They occur within the Malawian Rift Valley and the source of heat is the high heat fluxes from the crustal rocks due to conduction (Dulanya, 2006). Preliminary results from fluid geothermometry indicate that the reservoirs have temperatures of more than 160-250°C. A private company in Malawi has been concessioned the prospects and have signed an agreement with GDC to undertake detailed exploration in the prospects.

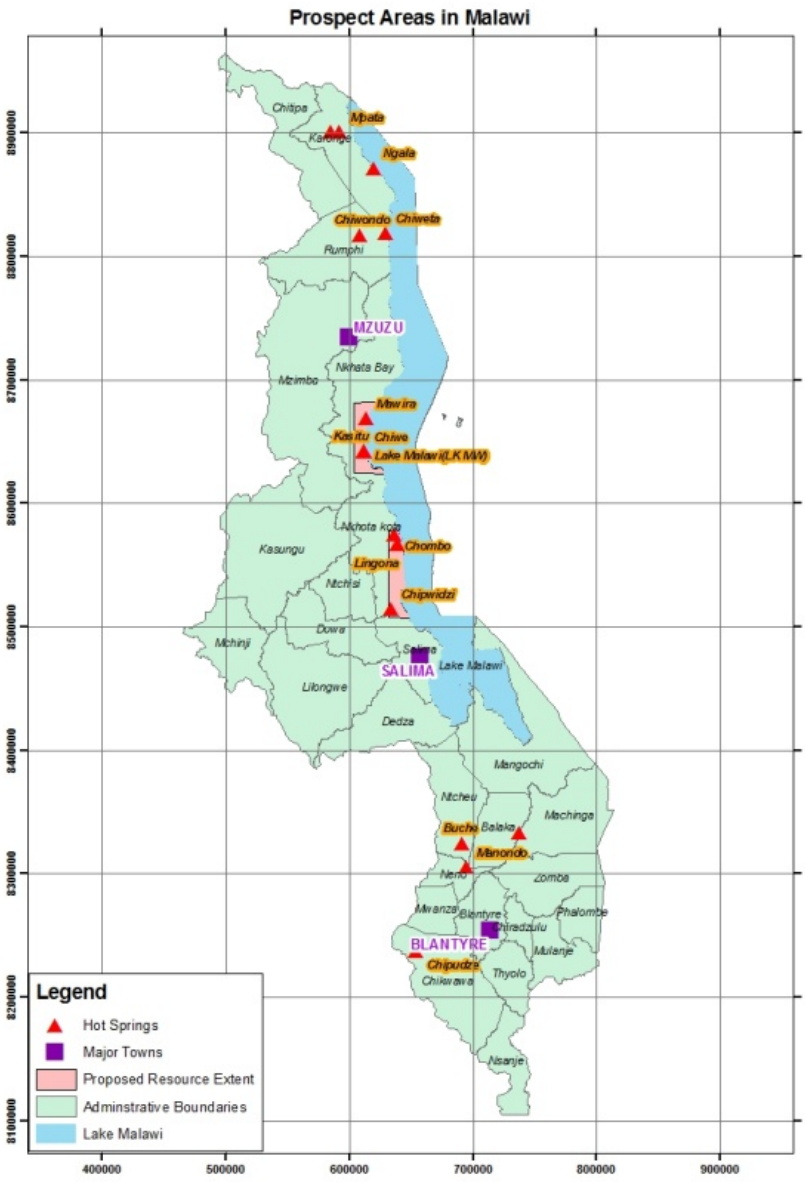

FIGURE 16: Map of Malawi geothermal prospects

2.6 Comoros

The island is formed by two coalescing shield volcanoes of La Grille in the north and Karthala which is an active volcanic centre in the south (Figure 17). The lavas from Karthala are predominantly alkali basalts and probably represent low pressure fractionation from an alkali basalt magma chamber. The Karthala volcano has been erupting episodically, with the most recent volcanic eruptions in 2005 and 2007. These signify that a heat source for the geothermal system exists under the volcano.

The alignment of the volcanic centers and the occurrence of fumaroles indicate that the tectonic setting is controlled by NNE and NW trending structures**.** The structural trends show four distinct fault trends in the northwest-southeast, northeast-southwest, north-south and nearly east-west. It is not very well established which faults channel hot hydrothermal fluids. Preliminary results from MT indicate that a geothermal system exists under Karthala at temperatures of more than 250°C from gas geothermometry. The prospect has since been licensed to a private developer.

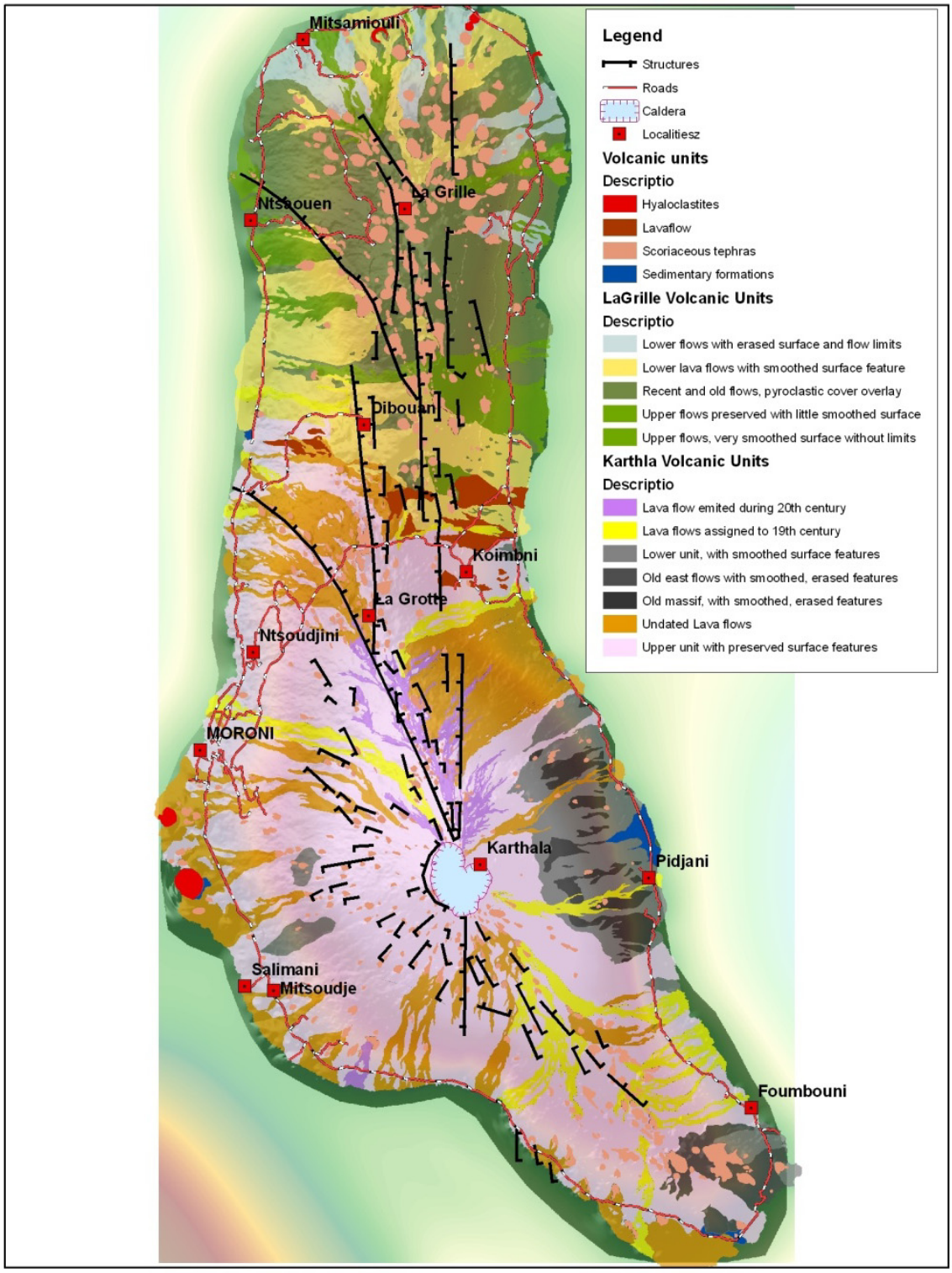
Mitsamiouli
La Grille
Ntsaouen
Dibouan
Koimbni
La Grotte
Ntsoudjini
MORONI
Karthala
Pidjani
Salimani
Mitsoudje
Foumbouni
Legend
Structures
Roads
Caldera
Localitiesz
Volcanic units
Descriptio
Hyaloclastites
Lavaflow
Scoriaceous tephras
Sedimentary formations
LaGrille Volcanic Units
Descriptio
Lower flows with erased surface and flow limits
Lower lava flows with smoothed surface feature
Recent and old flows, pyroclastic cover overlay
Upper flows preserved with little smoothed surface
Upper flows, very smoothed surface without limits
Karthla Volcanic Units
Descriptio
Lava flow emited during 20th century
Lava flows assigned to 19th century
Lower unit, with smoothed surface features
Old east flows with smoothed, erased features
Old massif, with smoothed, erased features
Undated Lava flows
Upper unit with preserved surface features

FIGURE 17: Map of Grand Comoro Island showing Karthala volcano

3. DISCUSSION

The geothermal activity in the East African rift system is closely tied to the occurrence of Quaternary volcanoes located within the axis of the rifts. The shield volcanoes are largely made of trachytes, rhyolites and associated pyroclastics. The presence of the silicic products attests to the occurrence of shallow magma (fossil) bodies that are considered the most important heat sources for the associated geothermal systems. This is premised on the fact that since the eruptives are products of mainly protracted fractional crystallization, massive heat must have been conductively transferred to the upper reservoirs. Further, heat would be transferred where assimilation of crust occurs to a significant level as has been demonstrated at Olkaria (Omenda, 2000, Macdonald et al 1987).

Evidence for the occurrence of shallow magma bodies has been demonstrated at Olkaria, Suswa, Longonot and Menengai geothermal areas in Kenya where seismic waves show "gaps" at shallow levels (e.g. Figures 18 and 19). The seismic "gaps" signify the presence of molten bodies at about 7-10 km of the surface. Therefore, shallow magma bodies are the single most important heat sources for the volcano hosted high temperature geothermal resources in the East African rift.

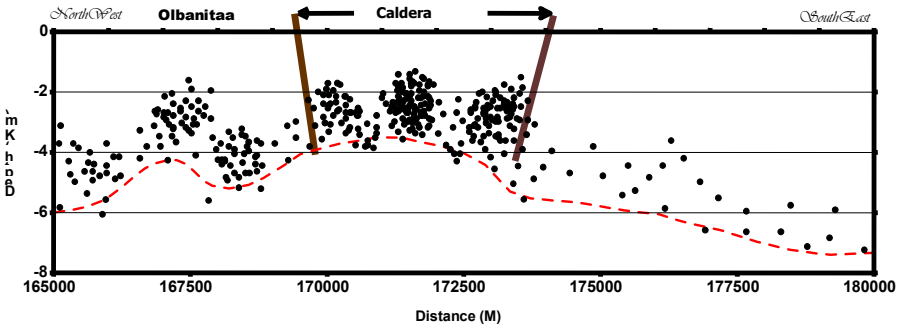

FIGURE 18: Seismic section across Menengai volcano (After Simiyu and Keller, 1997)

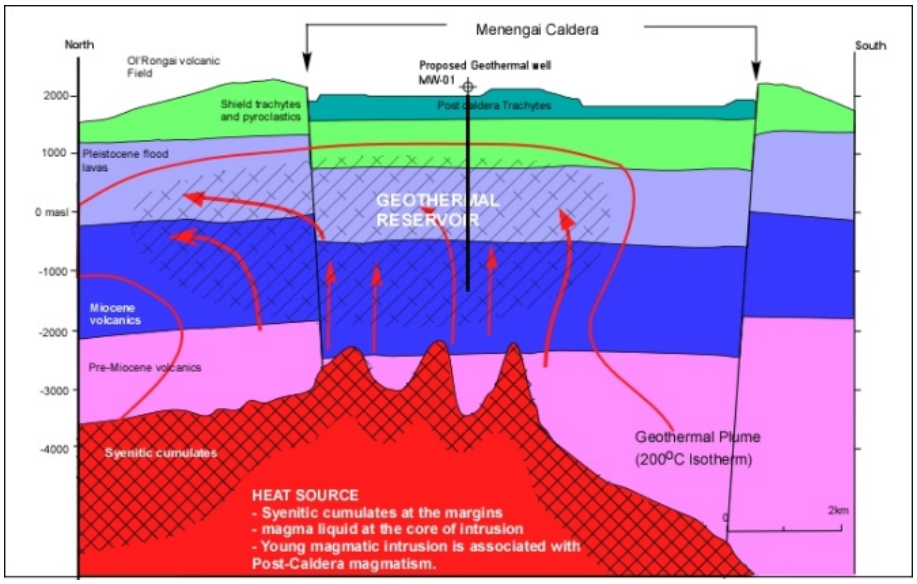

FIGURE 19: The W-E conceptualized geothermal model of Menengai geothermal prospect based on geology, gravity, seismics and MT data

Studies reveal that the crust under the EA rift ranges between 5km (Afar) and 35 km (Kenya) in thickness in the axis of the rift as compared to regions outside of the rift where the thickness is typically more than 45km (e.g. Prodehl et al., 1997; Simiyu and Keller, 1997; Figure 2). The thin crust and upwelling asthenosphere directly under the rift has resulted in generally high heat flow arising from high geothermal gradient within the entire length of the rift (Wheildon et al. 1994). Importance of asthenospheric heat would be more important in the Afar triple junction where the crust is less than 5km thick.

Deep circulation of ground waters through the master rift faults would mine heat from the rocks and upflow through the axial regions of the rift. Deep circulation has been indicated by the elevated boron contents of the fumaroles in some prospects in Kenya (Clarke et al., 1990, Dunkley et al, 1993, Geotermica Italiana, 1987). This deep groundwater circulation coupled with enhancement by young dike intrusions or plutons could explain some of the geothermal resources that occur outside of the quaternary volcanic centres in the rift and those in old terrains as in Kapisya and Chinyunyu in Zambia and western Uganda geothermal areas (Figure 20).

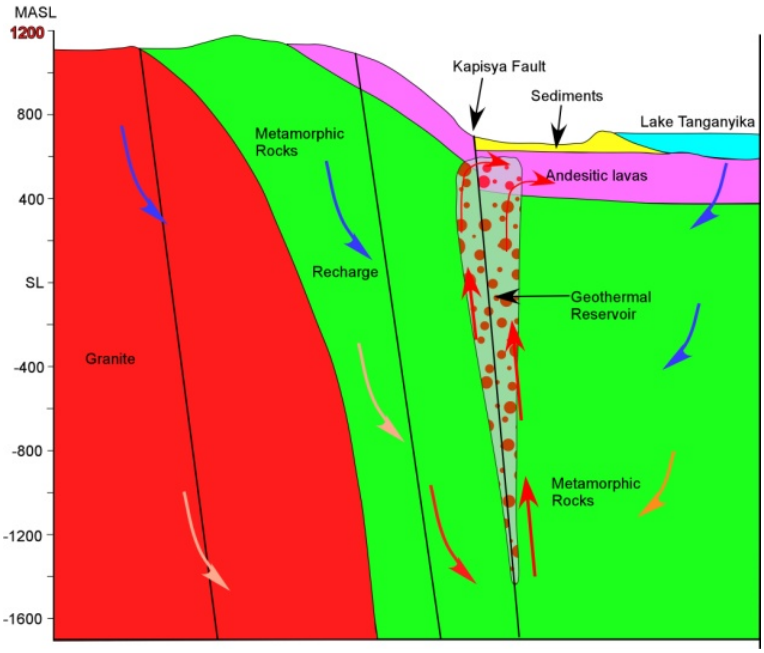

FIGURE 18: Geothermal model of the Kapisya geothermal system in Zambia

The main recharge for the geothermal systems in the East African rift, as has been determined by stable isotopes, originates largely from the flanks of the rifts. These regions are generally at higher elevations, wetter and are cut by faults parallel and oblique to the rift structural trends. Recharge would, therefore occur via the rift master faults and channelled to the rift axis by the oblique faults that cut through the rift faults (Abebe, 2000, Omenda, 1998, 1994). The high elevation ensures deep circulation through the master faults to the hot rocks. However, studies at Olkaria indicate that rift axial recharge is also important but mainly affects the upper parts of the geothermal reservoirs i.e. less than 1,000 m depth (Omenda and Karingithi, 2004).

Geothermal reservoirs in the Ethiopian and Kenya Rifts are mainly hosted within the faulted and layered Plio-Pleistocene rift volcanics. The permeability in such systems is due to fractures/faults and lithologic contacts. It is also thought that fractures caused by domal intrusion could also be important in enhancing permeability in some fields (Woldegiorgis et al. 2003). However, for the case of the geothermal resources in western branch of the rift, the reservoirs are largely hosted within the Precambrian metamorphic rocks where secondary permeability associated with faults and fractures are important.

The capping formation for the volcano hosted geothermal systems in the rifts is often a combination of lava flows and pyroclastics and shales and other sediments form capping formations in the Afar region where the volcanic products overlie sedimentary formations (Mohamed, 2003).

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GEOTHERMAL TRAINING PROGRAMME

GEOTHERMAL SYSTEMS IN GLOBAL PERSPECTIVE

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ABSTRACT

Geothermal systems are classified in three main categories: (a) volcanic geothermal systems with the heat source being hot intrusions or magma chambers in the crust, (b) convective systems with deep water circulation in tectonically active areas preferably of high geothermal gradient, (c) sedimentary systems with permeable layers at great depth (2-5 km), including geo-pressured systems often found in conjunction with oil resources.

Some 50 years ago geothermal fields were divided into high- and low- temperature fields or areas. This division was based on (arbitrarily) inferred temperature at 1 km depth. It was soon realized that most of the former are related to volcanism (>160 - >300 °C) (category a) and that the latter draw heat from the general heat flow of the crust (just above ambient to >160°C) (categories b and c). The temperature range given here is based on values measured in boreholes in Iceland or silica and gas geothermometry. Other subdivisions have been proposed by adding an intermediate group between the two main ones. There are several types in each of the two main groups. They are described below, emphasizing the geological control.

A fourth category constitutes the so called hot dry rock. The thermal resource there is abnormally hot, usually intrusive rock of very low permeability and not harnessable so far.

1. INTRODUCTION

The following definitions are used here:

- *Geothermal field* is a geographical definition, usually indicating an area of geothermal activity at the earth's surface. In cases without surface activity this term may be used to indicate the area at the surface corresponding to the geothermal reservoir below.
- *Geothermal system* refers to all parts of the hydrological system involved, including the recharge zone, all subsurface parts and the outflow of the system.
- *Geothermal reservoir* indicates the hot and permeable part of a geothermal system that may be directly exploited. For spontaneous discharge to be possible geothermal reservoirs must also be pressurized, either artesian or through boiling.

Geothermal systems and reservoirs are classified on the basis of different aspects, such as reservoir temperature or enthalpy, physical state, their nature and geological setting. Table 1 summarizes classifications based on the first three aspects.

TABLE 1: Classifications of geothermal systems on the basis of temperature, enthalpy and physical state (Bodvarsson, 1964; Axelsson and Gunnlaugsson, 2000)

<table>
<tr><td rowspan="2">***Low-temperature*** (LT) systems with reservoir temperature at 1 km depth below 150°C. Often characterized by hot or boiling springs.</td><td rowspan="2">***Low-enthalpy*** geothermal systems with reservoir fluid enthalpies less than 800 kJ/kg, corresponding to temperatures less than about 190ºC.</td><td>***Liquid-dominated*** geothermal reservoirs with the water temperature at, or below, the boiling point at the prevailing pressure and the water phase controls the pressure in the reservoir. Some steam may be present.</td></tr>
<tr><td>***Two-phase*** geothermal reservoirs where steam and water co-exist and the temperature and pressure follow the boiling point curve.</td></tr>
<tr><td>***Medium-temperature*** (MT) systems with reservoir temperature at 1 km depth between 150- 200°C.</td><td></td><td></td></tr>
<tr><td>***High-temperature*** (HT) systems with reservoir temperature at 1 km depth above 200°C. Characterized by fumaroles, steam vents, mud pools and highly altered ground.</td><td>***High-enthalpy*** geothermal systems with reservoir fluid enthalpies greater than 800 kJ/kg.</td><td>***Vapour-dominated*** geothermal systems where temperature is at, or above, the boiling point at the prevailing pressure and the steam phase controls the pressure in the reservoir. Some liquid water may be present.</td></tr>
</table>

The three main types of geothermal systems which concern us here, based on their nature and geological settings are:

A. *Volcanic geothermal systems* are in one way or another associated with volcanic activity. The heat sources for such systems are hot intrusions or magma (Figure 1). They are most often situated inside, or close to, volcanic complexes at or near plate boundaries or hot spots. Permeable fractures and fault zones but also permeable strata such as sediments, ignimbrites or lavas control the flow of water in volcanic geothermal systems.

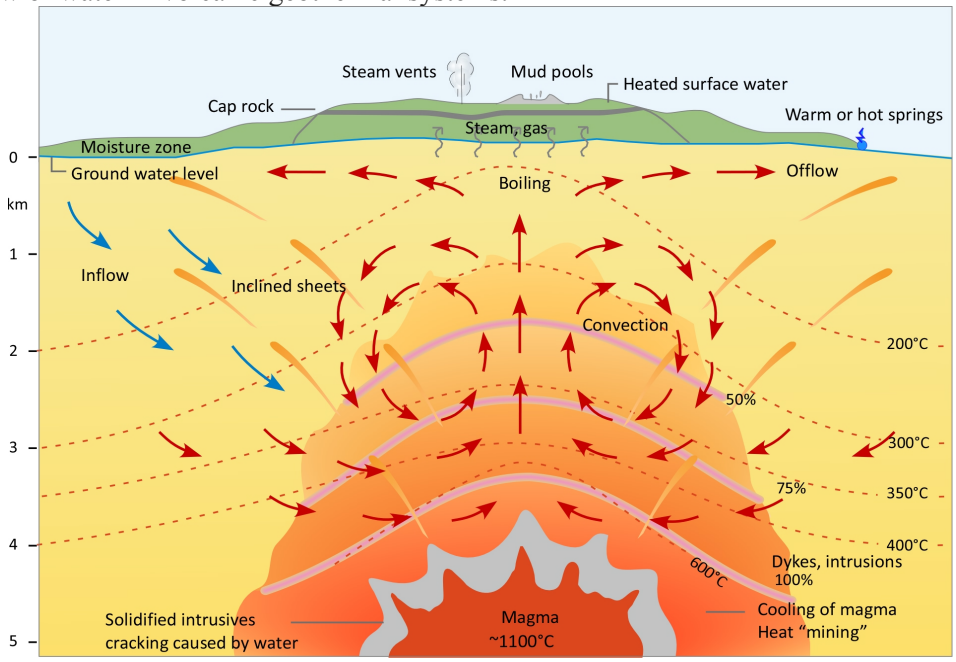

FIGURE 1: Simplified model of a high-temperature geothermal system

B. In *convective systems* the heat source is the hot crust at depth in tectonically active areas, preferably with above average heat-flow (Figure 2). Here the geothermal water has circulated to considerable depth (> 1 km), through mostly vertical fractures, to extract the heat from the rocks.

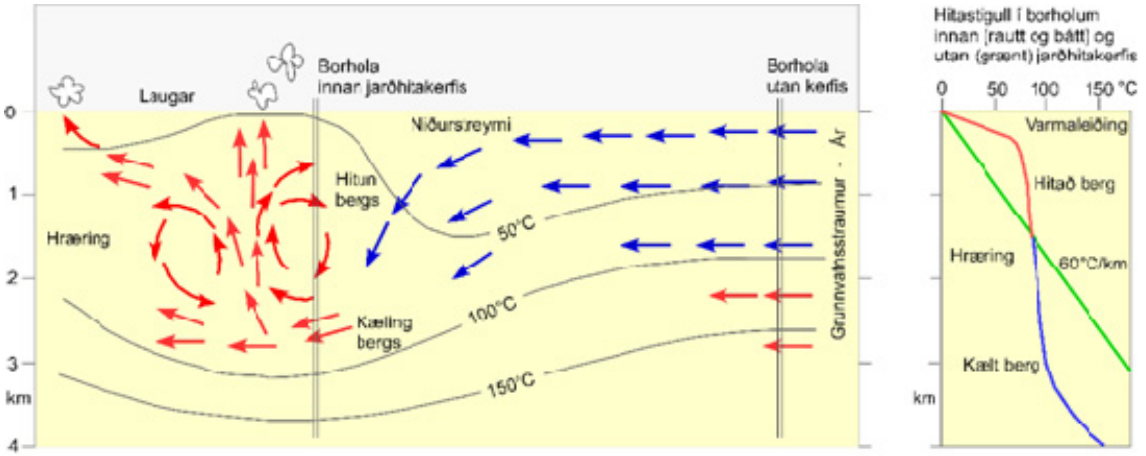

FIGURE 2: Main features of a low temperature fracture controlled geothermal system. Note bulging down of isotherms at depth. The section is drawn along a leaky fissure

C. Sedimentary geothermal systems are probably the most common type worldwide. We are concerned here with such that occur in the sediment filled parts of the East African Rift. They occur mainly in the Western Rift, but locally also in the Eastern Rift where volcanism was sparse.

2. LOW-TEMPERATURE GEOTHERMAL FIELDS

They depend on the regional geothermal gradient, permeability (primary or secondary) of the rock and depth of circulation if such exists.

2.1 Sedimentary basins

Sedimentary basins are layered sequences of permeable (limestone, sandstone) and impermeable strata (shale or mudstone) which alternate. Water is interstitial water, commonly a brine, formerly thought to be of connate origin. Temperature is variable, depending on depth of permeable rocks in basin. Examples are the Molasse basin north of the Alps, the Paris basin, the Hungarian basin and the sediment filled Rhine graben. Those are of different origin and the heat flow differs widely. Natural circulation of the geothermal fluid is minimal. Reinjection is needed to dispose of water after passing through heat exchangers. Doublette boreholes are needed.

2.2 Fracture or fault controlled convection systems

In fracture or fault controlled convection systems circulation may be deep or shallow. Heat is transported by water from base area of system to its upper zone (Figure 3). Recharge comes from precipitation. Water is generally low in TDS but may be high in sediment filled rift zones. Temperature is anywhere from little above ambient to 160°C depending on depth of circulation. Highly fractured ground hosts relatively cold systems. High discharge (such as over 100 l/s) of >100°C water from a single fault would suggest transient character. Temperature inversion commonly occurs in open, fracture controlled geothermal systems as hot water flows or spreads laterally in the near-surface part of the fractures.

Fracture permeability is dependent on the type of rock. Fracture-friendly rocks are hard and „non-yielding“ such as igneous rock (basalt, andesite and intrusive rock) and also granite, gneiss, quartzite, also limestone and indurate sandstone. Fracture-unfriendly are claystone, shale and the like which

react to rock stress by plastic deformation. Only a part of the fractures contribute to an effective fracture volume. Release joints and tension fractures have a relatively high effective fracture volume contrary to compression fractures. Water contained in matrix pores and microfractures is inaccessible in case of low-temperature geothermal exploitation. Pressure decrease due to drawdown in high-temperature reservoirs may cause pore and microfracture water to boil and hence contribute to the available part of the resource.

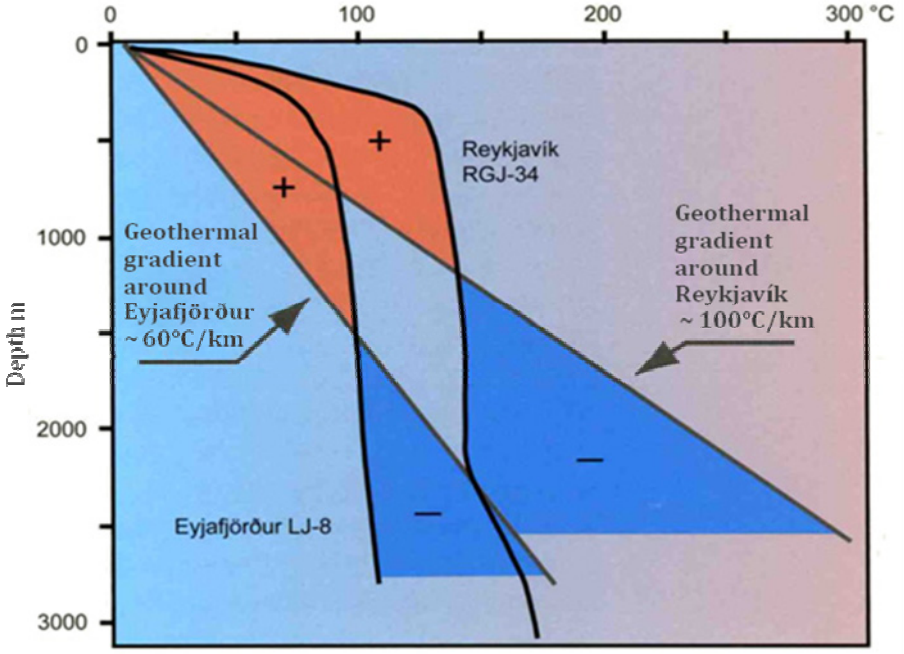

FIGURE 3: Reykjavík and Akureyri, Iceland. Bold lines show actual reservoir temperature, 130-140°C for Reykjavík, 90-95°C for Akureyri. Water transports heat from deep levels, thus cooling the rock (heat mining). Shallower levels consequently are heated up

2.3 Off-flow from volcanic (high-temperature) geothermal systems

Systems with off-flow from volcanic (high-temperature) geothermal areas include groundwater heated by contact with hot ground and/or mixing of deep reservoir water with local ground water. Commonly inversion of temperature is found and in some cases deposits of travertine occur, especially where the geothermal system is on the decline. Aquifers may be either stratabound or fracture related. Temperature decreases with distance from the source region.

2.4 Distal part of fissure swarms via their laterally injected dyke swarms

Fissure swarms of volcanic origin pass downwards into dyke swarms. These may extend into the marginal blocks of the rift zones and create secondary permeability within them and thus pathways for deep circulation (Figure 4). The proximal parts of fissure swarms are located within the rift zones (actually defining them), usually in areas of thick young volcanics of high permeability and sediments. Surface manifestations may be scarce under such conditions, but at deep levels (below 1-1.5 km) conditions for a geothermal system may exist.

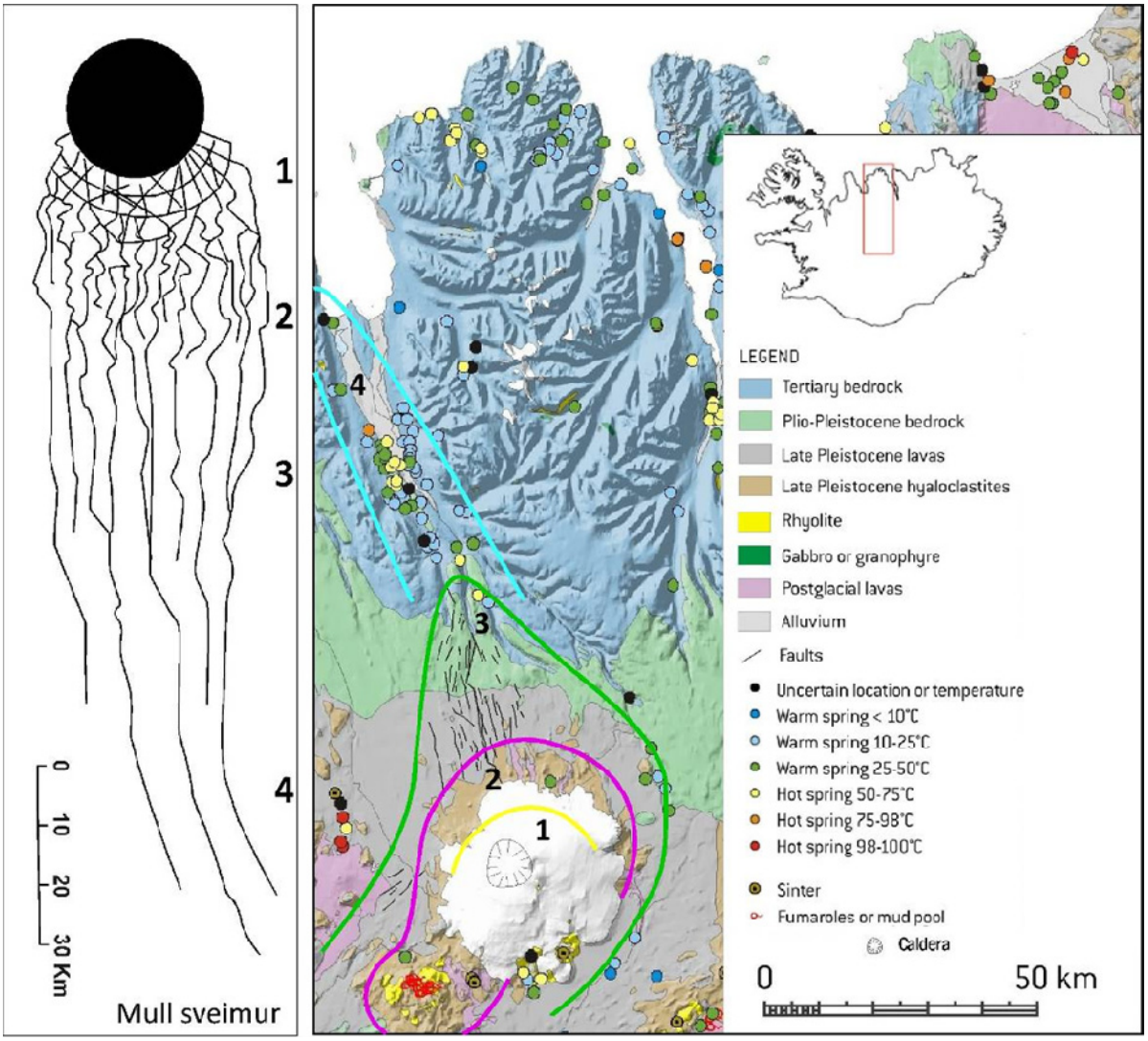

FIGURE 4: Hofsjökull volcanic system in central Iceland. A fissure system extends about 100 km to the NNW from the central volcano covered by glacier (area 1). Densely spaced fissure eruptions occur along the next 20 km (area 2), followed by faults, fissures and stray fissure eruptions for another 30 km (area 3). The distal part of the system (area 4) has narrow, cm-scale fissures, clearly visible in the south of the area, but only occasionally further away. Linearly arranged hot springs indicate fissure control. It is thought that dykes expelled from a magmatic source under Hofsjökull underlie the whole system, becoming deeper with distance and branching towards its end. These would cause fracturing and create permeability in an otherwise rather impermeable rock sequence, made of 7-8 Ma basalts

2.5 Active fracture zones on land

Active fracture zones on land host some of the richest low-temperature geothermal resources (China, South Iceland). In China enormous deformation zones have developed due to collision of India with Asia. The collision gives rise to lateral escape of China to the east along left lateral transcurrent fault systems (Figure 5). In Iceland the South Iceland Seismic Zone (left lateral) connects between offset spreading centres. It hosts about 30% of Iceland´s low-temperature geothermal resources.

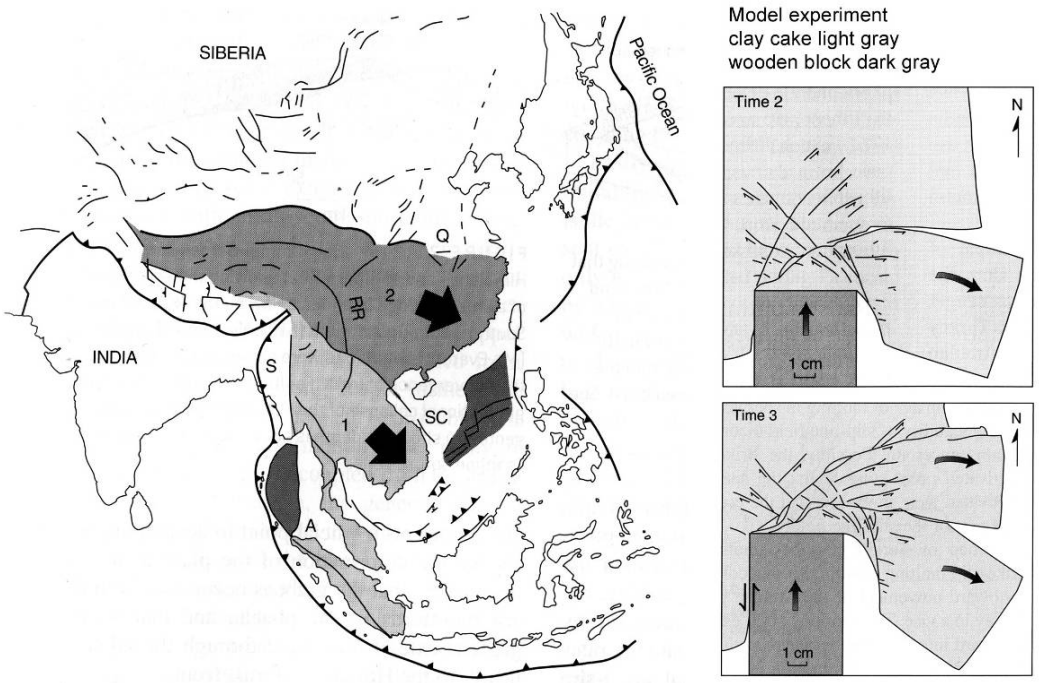

FIGURE 5: Tectonics of SE-Asia showing eastward escape of large crustal blocks along major strike-slip faults as suggested by Tapponier et al. (1982).
Model for comparison (from Pluijm and Marshak 2004)

3. HIGH-TEMPERATURE GEOTHERMAL FIELDS

These are volcanic/intrusive in origin as regards occurrence and heat source. Most magma does not reach the surface but heats large regions of underground rock. Most are of Pliocene to Recent age. Young batholiths at relatively shallow depth may still be hot. Rapid removal of uppermost overburden helps to get near to them. Aquifers are stratabound and or fracture controlled. The high-temperature geothermal fields occur in different types of geological settings, most of them at plate boundaries, but also in continental rifts and in hot spot environments.

High temperature systems are water dominaned, but often vapour dominated to a varying depth if the reservoir is boiling. Induced steam zone may develop as production proceeds. This is a corollary of drawdown in a boiling reservoir as characterize most of the high-temperature geothermal fields. A shallow steam zone may thus thicken by hundreds of metres if recharge is limited. The volume increase from water to steam under conditions such as prevail at shallow depth may be on the order of 50 fold with a corresponding pressure increase. This is manifest by increased steam flow from hot ground and fumaroles and locally also by new steam emanations from fissures.

3.1 Rift zone regime

3.1.1 Mid ocean ridges

Mid ocean ridges (black smokers) (Figure 6). Asal system in Djibouti may be the closest supramarine analogue. At slow spreading ridges as in Djibouti, high viscosity asthenosphere causes rift valley to form with uplifted, outwardly dipping flanks. Salton Sea California is also on a ridge crest. It is all buried in sediment except latest Pleistocene volcanics (Salton Buttes).

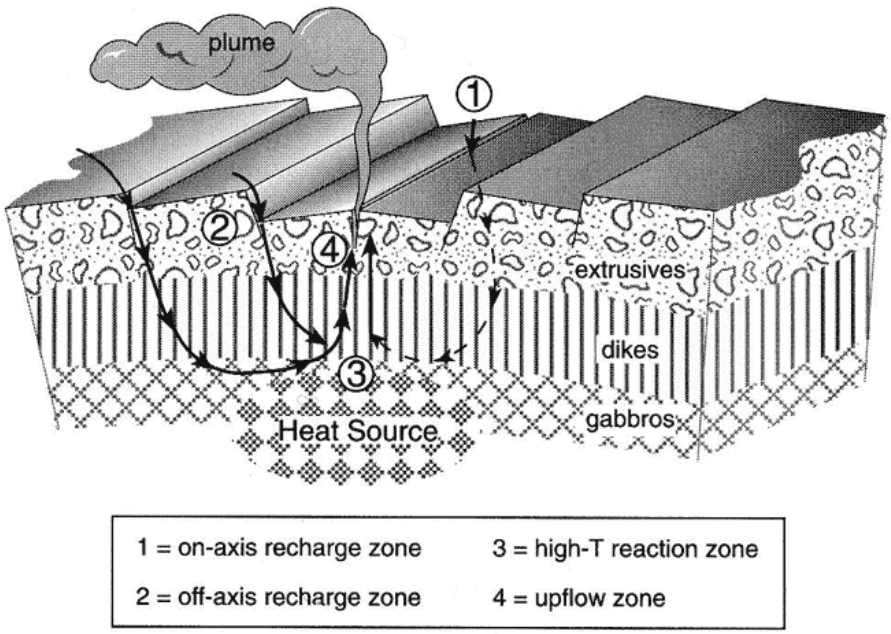

FIGURE 6: Schematic illustration of a black smoker geothermal system. Depth of circulation is about 3-4 km (Encyclopedia of Volcanoes 2000)

3.1.2 Supramarine oceanic rifts: Iceland

Geothermal systems develop at high volcanic foci of elongated volcanic systems (Figure 7). In Iceland the flanks of the rift dip inwardly, i.e. towards the rift zone, as at fast spreading oceanic ridges (such as the East Pacific Rise). This is because the asthenosphere is hot and of low viscosity due to an exceptionally powerful mantle plume.

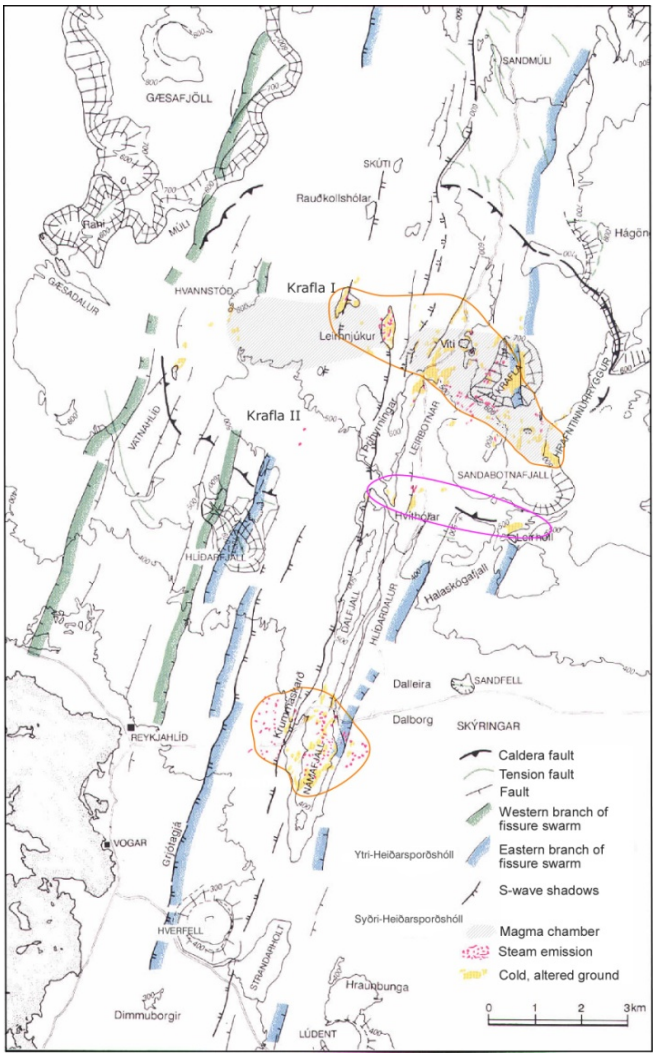

FIGURE 7: Central part of Krafla volcanic system showing caldera and fissure swarms which transect it. The Krafla caldera hosts a geothermal system. It has a magma chamber (S-wave shadow) at 3-7 km depth. A second geothermal area at Námafjall on the fissure swarm 7 km south of Krafla is located where basaltic fissure eruptions concentrate

3.1.3 Continental rifts: East Africa

The East African rift valleys, exclusive of the Western Rift, are at the apex of two domal uplifts. They developed from stray stratovolcanoes (Mt Elgon, Mt. Kenya, both at the southern dome) to a later stage rift valley with elongated volcanic systems on their floor. Again the geothermal systems formed in areas of high volcanic production, i.e. in the core areas of the volcanoes (Figure 8).

FIGURE 8: Apex of Kenya Rift domal uplift with two volcanically active rift branches and a third E-W branch dying. Stratovolcanoes are shown. Fissure swarms have partly been identified as integral parts of volcanic systems (Mwawongo 2004)

3.2 Hotspot volcanism

Hotspot volcanism is off, sometimes far off, from spreading centres. Two examples will be mentioned, one located on oceanic crust the other on continental crust. Both have a hot spot track associated with them.

3.2.1 Hawaii and Yellowstone

At Hawaii basaltic shield volcanoes begin on top of the plume, and are carried off from plume centre as the plate passes over it. Geothermal systems may develop at apex of the volcanoes and also on their associated fissure swarms in areas of local concentrations of dykes.

Yellowstone is the world's largest rhyolite volcano. A huge, composite caldera has formed in it following major ignimbrite eruptions. Rhyolite volcanoes generally contain little other than rhyolite the low density rock type possibly forming a volcanic shadow zone, impenetrable for heavier less silicic melts. Near-surface intrusions (magma chambers) of rhyolite magma at depth below these long-lived centres promote very active geothermal systems.

3.2.2 Flank zone volcanism

Flank zone volcanism (Iceland, Azores) (Figure 9) is characterized by alkalic rocks of deeper mantle origin than tholeiites. Both in Iceland and the Azores they occur where fracture zones intersect hot spots. Shear stresses prevail.

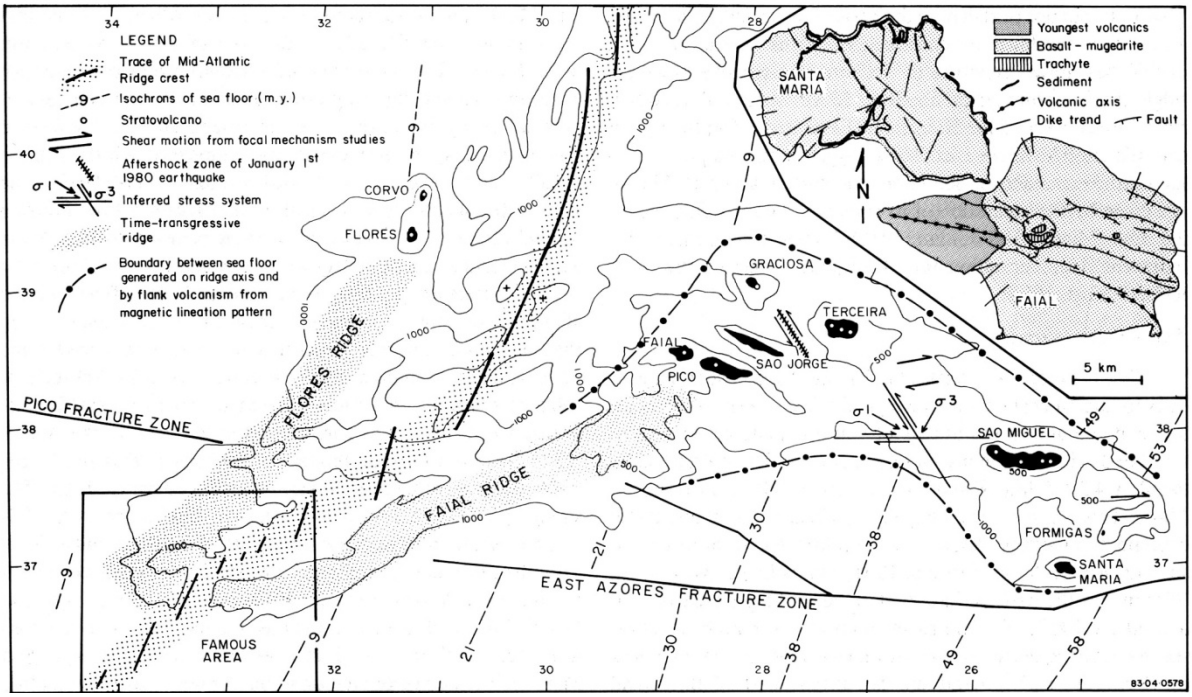

FIGURE 9: High-temperature geothermal fields on the Azores Islands are related to flank zone volcanism north of the Azores Fracture Zones. They developed in caldera regions of stratovolcanoes. Prominent fissure swarms formed in the direction of max. stress

3.3 Compressional regime

Compressional regimes are the most common type of high temperature geothermal fields, globally. The tectonic environment is variable (Circum Pacific Belt) (paragraphs 3.3.1-3.3.3 are from Cas and Wright, 1995). The main types are mentioned below.

3.3.1 Young island arc volcanoes and inter arc basins

Young island arc volcanoes and inter arc basins are such as occur in the Marianas, Tonga-Kermadec, the Philippines, the West Indies (Figure 10). Successive splitting and ocean-ward migration of the frontal half of the arc block creates new inter-arc basins. Rock types mainly comprise basalt and basaltic andesite (island arc tholeiite).

3.3.2 Micro-continental arc volcanoes

Micro-continental arc volcanoes, such as in Japan, New Zealand and Indonesia. Arc-block is wider and is thicker than in young island arcs. Magmatic products are much more silicic. Calc-alkaline rocks

are prominent. Taupo Volcanic Zone in New Zealand has erupted mainly rhyolite during the last 1 m. y. There are 15 harnessable geothermal fields with reservoir temperatures >220°C. Average size is 12 km², at 15 km intervals. The entire volcanic field is comparable in size to Yellowstone also as regards geothermal output. Corresponding magma "intrusion" rates are 1.9 m³/s (Yellowstone) and 1.7 m³/s (Taupo) (Taupo and Yellowstone comparison from Wilson et al. 1984).

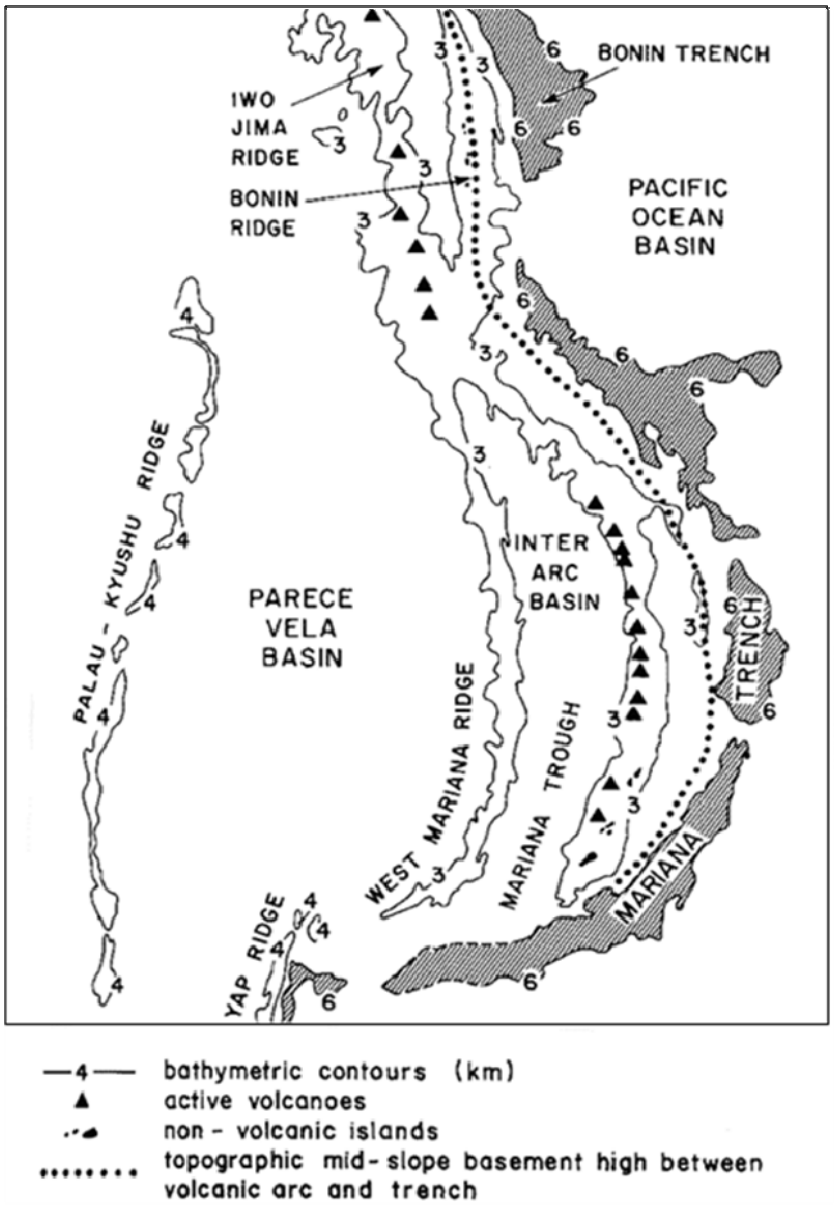

FIGURE 10: Example of a young island arc with inter arc basin and remnant arc. Evolved arcs develop from repeated splitting, crustal thickening and remelting. At the same time the volcanic products evolve from basaltic to acid (Cas and Wright, 1995)

3.3.3 Continental margin arc volcanism

Continental margin arc volcanism, such as in the Andes and the Cascades. Magmatism takes place upon a wholly sialic, continental type crust, up to 60 km thick. The proportion of silicic volcanics is high, including huge ignimbrites (Ilopango, El Salvador: 40 km³ erupted in 260 A.D.) and contemporaneous granitoids (batholiths).

3.3.4 Batholith driven geothermal systems

Batholith (pluton) driven geothermal systems, such as in Larderello in Italy and Geysers in California, are both vapour dominated. The geothermal resource is primarily found in the enveloping sedimentary strata.

4. HOT DRY ROCK GEOTHERMAL RESOURCE

This may be regarded as a downward extension of the batholith driven systems, the thermal resource being the cooling pluton itself. Permeability of the rock is low but fracture permeability is induced by injecting cold water under high pressure into the hot part of it. Natural fractures and fissures are supposed to widen and new flow paths be created. Shortcuts tend to occur between injection and production boreholes. The heat source is vast, but so far of limited use. Ambitious hot dry rock projects are still under way.

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GEOTHERMAL ENERGY UTILISATION

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ABSTRACT

Geothermal energy is energy derived from the natural heat of the earth. The earth's temperature varies widely, and geothermal energy is usable for a wide range of temperatures from room temperature to well over 300°C. Geothermal energy can be used for both electricity generation and direct uses depending on the temperature and chemistry of the resources. High to medium resources are used for electricity generation while medium to low resources is mainly used for direct application. For efficient utilization of resources, geothermal energy is being utilized for combined heat and power. Since geothermal energy is renewable, indigenous and environmentally benign, and can be used as base load, it will be the future source of energy in Kenya and most of the Eastern African countries especially those that are located within the east Africa Rift. This will reduce uses of fossil fuels and hence address global warming.

1. INTRODUCTION

The word geothermal was developed from two Greek words, "*geo*", meaning earth, and "*thermos*", meaning heat since it is power extracted from heat stored in the earth. This geothermal energy originates from radioactive decay of minerals, and from solar energy absorbed at the surface. Geothermal heat, is estimated to be about 5,500^{o}C at the Earth's core – about as hot as the surface of the sun. This energy been used for bathing since paleolithic times and for space heating since ancient roman times. Nowadays, it is used commercially for both generating electricity and direct uses. Worldwide, geothermal plants have the capacity to generate about 10 GW of electricity as of 2007, and in practice supply 0.3% of global electricity demand. An additional 28 GW of direct geothermal heating capacity is installed for district heating, space heating, hot spas, industrial processes, desalination and agricultural applications (Fridleifsson et. al, 2008).

Because of the near limitless ability of the earth to produce magma, and the continuous transfer of heat between subsurface rock and water, geothermal energy is considered a renewable resource. It is also cost effective, reliable, sustainable, and environmentally friendly, but has historically been limited to areas near tectonic plate boundaries. Recent technological advances have dramatically expanded the range and size of viable resources, especially for applications such as home heating, opening a potential for widespread exploitation. Geothermal power has the potential to help mitigate global warming if widely deployed in place of fossil fuels.

2. UTILISATION OF GEOTHERMAL ENERGY

The heat from the earth's own molten core is conducted to the adjacent rocks and eventually is transferred to underground water reservoirs through convection. Steam/water heated by the geothermal heat can be tapped using different technologies and channelled to various uses. Utilisation of geothermal fluid depends heavily on its thermodynamic characteristics and chemistry. These factors are determined by the geothermal system from which the fluid originated. Geothermal fluids have been classified differently by different authors. Some authors have done so by using temperatures while others have used enthalpy (Dickson and Fanelli, 2004). The most common criterion is that based on enthalpy. The resources are divided into low, medium and high enthalpy resources. Table 1 shows the classifications proposed by a number of authors.

TABLE 1: Classification of geothermal resources (°C) (Dickson and Fanelli, 2004)

	(a)	(b)	(c)	(d)	(e)
Low enthalpy resources	< 90	<125	<100	≤150	≤190
Intermediate enthalpy resources	90-150	125-225	100-200	-	-
High enthalpy resources	>150	>225	>200	>150	>190

a) Muffler and Cataldi (1978); b) Hochstein (1990); c) Benderitter and Cormy (1990);
d) Nicholson (1993); e) Axelsson and Gunnlaugsson (2000).

Depending on the enthalpy, geothermal fluid can be utilised either for electricity generation or direct applications. Electricity generation is the most important form of utilization of high-temperature geothermal resources while low to medium resources are better suited for non-electric (direct) application (Table 2).

TABLE 2: Basic technology commonly used for geothermal energy

Reservoir temperature	**Reservoir fluid**	**Common use**	**Technology commonly chosen**
High temperature, >220°C	Water or Steam	Power generation Direct use	Flash steam; Combined (flash and binary) cycle Direct fluid use; Heat exchangers; Heat pumps
Intermediate temperature, 100-220°C	Water	Power generation Direct use	Binary cycle Direct fluid use; Heat exchangers; Heat pumps
Low temperature, 30-150°C	Water	Direct use	Direct fluid use; Heat exchangers; Heat pumps

2.1 Electricity generation from geothermal energy

Geothermal energy is utilized in many parts of the world especially those that are located on plate boundaries or tectonically active regions (Figure 1). In 2005, 24 countries generated a total of 56,786 GW-hours (GWh) (204 PJ) of electricity from geothermal power, accounting for 0.3% of worldwide electricity consumption. Output is growing by 3% annually because of a growing number of plants and improvements in their capacity factors, development of binary cycle power plants and improvements in drilling and extraction technology. Since geothermal power does not rely on variable sources of energy, unlike, for example, wind or solar, its capacity factor can be quite large – up to 96% has been demonstrated (Lund, 2003). The global average was 73% in 2005 (Fridleifsson et. al, 2008).

Geothermal power plants are categorized in three main ways depending on the fluid temperature, pressures and chemistry.

- Condensing power plants (dry steam, single or double flash systems).
- Back-pressure turbines (release to the atmosphere).
- Binary plants (for lower temperature or separated brine).

Figure a global view of geothermal energy

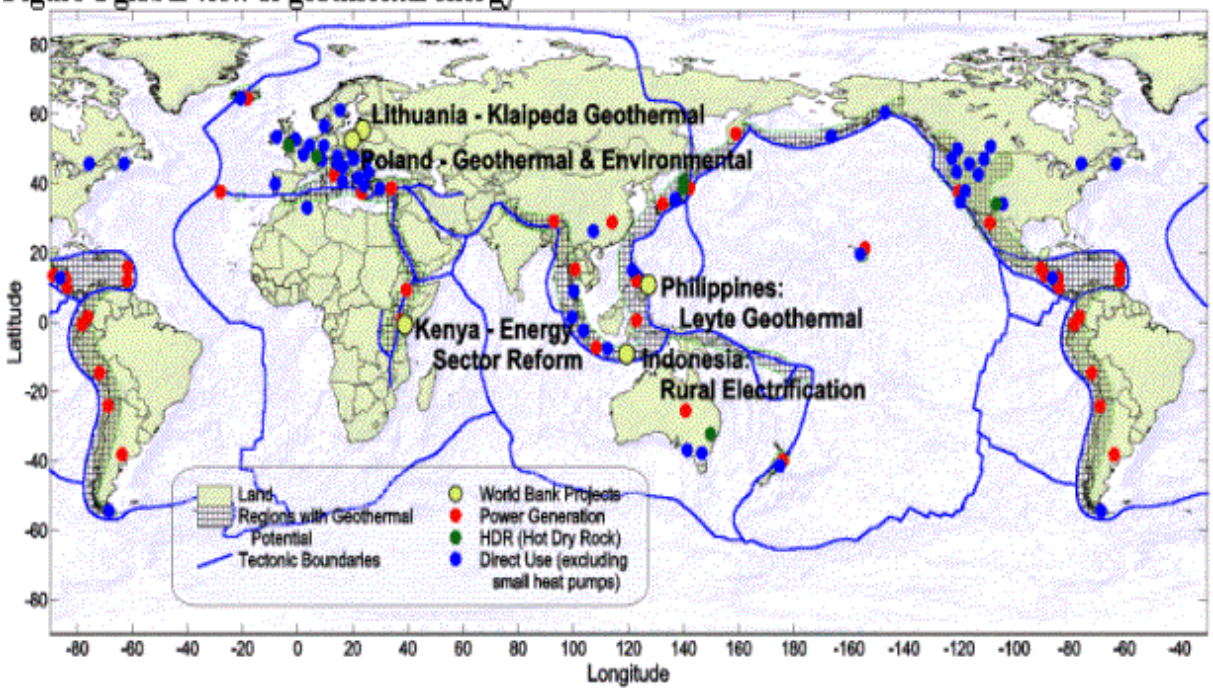

FIGURE 1: Plate and tectonic boundaries

The largest group of geothermal power plants in the world is located at The Geysers, field in California, United States As of 2004, five countries (El Salvador, Kenya, the Philippines, Iceland, and Costa Rica) generate more than 15% of their electricity from geothermal sources (WEA, 2004).
Geothermal resources vary in temperature from 30-350 ^{o}C, and can either be dry steam, two-phase (a mixture of steam and water) or just liquid water. In order to extract geothermal heat from the earth, water is the transfer medium. Naturally occurring groundwater is available for this task in most places but more recently technologies are being developed to even extract the energy from hot dry rock resources. The temperature of the resource is a major determinant of the type of technologies required to extract the heat and the uses to which it can be put. Table 3 lists the basic technologies normally utilised according to resource temperature and fluid availability.

High temperature geothermal reservoirs containing water and/or steam can provide steam to directly drive steam turbines and electrical generation plant. More recently developed binary power plant technologies enables more of the heat from the resource to be utilised for power generation. A combination of conventional flash and binary cycle technology is becoming increasingly popular.

High temperature resources commonly produce either steam, or a mixture of steam and water from the production wells. The steam and water is separated in a pressure vessel (Separator), with the steam piped to the power station where it drives one or more steam turbines to produce electric power. The separated geothermal water (brine) is either utilised in a binary cycle type plant to produce more power, or is disposed of back into the reservoir through deep (injection) wells. The following is a brief description of each of the technologies most commonly used to utilise high temperature resources for power generation.

TABLE 3: Geothermal energy applications

Electricity production	Wells drilled into a geothermal reservoir produce hot water and steam from depths of up to 3 km. The geothermal energy is converted at a power plant into electric energy, or electricity. Hot water and steam are the carriers of the geothermal energy.
Direct use	Applications that use hot water from geothermal resources directly. Examples: space heating, crop & lumber drying, food preparation, aquaculture, industrial processes, etc. Historical traces back to ancient Roman times, e.g. for baths
Geothermal heat pumps	Taking advantage of relatively constant earth temperature as the source and sink of heat both for heating and cooling, as well as hot water provision. One of the most efficient heating and cooling systems available.
Hot Dry Rock Deep geothermal/EGS (both not commercial yet)	Extracts heat by creating a subsurface fracture system to which water can be added through injection wells. Water is heated by contact with the rock and returns to the surface through production wells. Energy is then converted at a power plant into electric energy as in a hydrothermal geothermal system.

2.1.1 Dry steam power plants

Power plants using dry steam systems were the first type of geothermal power generation plants built. They use steam from the geothermal reservoir as it comes from wells and route it directly through turbine/generator units to produce electricity (Figure 2). An example of a dry steam generation operation is at the Geysers in northern California.

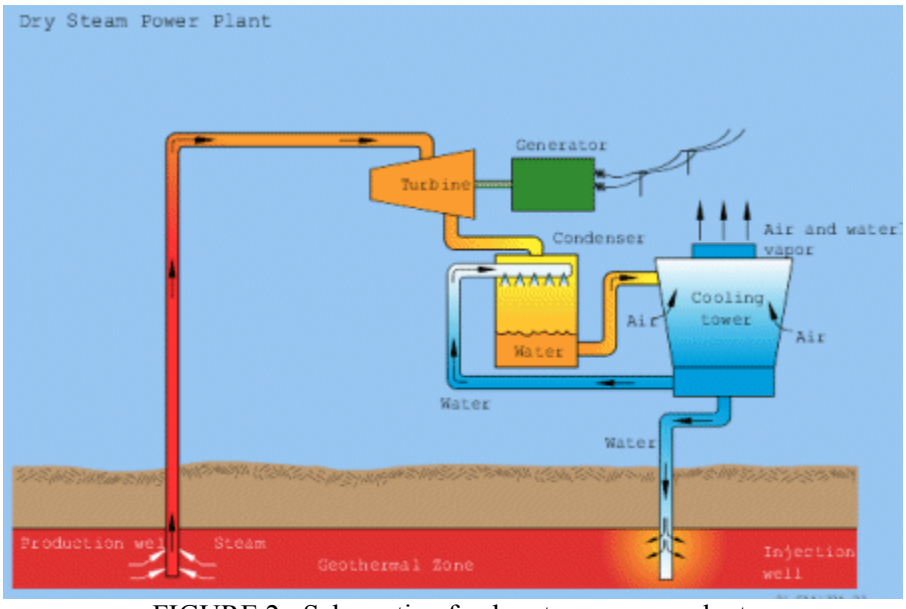

FIGURE 2: Schematic of a dry steam power plant.

2.1.2 Flash Steam Power Plant

Flash steam power plants (Figure 3) are the most common type of geothermal power plant. The steam, once it has been separated from the water, is piped to the powerhouse where it is used to drive the

steam turbine. The steam is condensed after leaving the turbine, creating a partial vacuum and thereby maximizing the power generated by the turbine-generator. The steam is usually condensed either in a direct contact condenser, or a heat exchanger type condenser. In a direct contact condenser the cooling water from the cooling tower is sprayed onto and mixes with the steam. The condensed steam then forms part of the cooling water circuit, and a substantial portion is subsequently evaporated and is dispersed into the atmosphere through the cooling tower. Excess cooling water called blow down is often disposed of in shallow injection wells. As an alternative to direct contact condensers shell and tube type condensers are sometimes used, as is shown in the schematic below. In this type of plant, the condensed steam does not come into contact with the cooling water, and is disposed of in injection wells.

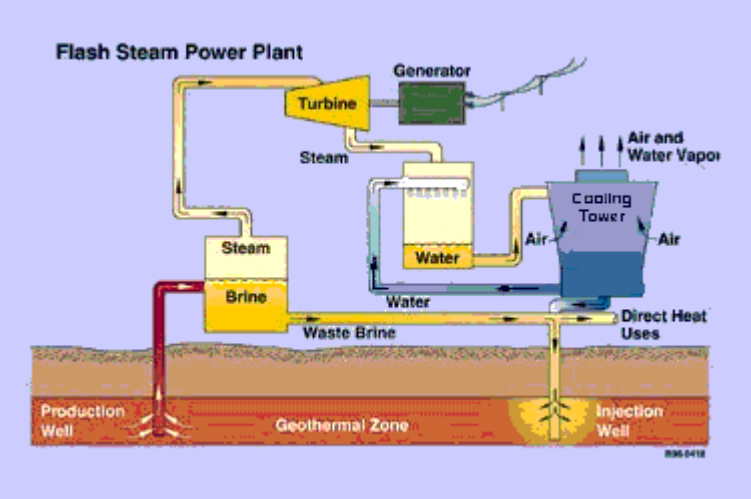

FIGURE 3: Schematic of a single flash steam power plant

Typically, flash condensing geothermal power plants vary in size from 5 MW to over 100 MW. Depending on the steam characteristics, gas content, pressures, and power plant design, between 6000 kg and 9000 kg of steam each hour is required to produce each MW of electrical power. Small power plants (less than 10 MW) are often called well head units as they only require the steam of one well and are located adjacent to the well on the drilling pad in order to reduce pipeline costs. Often such well head units do not have a condenser, and are called backpressure units. They are very cheap and simple to install, but are inefficient (typically 10-20 tonne per hour of steam for every MW of electricity) and can have higher environmental impacts.

2.1.3 Binary cycle power plants

In reservoirs where temperatures are typically less than 220° C. but greater than 100° C binary cycle plants are often utilised. The illustra-tion (Figure 4) shows the principal elements of this type of plant. The reservoir fluid (either steam or water or both) is passed through a heat exchanger which heats a secondary working fluid (organic) which has a boiling point lower than 100° C. This is typically an organic fluid such as Isopentane, which is vaporised and is used to drive the turbine. The organic fluid is then condensed in a similar manner to the steam in the flash power plant described above, except that a shell and tube type condenser rather than direct contact is used. The fluid in a binary plant is recycled back to the heat exchanger and forms a closed loop. The cooled reservoir fluid is again re-injected back into the reservoir.

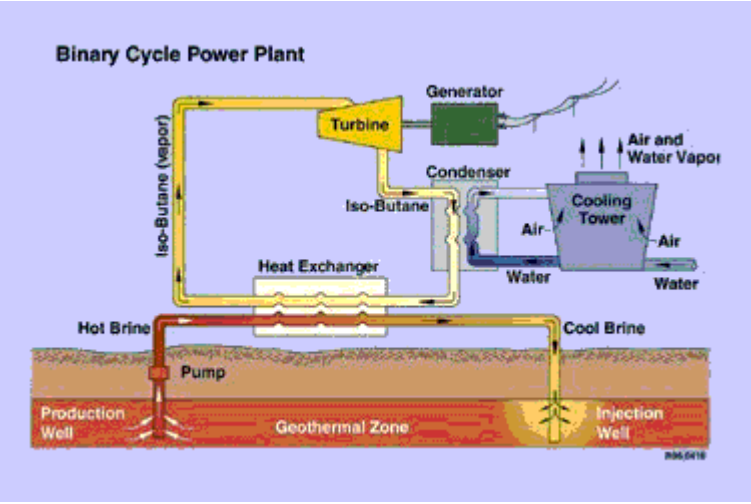

FIGURE 4: Power schematic of a binary cycle power plant

Binary cycle type plants are usually between 7 and 12 % efficient, depending on the temperature of the primary (geothermal) fluid. Binary Cycle plants typically vary in size from 500 kW to 10 MW.

2.2 Direct uses of geothermal energy

Low to medium temperature geothermal resources are utilized for direct uses or binary power plants. The oldest and probably best known direct application of geothermal energy is in baths and spas, used during Roman times. Other more coordinated and commercial uses include district heating systems, like those found in Iceland which are the largest geothermal district heating system in the world, tourist centres thermal baths in Hungary and China; geothermally heated fish farms and food processing and de-hydration in Greece and the USA. Furthermore the possibility to utilize ground source (geothermal) heat pumps to either heat homes directly or through energy efficiency programs, allowing savings in energy costs, has vast possibilities for individual or industrial use.

All those "direct use" applications utilize geothermal energy produced from lower temperature water of less than 150 degrees centigrade that is being derived from wells of 100-3,000 m deep wells. Today, around 73 nations utilize geothermal energy directly, with an overall energy output of 75.9 TWh thermal per year. The number of nations using geothermal heat is growing constantly.

Approximately 70 countries made direct use of a total of 270 PJ of geothermal heating in 2004. More than half of this energy is being used for space heating, and another third for heated pools. The remainder supported industrial and agricultural applications. The global installed capacity was 28 GW, but capacity factors tend to be low (30% on average) since heat is mostly needed in the winter. The above figures are dominated by 88 PJ of space heating extracted by an estimated 1.3 million geothermal heat pumps with a total capacity of 15 GW. Heat pumps for are the fastest-growing means of exploiting geothermal energy, with a global annual growth rate of 30% in energy production. Most of these new heat pumps are being installed for home heating.

Direct heating in all its forms is far more efficient than electricity generation and places less demanding temperature requirements on the heat resource. Heat may come from co-generation with a geothermal electrical plant or from smaller wells or heat exchangers buried in shallow ground. As a result, geothermal heating is economical over a much greater geographical range than geothermal electricity. Where natural hot springs are available, the heated water can be piped directly into radiators. If the ground is hot but dry, earth tubes or downhole heat exchangers can collect the heat. But even in areas where the ground is colder than room temperature, heat can still be extracted with a geothermal heat pump more cost-effectively and cleanly than it can be produced by conventional furnaces (Lund, 2006). These devices draw on much shallower and colder resources than traditional geothermal techniques, and they frequently combine a variety of other functions, including air conditioning, seasonal energy storage, solar energy collection, and electric heating. Geothermal heat pumps can be used for space heating essentially anywhere in the world.

Geothermal heat supports many applications. In Iceland, Reykjavík and Akureyri pipe hot water from geothermal plants below pavement to melt snow. District heating applications use networks of piped hot water to heat buildings in whole communities. Geothermal desalination has been demonstrated. Some of the main direct uses of geothermal energy are

3. GEOTHERMAL UTILISATION IN KENYA

Kenya has a large potential of geothermal energy estimated to be more than 4000 MWe (Omenda and Simiyu, 2006). Currently, only 4% of this energy is being exploited primarily for electricity generation. Other non electric applications have not been given the necessary attention (Mwangi, 2005). There are a number of potential applications of geothermal energy in Kenya.

3.1 Electricity generation using geothermal energy in Kenya

Geothermal energy exploitation in Kenya has been primarily for electricity generation and it constitutes 14 % of the country's electricity. KenGen generates 89% of this energy from two power plants. Olkaria I power plant was commissioned in the year 1981 while Olkaria II (Figure 5) was commissioned in the year 2003. Drilling for a third power plant, Olkaria IV is currently ongoing for a 140 MWe power plant expected in late 2013.

FIGURE 5: Olkaria II power station, commissioned in 2003

OrPower 4, Inc., an independent power producer (IPP) is currently generating 48 MWe, 12 MWe from an Ormat binary plant commissioned in the year 2000 and 36 MWe is from a single flash plant commissioned in 2009. Oserian Development Company, (Oserian), constructed a 1.8 MWe binary plant Ormat OEC in 2004 and 2MWe from a back pressure turbine commissioned in 2007. Both of these plant use wells leased from KenGen (Knight et al, 2005).

3.2 Direct utilisation of geothermal energy in Kenya

The only commercial application of geothermal energy for other uses other than electricity generation (direct applications) in Kenya is at Oserian. Since 2003, the firm has been utilising energy from a geothermal well OW-101 leased from KenGen for greenhouse heating. The system started by heating 3 hectares and has been expanded to 50 hectares (Figure 6). Other minor geothermal direct uses are at Lake Borogia hotel, where a naturally occurring geothermal hot spring is being used to warm a swimming pool and at Eburru geothermal resource where the local community use geothermal energy for drying pyrethrum products (Mwangi and Mburu, 2005). Other potential applications include greenhouse farming, domestic hot water supply, animal husbandly, and balneology among others.

Hot springs have been used to heat spas in tourist hotels for example in Borogia hotel which is located near the Bogoria prospect The Local community at Eburru geothermal resource condenses the steam from fumarole and uses the water for domestic purposes. They also use geothermally heated driers to dry their pyrethrum products. A study carried out in 2008 (Mburu, 2008) revealed potential market for direct utilisation in Kenya.

3.2.1 Some of the main potential uses

Although there is great potential for both electricity generation and direct utilisation of geothermal energy in the Kenyan Rift valley, geothermal energy has been primarily used for electricity generation (Mwangi, 2005). Investigations into possible applications of this energy for direct applications show potential in swimming pools and spas, balneology, drying of farm produce and greenhouse heating (Lagat, 2006). This study will also investigate the feasibility of some of these applications together with domestic hot water supply and space cooling.

FIGURE 6: Geothermal greenhouse heating at Oserian Company, Kenya.

3.2.2 Greenhouse heating

Heating of greenhouses using geothermal energy has been practiced in many countries in the world with encouraging economic, social and environmental benefits (Lund and Freeston, 2000).

In 2003, Oserian Development Company Ltd, a private firm growing rose flowers for export leased a geothermal well from KenGen for use in greenhouse heating. Steam and brine from this well are being used in a heat exchanger to supply hot water to heat 50 hectares of the greenhouses. In Kenya and other warmer countries, greenhouse heating is done primarily for humidity control since, increase in humidity results in multiplication of fungus affecting the crops. Heating also enhances growth and saves on fuel costs that would be incurred if heating is to be done using fossil fuels (Hole and Mills, 2003).

3.2.3 Domestic hot water uses

District heating and domestic hot water supply using geothermal energy is dominant in many cold European countries. Though most of them use ground source heat pumps, those which have large geothermal resources like Iceland use geothermal energy (Fridleifsson, 2001).

The various uses for domestic hot water include dish washing, laundry, bathing and hand washing. Hot water consumption depends on uses and application temperature (Yao et. al., 2003). According to BRE, 2008, domestic hot water should be supplied at 60°C to avoid multiplication of Legionnaire bacteria (Figure 7) and to avoid scalding.

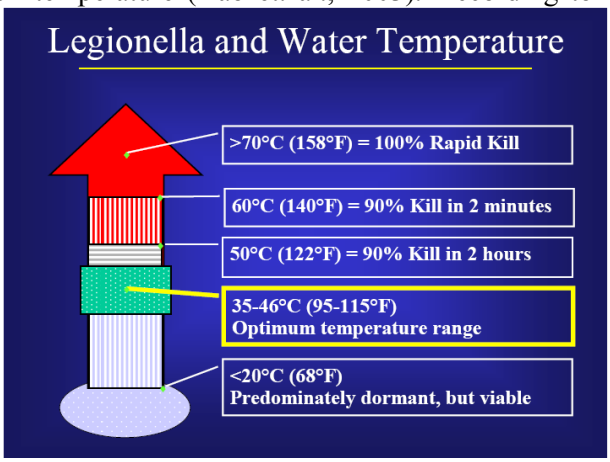

FIGURE 7: Safe temperature for domestic hot water (AWT, 2003)

3.2.4 Leisure therapeutic hot water uses

Water at elevated temperatures has been used for leisure and for its therapeutic potential for many centuries. Geothermal waters have in particular been used widely for this purpose. In Iceland for example, many tourist centres have geothermally heated pools, spas and steam bath. Blue lagoon, which uses geothermal brine from Svatsengi geothermal power plant, is a major tourist attraction with about 300,000 per year (Sigurgeirsson and Olafsson, 2003).

For safety and hygiene of swimmers, swimming pool water requires continuous cleaning and filtering at a circulation rate of between 4-8 hours. This depends on size and usage of the pool. A conventional commercial swimming pool 25m length, 10m width and average height of 1.5 m requires a circulation time of 6 hours (Dayliff, 2006). Water temperature at the swimming pool ranges between 26-30°C (Seneviratne, 2007). Saunas temperature must be between 80°C and 100°C while steam baths are requires water from 43-60°C (Hillingdon, 2008).

3.2.5 Crop drying

Geothermal energy has been used to dry vegetables, fruits wheat and other cereals (Lund et al, 2005). Due to high solar radiation in Kenya, crops have been traditionally dried using solar energy but farmers incur heavy crop losses due to these unreliability of solar energy during rainy and cold seasons and at night. Alternative energy sources have to be used during such times. Farmers in Eburru Kenya, use geothermal energy to dry pyrethrum flowers (Mwangi, 2005). However, this is uncoordinated and is on a very small scale. When such activities are co-ordinated, they can be a major benefit to the farmers of the area and to the environment.

4. CONCLUSIONS

Geothermal energy has been utilized for direct uses for along time in human history especially where the energy has been occurring naturally for example in Romans, Chinese, Ottomans and the Japanese. This was mainly in bathing and on small-scales. Currently, direct uses are on commercial level and are replacing fossil fuels in uses of low heat applications such as district heating, processing of agricultural products, therapeutic uses as well as in aquaculture.

The earliest industrial exploitation began in the 19th century with the use of geyser steam to extract boric acid from volcanic mud in Larderello, Italy. In the 20th century, demand for electricity led to the consideration of geothermal power as a generating source. In 1904, at the same Larderello dry steam field where geothermal acid extraction began, electricity generation was begun. Cierro Prietto in Larderello is the world's first commercial geothermal power plant. It was the world's only industrial producer of geothermal electricity until New Zealand built a plant in 1958. These two plants are operational to date.

Depending on the temperature, pressure and chemistry of geothermal resources, geothermal energy can be used in electricity generation using either conventional or binary power plants. In Kenya for example, 167 MWe is used for electricity generation using condensing, binary and back-pressure turbines.

The African Rift has a geothermal potential of more than 10,000 MWe and much more thermal energy. This energy if utilized can go a long way to replacing uses of fossil fuels and hence address the global warming.

Where temperature and pressure allow, combined heat and power should be adopted in all future geothermal developments. This will enhance efficient utilization of geothermal resources. This calls for research to explore potential direct uses especially among the communities living in geothermal resource area.

Geothermal energy has been used for direct applications in many parts of the world such as Iceland, USA, Turkey, China and many European countries. This has proved to be very economical and reliable since geothermal energy is has very high availability (>90%). In Africa, geothermal energy has not been widely used for direct uses mostly due to absence of cold seasons which requires applications low heat. This is however changing as the prices of fossil fuels continue to increase and as more and more focus goes to the utilisation of renewable energy sources to address the climate change. Geothermal energy can be used to replace fossil fuels in greenhouse heating, aquaculture and crop drying as well as in leisure and therapeutic uses. 16 MWt is used for direct applications in greenhouse heating and a limited amount of thermal energy is used for low heat energy applications in crop drying and swimming.

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BASIC HYDROGEOLOGY IN GEOTHERMAL SYSTEMS

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ABSTRACT

Hydrogeology is the part of hydrology that deals with the occurrence, movement and quality of water beneath the Earth's surface. Hydrogeology deals with water in a complex subsurface environment, but much of its basic terminology and principles can be understood readily by non-hydrogeologists.

This paper presents basic terms and principles of hydrogeology in geothermal systems. The first section introduces many key terms and concepts in definition form. The following section introduces principles of ground water movement, using these terms. The last section gives an overview of the hydrogeology of the Kenyan rift, with special reference to geothermal system.

1. INTRODUCTION

Hydrogeology (hydro- meaning water, and geology meaning the study of the Earth) is the area of geology that deals with the occurrence, distribution and movement of groundwater in the soil and rocks of the Earth's crust (commonly in aquifers). The term geohydrology is often used interchangeably. Some make the minor distinction between a hydrologist or an engineer applying himself to geology (geohydrology), and a geologist applying himself to hydrology (hydrogeology).

The very shallow flow of water in the subsurface (the upper 3 m or 10 ft) is pertinent to the fields of soil science, agriculture and civil engineering, as well as to hydrogeology. The general flow of fluids (water, hydrocarbons, geothermal fluids, etc.) in deeper formations is also a concern of geologists, geophysicists and petroleum geologists. Groundwater is a slow-moving, viscous fluid (with a Reynolds number less than unity); many of the empirically derived laws of groundwater flow can be alternately derived in fluid mechanics from the special case of Stokes flow.

When rain falls to the ground, some water flows along the land surface to streams or lakes, some water evaporates into the atmosphere, some is taken up by plants, and some seeps into the ground. As water begins to seep into the ground, it enters a zone that contains both water and air, referred to as the unsaturated zone or vadose zone. The upper part of this zone, known as the root zone or soil zone, supports plant growth and is crisscrossed by living roots, holes left by decayed roots, and animal and worm burrows. Below lies an intermediate zone, followed by a saturated capillary fringe, which results from the attraction between water and rocks. As a result of this attraction, water clings as a film on the surface of rock particles. Water moves through the unsaturated zone into the saturated zone, where all the interconnected openings between rock particles are filled with water. It is within this saturated zone that the term "ground water" is correctly applied.

2. TERMINOLOGIES

Ground water is water held within the interconnected openings of saturated rock beneath the land surface. Figure 1 illustrates some of the terms used.

Artesian well - A well whose source of water is a confined (artesian) aquifer. The water level in artesian wells stands at some height above the water table because of the pressure (artesian pressure) of the aquifer. The level at which it stands is the potentiometric (or pressure) surface of the aquifer. If the potentiometric surface is above the land surface, the well is a flowing artesian well.

Water table - The top of an unconfined aquifer below which the pore spaces are generally saturated; the level in the saturated zone at which the pressure is equal to the atmospheric pressure.

Capillary fringe - The area of the saturated zone just above the water table in which water is held in the soil by surface tension.

Confined aquifer - An aquifer in which ground water is held under pressures greater than atmospheric pressure by upper and lower confining layers, forcing water to rise in wells to heights above the top of the aquifer (artesian wells). Also known as artesian aquifer.

Confining layer - A layer of geologic material which hampers the movement of water into and out of an aquifer. Examples are unfractured igneous rock and metamorphic rock, and shale, or consolidated sediments such as clays. This is also known as a confining bed.

Consolidated rock/ Bedrock - A general term for the solid rock that underlies soils or other surficial material; consists of mineral and/or rock particles of different sizes and shapes that have been welded into a mass by heat and pressure or by chemical reaction. This rock must contain interconnected pores or fractures to serve as an aquifer.

Discharge - The movement of ground water to the surface into a spring, lake, river, or other surface water body; or outflow of ground water from a pumping or flowing well.

Groundwater aquifer - A water-bearing layer of rock or sediment capable of yielding usable quantities of water; composed of unconsolidated materials such as sands and gravel, or fractured consolidated rock such as sandstone or fractured limestone and lava. Note: Although the term *aquifer* is used to mean *ground water aquifer,* there are also oil aquifers, natural gas aquifers, and saltwater aquifers.

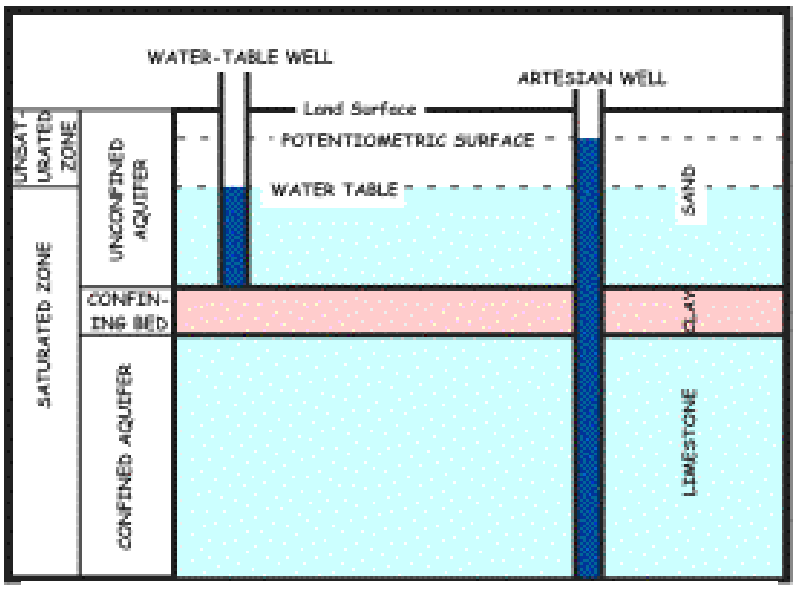

FIGURE 1: An illustration of groundwater terms, adapted from Heath (1993)

Perched aquifer - An aquifer in which a ground water body is separated from the main ground water below it by an impermeable layer (which is relatively small laterally) and an unsaturated zone. Perched aquifers are common in glacial outwash, where lenses of clay formed in small glacial ponds are present. They are also common in volcanic depositional sequences where weathered ash layers of low permeability are sandwiched between high permeability basalts. Water moving downward through the

unsaturated zone will be intercepted and accumulate on top of the lens before it moves laterally to the edge of the lens and seeps downward to the regional water table or forms a spring on the side of a hillslope.

Permeability - The capacity of a porous rock, sediment, or soil to transmit ground water. It is a measure of the inter-connectedness of a material's pore spaces and the relative ease of fluid flow under unequal pressure.

Pores - The spaces between particles within geological material (rock or sediment) occupied by water and/or air.

Porosity is defined as the ratio of the volume of voids to the volume of aquifer material. It refers to the degree to which the aquifer material possesses pores or cavities which contain air or water (compare permeability).

Drawdown - The vertical drop of the water level in a well caused by ground water pumping; also, the difference between the water level before pumping and the water level during pumping, also water rest level.

Overwithdrawal - Withdrawal of ground water from an aquifer at a rate that exceeds the recharge rate of that aquifer. This can lead to lowered water table, saltwater intrusion and sinkholes.

Recharge area/zone - Recharge is the process that allows water to replenish an aquifer. This process occurs naturally when rainfall filters down through the soil or rock into an aquifer. Artificial recharge is achieved through the pumping (called injection) of water into wells or by spreading water over the surface where it can seep into the ground. The land area where recharge occurs is called the recharge area or recharge zone.

Saturated zone - The subsurface zone in which all pores in the aquifer are filled with water.

Unsaturated zone - The subsurface zone in which the geological material contains both water and air in pore spaces. The top of the unsaturated zone typically is at the land surface, otherwise known as the vadose zone.

Spring - A place where ground water naturally comes to the surface at the intersection of the water table and land surface.

Subsidence - The sinking or depression of the land surface as a result of too much ground water withdrawal (or overwithdrawal of any mined fluid such as petroleum, gas).

Watershed - All the land area and water within the confines of a drainage divide in which all surface runoff will pass through an identifiable outlet, such as a stream or river.

Cone of depression - As water is withdrawn from a well, the water level in the well begins to decline as water is removed from storage in the well. The head in the well will fall below the level of the surrounding aquifer and water begins moving from the aquifer into the well. The water level will continue to decline and the flow rate of water into the well will increase until the inflow rate is equal to withdrawal rate. Water from the aquifer must converge on the well from all directions and the hydraulic gradient must get steeper near the well. For this reason the resultant 3-D shape of water withdrawal is a called a cone of depression.

3. PRINCIPLES OF A GROUND WATER MOVEMENT

Hydrogeology is an interdisciplinary subject; it can be difficult to account fully for the chemical, physical and biological interactions between soil, water and nature. The study of the interaction between groundwater movement and geology can be quite complex. Groundwater does not always flow in the subsurface down-hill following the surface topography; groundwater follows pressure gradients (flow from high pressure gradient to low) often following fractures and conduits in circuitous paths. Taking into account the interplay of the different facets of a multi-component system often requires knowledge in several diverse fields at both the experimental and theoretical levels.

3.1 Governing equations

Darcy's law - Darcy's law is a constitutive equation (empirically derived by Henri Darcy, in 1856) that states the amount of groundwater discharging through a given portion of aquifer is proportional to the cross-sectional area of flow, the hydraulic head gradient, and the hydraulic conductivity.

Groundwater flow equation – The groundwater flow equation, in its most general form, describes the movement of groundwater in a porous medium (aquifers and aquitards). It is known in mathematics as the diffusion equation, and has many analogies in other fields. Many solutions for groundwater flow problems were borrowed or adapted from existing heat transfer solutions.

It is often derived from a physical basis using Darcy's law and a conservation of mass for a small control volume. The equation is often used to predict flow to wells, which have radial symmetry, so the flow equation is commonly solved in polar or cylindrical coordinates.

The *Theis equation* is one of the most commonly used and fundamental solutions to the groundwater flow equation; it can be used to predict the transient evolution of head due to the effects of pumping one or a number of pumping wells.

The *Thiem equation* is a solution to the steady state groundwater flow equation (*Laplace's equation*). Unless there are large sources of water nearby (a river or lake), true steady-state is rarely achieved in reality.

3.2 Calculation of groundwater flow

To use the groundwater flow equation to estimate the distribution of hydraulic heads, or the direction and rate of groundwater flow, this partial differential equation (PDE) must be solved. The most common means of analytically solving the diffusion equation in the hydrogeology literature are:

- *Laplace, Hankel and Fourier transforms* (to reduce the number of dimensions of the PDE);
- *Similarity transform* (also called the *Boltzmann transform*) is commonly how the Theis solution is derived; separation of variables, which is more useful for non-Cartesian coordinates; and,
- *Green's functions*, which is another common method for deriving the Theis solution — from the fundamental solution to the diffusion equation in free space.

No matter which method we use to solve the groundwater flow equation, we need both initial conditions (heads at time (t) = 0) and boundary conditions (representing either the physical boundaries of the domain, or an approximation of the domain beyond that point). Often the initial conditions are supplied to a transient simulation, by a corresponding steady-state simulation (where the time derivative in the groundwater flow equation is set equal to 0).

There are two broad categories of how the (PDE) would be solved; either analytical methods, numerical methods, or something possibly in between. Typically, analytic methods solve the groundwater flow

equation under a simplified set of conditions, while numerical methods solve it under more general conditions to an approximation.

3.2.1 Analytic methods

Analytic methods typically use the structure of mathematics to arrive at a simple, elegant solution, but the required derivation for all but the simplest domain geometries can be quite complex. Analytic solutions typically are simply an equation that can give a quick answer based on a few basic parameters. The Theis equation is a very simple analytic solution to the groundwater flow equation, typically used to analyze the results of an aquifer test or slug test.

3.2.2 Numerical methods

The topic of numerical methods is quite large, obviously being of use to most fields of engineering and science in general. There are two broad categories of numerical methods used in hydrogeology: gridded or discretized methods and non-gridded or mesh-free methods. In the common finite difference method and finite element method (FEM) the domain is completely gridded ("cut" into a grid or mesh of small elements). The analytic element method (AEM) and the boundary integral equation method (BIEM — sometimes also called BEM, or Boundary Element Method) are only discretized at boundaries or along flow elements (line sinks, area sources, etc.), the majority of the domain is mesh-free.

3.3 Hydraulic head

Changes in hydraulic head (h) are the driving force which causes water to move from one place to another. It is composed of pressure head and elevation head. The head gradient is the change in hydraulic head per length of flowpath, and appears in Darcy's law as being proportional to the discharge.

Hydraulic head is a directly measurable property that can take on any value; pressure head can be measured with a pressure transducer, and elevation head can be measured relative to a surveyed datum (typically the top of the well casing). Commonly, in wells tapping unconfined aquifers the water level in a well is used as a proxy for hydraulic head, assuming there is no vertical gradient of pressure.

Darcy's law & hydraulic conductivity (K)- In 1856 the French engineer Henry Darcy successfully quantified several factors controlling ground water movement. These factors are expressed in an equation that is commonly known as Darcy's Law.

$$Q = KA\left(\frac{dh}{dl}\right)$$

where Q = Discharge (volume of water per unit time);
K = Hydraulic conductivity (depends upon size and arrangement of pores, and fluid dynamics such as viscosity, density and gravitational effects)
A = Cross-sectional area (at a right angle to ground water flow direction)
dh/dl = Hydraulic gradient (the common notation for a change in head per unit distance).

By rearranging Darcy's Law and solving for hydraulic conductivity (K) in common units we can get a sense of what hydraulic conductivity really represents:

$$K = \frac{Qdl}{Adh} \; or, K = \frac{Q = volume\ in\ ft^3 per\ time(day)}{A = a\ cross-sectional\ area\ in\ ft^2}\left(\frac{dl = distance\ in\ ft}{dh = head\ change\ in\ ft}\right)$$

Thus, in practical terms hydraulic conductivity is the volume of water flowing through a 1 ft. x 1 ft. cross-sectional area of an aquifer under a hydraulic gradient of 1 ft. / 1 ft. in a given amount of time (usually a day). If we cancel out units, we see that hydraulic conductivity is usually expressed in ft/day.

Hydraulic conductivity ranges approximately 12 orders of magnitude depending upon differing water transmitting characteristics of aquifer materials (Figure 2). As one may conclude from the chart below, the volume of water that can flow from sandy and cavernous carbonate aquifer materials of the coastal plains are in most cases far greater than igneous and metamorphic rocks.

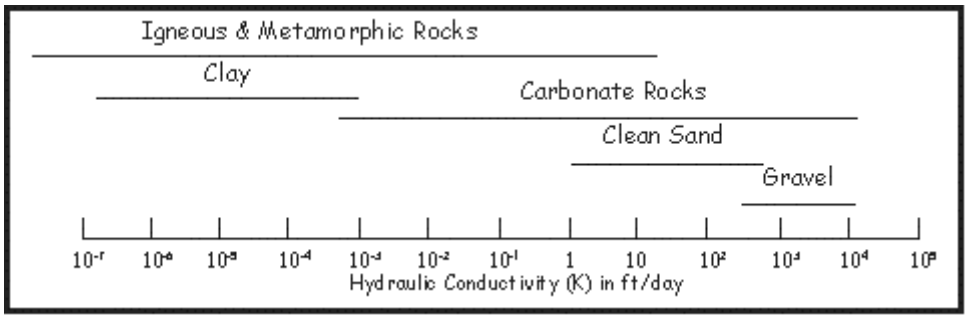

FIGURE 2: Hydraulic conductivity in different aquifer material

There are also some other terms used when regarding the spatial distribution of hydraulic conductivity within an aquifer. If the value of hydraulic conductivity is the same in all directions, the aquifer is said to be isotropic. If hydraulic conductivity is different in different directions, the aquifer is said to be anisotropic. The terms homogeneous and heterogeneous are used when comparing hydraulic conductivity at separate locations of the aquifer, regardless whether the value is the same or different in all directions. The aquifer is homogeneous if hydraulic conductivity is the same and heterogeneous if different. The diagram below shows the four possible combinations when describing the hydraulic conductivity of aquifers.

Another important factor controlling ground water movement is its velocity. The ground water velocity equation can be derived from a combination of the velocity equation of hydraulics and Darcy's law, with the velocity equation as:

$$Q = Av$$

where Q = Discharge (volume of water per unit time)
v = Velocity.

Solving for ground water velocity gives;

$$v = k\left(\frac{dh}{dl}\right)$$

In practical terms we know that ground water does not move in open space, rather it moves through aquifer materials that impede ground water velocity. To account for this we need to include effective porosity (specific yield) to accurately quantify ground water velocity. Remember that hydro-geologists use effective porosity because this value better represents water flowing through an aquifer under the forces of gravity. Thus, the velocity equation is modified as:

$$v = \left(\frac{Kdh}{n_e dl}\right)$$

where n_e = Effective porosity

3.4 Transmissivity (T)

Transmissivity (T) is the volume of water flowing through a cross-sectional area of an aquifer that is 1 ft. x the aquifer thickness (b), under a hydraulic gradient of 1 ft./ 1 ft. in a given amount of time (usually a day). Thinking about the definition of hydraulic conductivity, we can conclude that transmissivity (T) is actually equal to hydraulic conductivity (K) times aquifer thickness (b). Or otherwise denoted as T = Kb. We can also conclude that transmissivity is expressed as ft2/day because if T = Kb, then T = (ft./day)(ft./1).

3.5 Storage coefficient (S)

The "S" is used to represent the storage coefficient of an aquifer which is the volume of water released from an aquifer per 1 foot surface area per 1 foot change in head. Notice that we are not speaking of water flowing through an aquifer, rather we are referring an aquifer's ability to store water. Mathematically, the storage coefficient is dimensionless as the equation below illustrates:

$$S = \frac{Q = volume\ of water\ in\ ft^3}{(surface\ area\ in\ ft^2)(head\ change\ in\ ft)}$$

The size of the storage coefficient is dependent whether the aquifer is unconfined or confined. In regard to a confined aquifer, water derived from storage is relative to the expansion of water as the aquifer is depressurized (pumped) and compression of the aquifer.

4. DISCUSSION

The aquifer parameters of transmissivity (T) and storage coefficient (S) are variables that can dictate the shape of the cone of depression. Relative to a confined aquifer, the expansion of water in response to depressurizing (pumping) is very small, yet compression of the rock skeleton is great. This permits the cone of depression to expand and deepen rapidly when pumped. Thus, lower "S" values create deeper and wider cones than higher "S" value aquifers that do not deepen and expand as readily. In regards to transmissivity, aquifers of low "T" develop deep and narrow cones of depression and aquifers of high "T" area characterized by shallow and wide cones.

Utilizing the heating and cooling demand for a geothermal project, the best source water for the geothermal system will be determined based on an understanding of the local geology and hydrogeology. When an underground source is to be utilized, there are several source "development" tools available to help achieve a higher probability for success. This includes the use of fracture trace analysis, coupled with very low frequency (VLF) surveys and magnetometer readings. A review of well completion records for a region can also be conducted to determine aquifer (bedrock) geology and yield potential. If necessary, a pumping test can be performed on both surface and groundwater sources for the determination of a long-term safe yield for the water source, and to determine what effects (changes in water chemistry, temperature, level, etc.) the pumping is predicted to have. These data are incorporated into the thermal model to "fine tune" the predicted capability of the heat/cooling source capabilities.

Study of a possible geothermal system would include geologic mapping, hydrogeochemical analyses, and geophysical interpretation. Geologic and geophysical methods emphasized structure, particularly faults, reservoir and heat sources. Hydrogeochemical analyses shows the geochemistry of the expected geothermal fluids and whether they are of meteoric origin, so as to create a geothermal model predicting reservoir temperatures, including location and trend of heat flow anomalies. For example the proposed model may call for deep circulation of meteoric water along fault zones. Surface waters from nearby rivers, lakes or catchment areas percolating down the faults and being heated to high temperatures. The thermal waters then migrates laterally, then rises back up the fault.

In geothermal exploration and exploitation the application of reactive flow modelling provides a means to lower risk, costs and time during reservoir management, remediation or exploration targeting. In order to deal with the complexity of natural systems, simplified models are employed to illustrate the principal and regulatory factors controlling a chemical system. Following the aphorism of Albert Einstein: "Everything should be made as simple as possible, but not simpler", models need not to be completely realistic to be useful, but need to meet a successful balance between realism and practicality. Properly constructed, a model is neither so simplified to be unrealistic nor too entailed so that it cannot be readily evaluated and applied to the problem of interest. The results of a model have to be at least partially observable or experimentally verifiable.

Reactive transport modelling is extremely useful in understanding the spatial and temporal distributions of solute concentrations and mineral assemblages in the environment. The main target of reactive flow modelling is the simulation on a real time scale with real spatial coordinates, but generally this goal is only partially achievable. The limitations of reactive transport simulation are embedded in the conceptualized set of equations used to best approximate the real situations. But models provide a tool for critical analysis. They are a means to organize our thinking, test ideas and indicate which the sensitive parameters are. They direct further studies and help to design new experiments and to critically test hypotheses. Particularly surprising model outputs often provide new insight otherwise inaccessible.

Studies of hydrothermal systems should begin by considering the following five questions:

(1) What is the architecture of the system?
(2) What is its geodynamic history?
(3) What processes are driving fluid flow on the scale of the system?
(4) What is the nature of the fluids in the hydrothermal system?
(5) What are the mechanisms of alteration?

Qualitative answers to these questions lead the way to conceptual models, which in turn provide a framework for quantitative, numerical models. Answering these questions as good as possible will help to conceptualise the scientific problem.

Key steps in conceptualising the models are:

(1) Simplifying assumptions must be made;
(2) Appropriate boundary conditions and initial conditions must be identified;
(3) The range of applicability and limits of prediction of the models need to be understood.

Models for coupled simulation of reactive transport processes consist of five physical and chemical processes to be solved numerically:

(1) mechanical deformation;
(2) fluid flow;
(3) heat transfer;
(4) multi species transport and
(5) chemical reactions.

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5. HYDROGEOLOGY OF THE CENTRAL KENYAN RIFT

The hydrogeology of central to southern portion of the rift valley is mainly controlled by the rift flanks faults, the grid faulting and the tectono-axis along the rift floor (Clark et al., 1990). Fluids are recharged laterally from the high rift flanks and axially along the rift floor southwards. The grid faulting act as channels for ground water or they provide permeable barriers to lateral flow. A microseismic study has shown that the grid faulting unlike the escarpment faulting is quite active suggesting they are open (Allen et al., 1989). Thus the faulting causes the ground water to flow from the escarpment to the center and then follow longer flow paths reaching greater depths, and aligning their flow within the rift along its axis.

In Olkaria and Eburru where drilling has been carried out, the geothermal reservoirs are hosted by the faulted trachytes and basalts and from contacts between these lavas and pyroclasts, which are common within the floor of the southern Kenya Rift valley (clark et al., 1990). It is therefore probable that the reservoirs of Suswa and Longonot are hosted in the same formation. Groundwater flows are generally directed towards the lakes. Some flow away from the area to the North West, North East from the Mau Escarpment, South West from the Bahati escarpment and North Ward from Eburru. It is also probable that there is some southerly flow from Menengai towards Lake Nakuru (Becht et al., 2005). However at depth it is likely that flow occurs to the northeast away from the Nakuru- Elementaita catchment towards the lower lying catchment around Lake Bogoria (Clarke et al., 1990).

Tectonic movements of the rift valley have important effects on aquifer properties, both on a small scale by creating the local fracture system which comprise many aquifers. In such settings fractures provide conduits for fluid flow through such rocks. Therefore, the fracture system of the Kenyan rift, are important for successful operation of the geothermal reservoir. Groundwater flow to depths through faults and conduits where its heated by a heat source, later manifesting as High enthalpy steam vents, through hot and boiling springs Eburru and Olkaria. Scattered warm springs are also seen rising from underneath lavas and fissures along the foot of escarpments to the east of the rift valley axis.

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STRUCTURAL GEOLOGY – TECTONICS, VOLCANOLOGY AND GEOTHERMAL ACTIVITY

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ABSTRACT

Discussion will concentrate on rift zone geothermal systems, continental and oceanic, with side look on the hotspot environment. "Volcanology" is contained in the title of this summary/lecture because the discussion will be limited to high-temperature geothermal systems which might as well be called volcanic geothermal systems. The volcanic systems concept is introduced as "a system including the plumbing, intrusions and other expressions of volcanism as well as the volcanic edifice" (Walker 1993). Different types of high temperature geothermal fields occur. Their main characteristics are described including the structures which control their geothermal system. Hotspots are referred to. Many are associated with rift zones (East Africa, Iceland) others are intraplate in continental (Yellowstone) or oceanic (Hawaii) settings. Their magma supply is excessive and they provide a long term thermal high of regional extent.

1. INTRODUCTION

The intrusive part of a volcanic system is most important as a potential heat source for high-temperature geothermal systems (Figure 1). The intrusions form large bodies at a few km depth. They feed a multitude of dykes and sheets underneath a volcanic centre which are relatively shallow and contribute significantly to maintaining and driving geothermal circulation. With increasing distance from the centres dykes become dominant. Concentration of dykes and clustering of volcanic eruptions may occur away from the centre and a geothermal system may develop.

How and why do the intrusions form at preferred levels? Walker´s (1989) ideas about the significance of neutral buoyancy in distributing incoming magma between magma chamber, rift zones, intrusions and surface flow are discussed. Neutral buoyancy is defined as the depth where pressure in the magma (or magma density) equals lithostatic pressure. At this level the magma may form sheet/sill intrusions or may pool to form a large magma chamber. Realize that volcanic edifices may expand nearly as much by growth of subsurface intrusions as by surface outpourings. However, volcano growth is countered by subsidence and collapse.

Calderas as a rule, or at least at some stage, are underlain by a magma chamber. It may be active, ready to erupt, depending on inflow rate and residence time of magma, irrespective of regional tensional stress. Characteristic structures are concentric and radial eruption fissures with radial dykes and cone sheets at depth (Figure 2). Some calderas are more passive. They depend on the regional

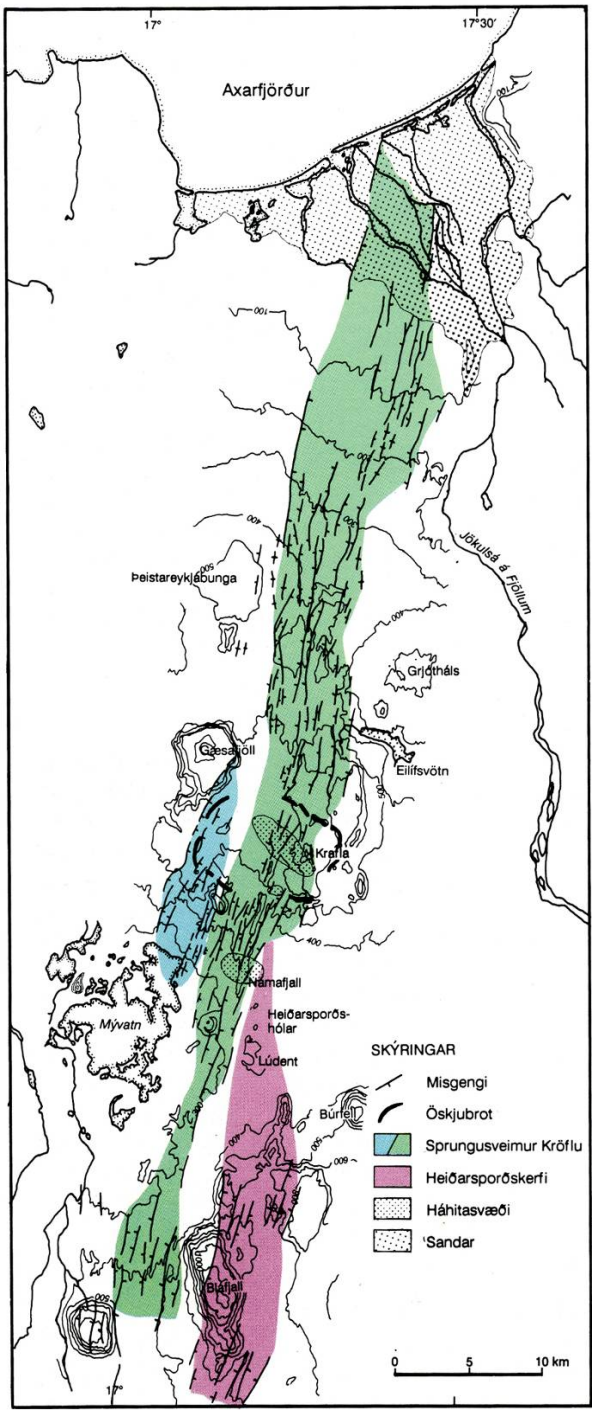

FIGURE 1: Krafla volcanic system. Shield volcano near centre defined by maximum volcanic production (topographical high), silicic rocks, a caldera and geothermal activity. It is transected by fissure swarms totalling over 80 km in length, with aligned basaltic crater rows, faults and ground fissures. Volcanic eruptions extend for about 40 km along the swarm. Non-volcanic faults and fissures (surface expression of dykes) extend far beyond surface volcanism

stress build up for eruptions or triggering by dyke injection from a neighbour volcano. Is Olkaria one such?

So called, volcanic shadow zones define areas within volcanic systems where almost only silicic melts reach the surface, whereas the basaltic melts erupt on the flanks or are emplaced as intrusions at depth. Shadow zones correlate closely with calderas and geothermal manifestations (Figure 3). Olkaria may be an example. Stacking of basaltic intrusions (of relatively high density) below caldera floor may contribute to subsidence.

Types of faults (Figure 4) and gross features of rift zones and fissure swarms are discussed as well as the importance of dyke swarms in controlling underground flow pattern. Listric faults (dip decreases with depth) are a main feature of continental rifts. They are well documented seismically. Planar faults (dip remains constant with depth) also occur. They are nearly vertical in the volcanic part of the fissure swarms. A distinction between listric and planar faults can be seen at the surface as listric normal faults result in rotation of the hanging wall block, whereas planar faults do not. Verticality is indicated by open tension gashes thought to be the surface expression of dykes. En echelon offsets are typical of rift zones.

The volcanic systems are commonly arranged en echelon. Their fissure swarms (defined by faults, open fissures and crater rows) are segmented on a smaller scale in the same fashion. This is prominent where the extension direction is oblique to the rift axis (now easily determined by GPS-network extending on to the marginal blocks) (see e.g. Figure 5 of Iceland).

Dyke swarms may extend over 400 km from their source. An example is the Mull swarm in Scotland and England (Figure 6, left). Fissure swarms which are the surface expression of dykes extend well over 100 km in the rift zones of Iceland and probably also in East Africa. There is a gradation in the dyke and fissure pattern with distance from the source of the magma underneath a central volcano to 1) net dyking, planar and inclined sheets and a wide range of orientations around the source and in the nearest surroundings of the volcano including concentric fissures/faults to 2) dykes, ground fissures and

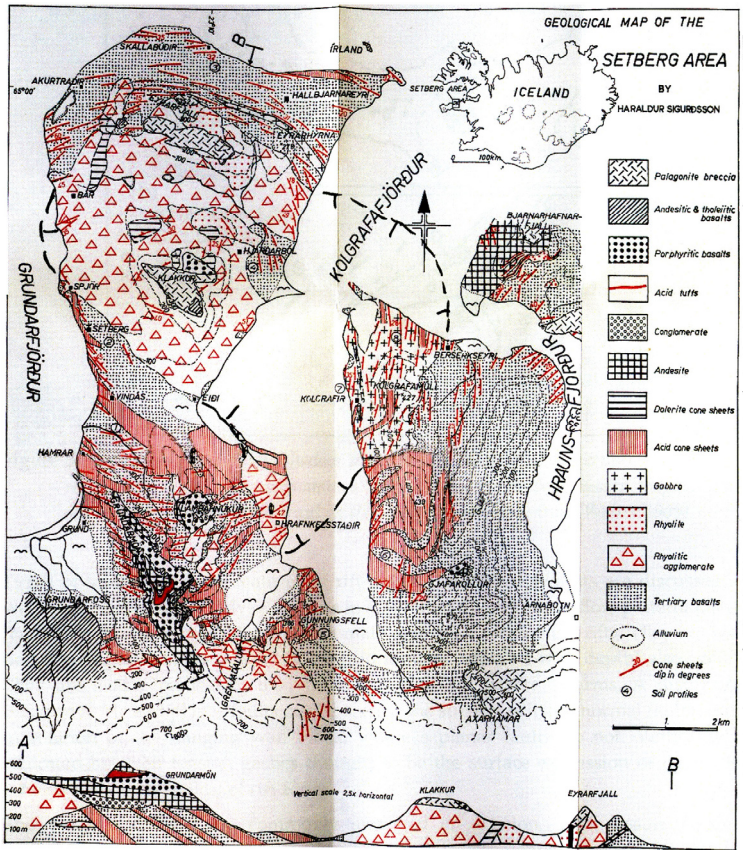

FIGURE 2: Cone sheet swarm of Setberg volcanic centre, West Iceland. The sheets are inclined 25-40° towards a focus at about 3 km depth underneath a caldera, filled with silicic breccia and a gabbro intrusion (Sigurdsson, 1967)

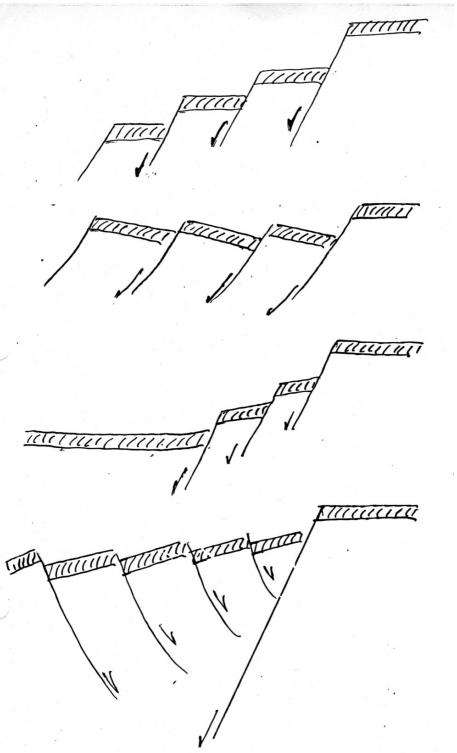

FIGURE 4: Types of normal faults

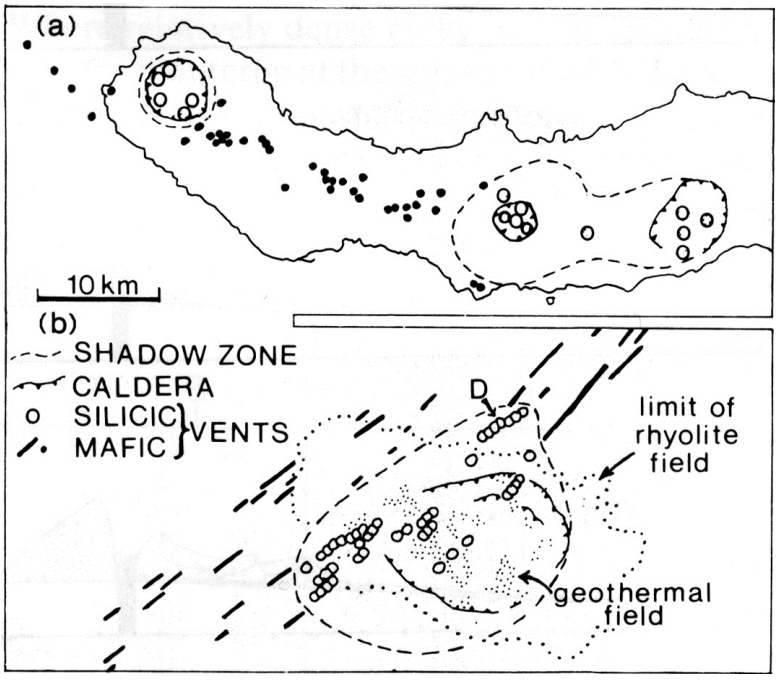

FIGURE 3: Sete Cidades, Azores, and Torfajökull, Iceland. Examples of magmatic shadow zones (where basalt does not erupt) in calderas of rhyolite volcanoes. Magma chambers with silicic melts prevent basaltic magmas from attaining the surface. Such erupt on the adjoining fissure swarms (Walker, 1989)

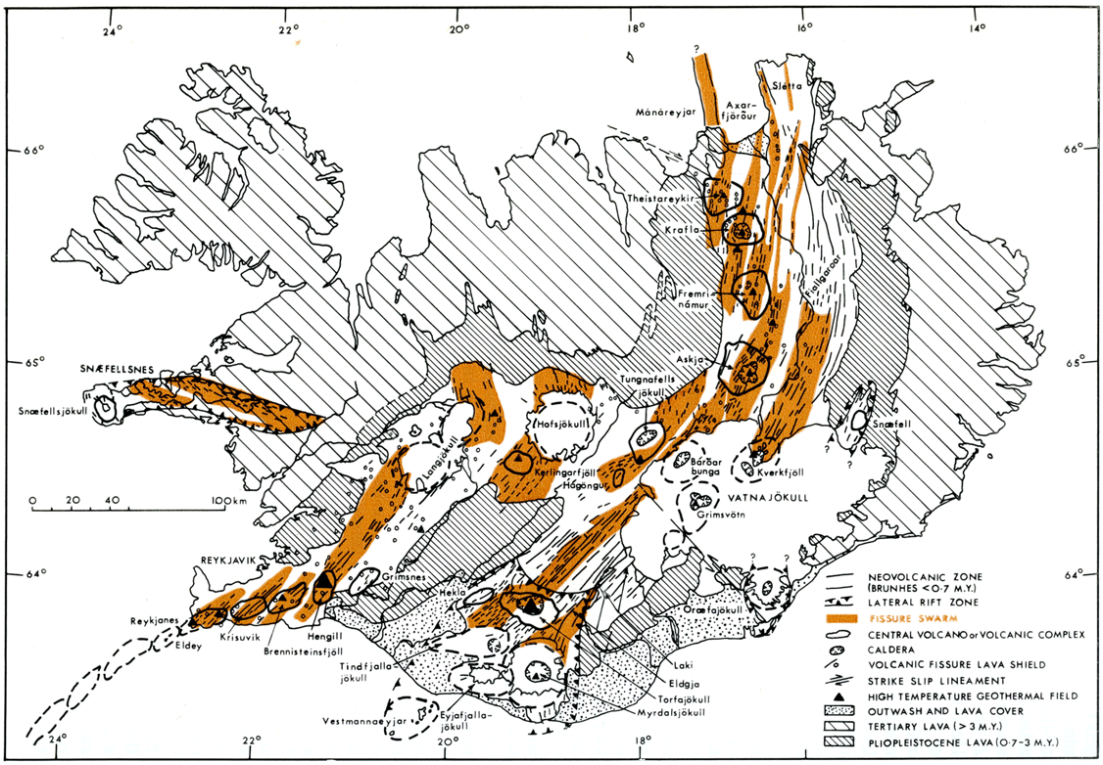

FIGURE 5: Magmatic rift segmentation is reasonably well defined in Iceland. However there are cases where the fissure swarms of volcanic systems overlap and interact: activity of one triggering eruption of another. Differences in petrochemistry help to sort out. This relationship may be more obscure in continental rifts, but little attention has been paid to it so far (Saemundsson, 1978)

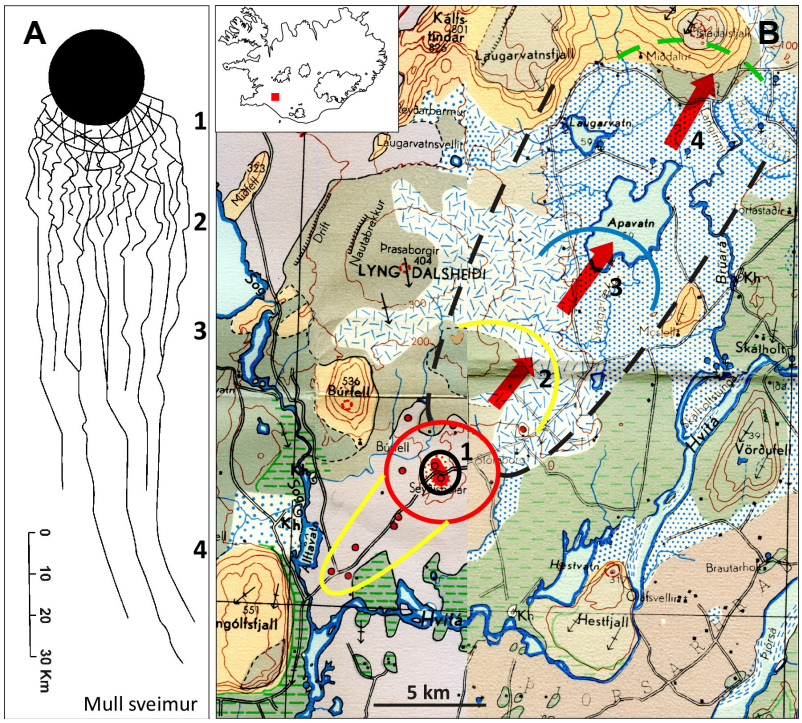

FIGURE 6: A) Variation in trend of the dykes of the Mull dyke swarm. Only 120 km of it are shown including the central and proximal parts. Erosion amounts to 1500-2000 m (Jolly and Sanderson, 1995);
B) Grímsnes volcanic system in South Iceland, shown for surface comparison. Red circle shows the volcanic centre. Yellow lines show how far eruption fissures reach. Blue line how far wide ground fissures reach. Broken green line the approximate outer limit of narrow cracks.
The interpretation is that fracturing is caused by dykes all along the system. They have not reached the surface beyond the yellow line and deepen towards NE. The NE-extension of the system from the centre is about 25 km. Low temperature geothermal systems occur between the blue and green lines.

fissure eruptions becoming more aligned with distance from the volcano to 3) metre scale faults and ground fissures and only rare eruptive fissures to 4) centimetre scale cracks dominating. The gradation correlates with depth to the dykes. They reach the surface only rarely at over 50 km distance from the volcanoes. In the distal part of the swarms where minor fissures on surface indicate propagating dykes they may branch, and not extend higher than about a ½-1km below surface. In Iceland high temperature geothermal systems develop primarily in the source and proximal area. Areas 2) and 3) host low temperature geothermal systems of generally high permeability and rather low temperature whereas the distal areas of type 4) host low temperature geothermal systems often in the range 80-120°C but are of a more restricted fracture permeability. The gradations are indicated for the Grímsnes volcanic system (Figure 6 right) from 1 to 4 and the corresponding subsurface analogies of the Mull swarm.

2. GENERAL ISSUES TO BE CONSIDERED AND KEPT IN MIND

Exploration strategy should be fitted to detect and map the outline of an upwelling geothermal plume and its outflow. Role of geologist is to investigate a variety of features that may shed light on the nature, geological history and present state of the respective geothermal system with emphasis on the central volcanic focus.

Information about the volcanic stratigraphy, structure and rock composition is needed as a basis for interpreting results of geophysical and geochemical surveys, and exploration drilling conducted before drilling of production wells. The volcanic history and mode of eruption needs to be known. This is important also for assessment of volcanic hazard.

2.1 Segmentation of rifts and characteristics of volcanic systems

Look for segmentation of rifts and define volcanic systems by area (from fault trends, crater rows and rock composition). Evaluate volcanic production and mode of eruption. Define rock types. Try to estimate ground movements, vertical and horizontal, their rate – latent creep and/or rifting episodes accompanied by volcanic or intrusive activity. Rifting episodes have been ongoing in the East African Rift since 2005 in Ethiopia (Dabbahu) (Last event occurred in 2009. Rift segmentation and recognition of volcanic systems is widely recognized in Icelandic geology. This may also be applied to the Kenya and Ethiopian rifts, although individual systems have as yet not been well defined.

2.2 How volcanic systems operate

Most magma involved in formation of a volcanic system does not reach the surface but heats a large volume of underground rock. This is difficult to measure, but the volume of evolved (acidic) rocks indicates the degree of partial melting or crystal fractionation, and storage in the crust (before eruptions) underneath the centres. The deeper mafic magma chamber constitutes a large volume which it distributes among sheets (in the central region), dykes in the fissure swarms and gabbros in the roots of the main centres which tend to subside gravitationally.

2.3 Internal structure of volcanic systems

The internal structure of volcanic systems is characterized by dyke complexes in rift zones (deep levels of entire rift zones have been observed in deeply eroded Precambrian terranes). Sheets, dykes and minor intrusions constitute a high percentage of the rock mass at shallow depth (1-3 km) underneath volcanic centres where magma pressure overcomes lithostatic pressure. Larger intrusions (magma chambers) form at greater depth near level of neutral buoyancy (LNB). These act as long term heat sources which also give off volatiles upon solidifying.

2.4 Sheet complexes form in the roots of central volcanoes

Sheet complexes form in the roots of central volcanoes. These are inclined sheets or near horizontal sills, commonly forming coherent sets (Figure 7). From cross cutting relationships it is clear that dyke and sheet intrusions may alternate. Magma injections into roots of central volcano cannot all be accommodated as dykes if extension is slow. Minimum stress orientation then oscillates between horizontal (dykes) and vertical (sheets and sills). Sheets and sills contribute to thickening of the volcanic edifice (mostly balanced by subsidence) which may amount to hundreds to over 1000 metres. They constitute a significant part of the heat source. Their depth is controlled by the LNB (Walker 1989).

FIGURE 7: Cone sheets of Lýsuskard central volcano, W- Iceland, intersecting basalt lavas and their surface breccia (scree covered ledges).

2.5 Calderas

Calderas are a common feature of central volcanoes including shield-volcanoes and stratovolcanoes. These are collapse structures that may be up to 1000 m deep or more. The down dropped block usually consists of the formerly high ground (or volcanic cone). Pre-caldera geothermal alteration may not have reached as high there as it did on the lower slopes of the volcanic edifice. Also calderas tend to fill up within geologically a short span of time. A young caldera may therefore contain a thick pile of rock, as yet little affected by alteration and therefore too permeable for a high temperature system to evolve or become conspicuous. Figure 9 is an example of a shallow caldera showing this feature.

3. IMPORTANT MAPPING FEATURES

3.1 Mapping of geothermal features

Mapping of geothermal features, both active and extinct, is important. As to the active features areal distribution, intensity, size and coherence of fumarole fields or steaming ground, efflorescence minerals and directional trends is quickly assessed. At low levels where hot or boiling springs dominate the same applies except that the deposits from the water must be identified: travertine (tufa) or silica sinter. The first is a bad omen as regards chemistry of reservoir water and temperature the latter a good sign especially if silica sinter is the sole or predominant precipitate. As to the extinct features it is necessary to study the type of alteration (what type of clay, especially transition from smectite to chlorite which is temperature dependant) and its relation to the unaltered rock or soil nearest to it. This may show if the feature became recently extinct (Figure 8).

3.2 Surface geology

Besides plain stratigraphic and tectonic mapping significant features to be defined include volcano type (stratovolcano – shield volcano), dominant rock type (basaltic or acidic), occurrence of acid rocks (lavas, domes, ignimbrite, pumice), caldera whether incremental (Silali) or collapse with related volcanics, (Menengai: ignimbrite flow of ~1000 km² about 8000 or 12.000? years ago), type of basalt eruptions and their structural control such as: unidirectional fissure swarm, radial or circumferential fissures around caldera, central vent eruptions. Hydrothermal and volcanic explosion craters, their age, distribution, size and ejecta. Those indicate nearness to an upflow or a boiling reservoir and are targets for drilling production boreholes. These also constitute a hazard to be assessed properly before siting of surface constructions.

FIGURE 8: Fresh volcanic breccia overlying altered breccia. The altered rock is of low permeability and retains some of the rain water supporting vegetation, whereas most of it percolates rapidly down through the fresh breccia which thus is unfavourable for vegetation in a cold climate

3.3 Life time and development of volcanic systems

Life time of volcanic systems varies from hunderd of thousands to millions of years. It may be assessed from study of well exposed extinct and eroded volcanoes in geologically similar terranes. Development through the nearest geological past and history of activity can usually be found out for at least the last few thousand years. Extension across rift zone during a much longer active period can often be estimated from fault density and throws. With time a preferred stationary intrusion focus would produce an intrusive body, elongated in the direction of stretching (spreading), as calderas also do. Distal parts cool off with time and increasing distance from centre of active magma chamber. CO_2 fluxing of marginal parts of geothermal system is a corollary.

3.4 Permeability

The near surface rocks of a geothermal area are often permeable (lavas and pyroclastics, densely spaced faults). Permeability decreases downwards as alteration progresses and finally secondary

permeability may prevail. Directional drilling is best suited to intersect promising targets if the upflow is fracture controlled or to track feed zones for stratabound aquifers.

3.5 Extinct and eroded volcanic centres

It is most informative to study extinct and deeply eroded volcanic centres, the internal volcanic feed system and their hydrothermal aureoles (Figure 9). The alteration zones can be seen with their characteristic secondary minerals. Dyke complexes can be separated by rock type, distribution and relative age relationships. Dense dyke complexes correlate with increase in high-temperature mineralization. Retrograde mineralization towards end of activity is seen as overgrowth by zeolites. Deeper roots of hydrothermal systems (supercritical conditions, beyond depth of drilling) are well known from study of epithermal ore deposits around exhumed intrusive bodies (former magma chambers).

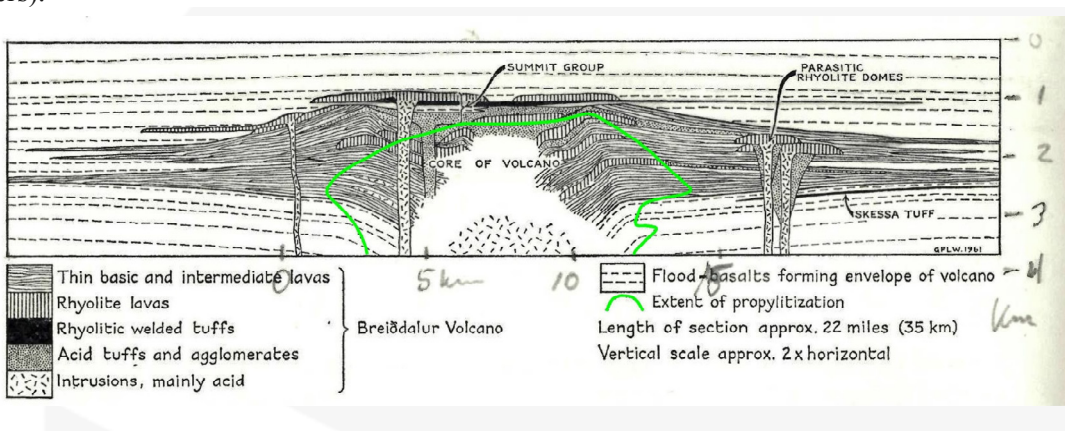

FIGURE 9: Schematic composite section across the Miocene Breiddalur central volcano in East Iceland, long extinct and exhumed by erosion (Walker, 1963). A caldera in the core area of the volcano once hosted a geothermal system of which high-temperature alteration is evidence. Intrusive complex is found in roots of volcano

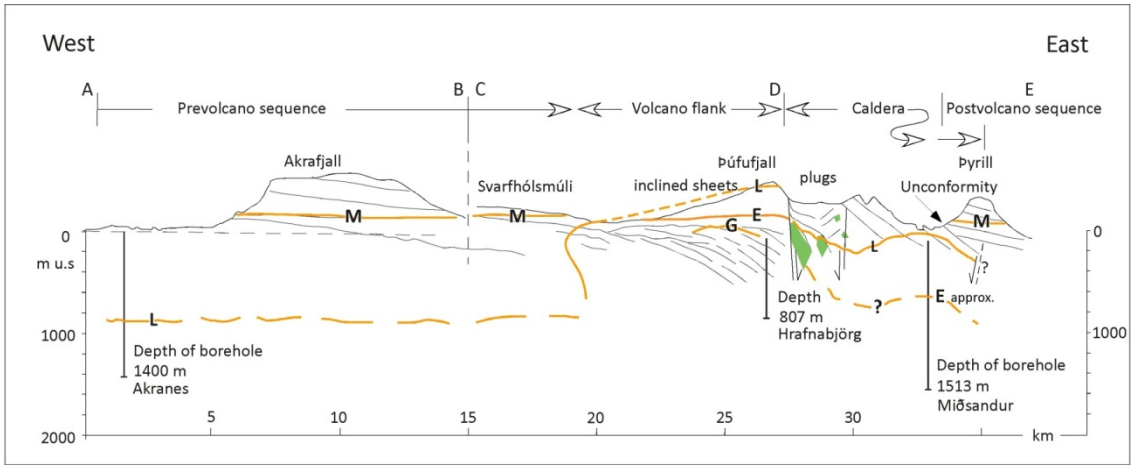

FIGURE 10: Section through the exhumed Pliocene Hvalfjördur central volcano in West Iceland. Flank of volcano is intruded by a multitude of inclined (cone) sheets. The central part has collapsed to form a deep caldera. A geothermal system left its imprint as a high temperature secondary mineral zoning from laumontite to chlorite-epidote and garnet-actinolite. The upper limit of index minerals is marked as L, E and G. The laumontite zone is followed upwards by zeolite zones. M= upper limit of mesolite-scolecite zone. Here the geothermal system did not recover after the caldera collapse.

4. STRUCTURAL FEATURES AND WAYS TO RECOGNIZE THEM

Let us look at large features first that are visible from space or air planes and go on to mapping at ground level. Try to make such features as faults accessible by excavation if they are buried and you think that they are significant.

4.1 Satellite images

Satellite images are useful for overview, however, they lack details. Ground check is needed.

4.2 Air photos

Air photos (stereo pairs) are a very important guide to structures, ground control is a must.

4.3 Mapping

Plain mapping involves: fissures and faults (trend, throw, width, hade, sense of motion, relative age from cross cutting relationships), craters and volcanic fissures (trends, swarming, age relations, explosivity), tilting of the ground (most obvious in antithetic fault zones). Take care on flanks of volcanic edifices where dips are depositional. Mapping of geothermal features in order to recognize directional trends or local concentrations include: mapping of hot and tepid springs, silica or travertine deposits, steam emissions, gas vents, hot ground, efflorescence minerals, alteration (cold or active, local or pervasive, clayey (rock altered beyond recognition of primary rock type) or moderate if original structure of rock is preserved), sliding on clayey slopes may constitute a hazard.

4.4 Faults

Faults are not always topographically distinct unless young or recently activated. Faults are sometimes smoothed out by lava, levelled by erosion, disguised by vegetation, or draped over by scree, pumice or other sediment and only visible in erosive channels, quarries, road cuts or other exposures. Reference markers should be looked for. Various types of faults occur. Normal faults and tension gashes dominate in extensional regimes. Whether listric, planar or vertical depends on whether they are dry or magma generated (the vertical ones). Strike slip faults dominate in fracture zone regimes. Look for riedel shears to determine sense of motion. Normal and strike slip faults both occur in oblique (transtensional) rift zone settings. The two types may be active alternately. Reverse faults occur in Circum Pacific Belt. Volcanic systems in subduction zones may develop fissure swarms which are parallel with the axis of maximum compression.

4.5 Minor faults or fractures

Minor faults or fractures may give a clue to prevailing stress field. Look for striations and riedels on fault surfaces. Helps define stress field. Max. stress axis is near vertical in rift zones. Point source stress develops above inflating magma chambers, causes circumferentially inclined sheets and fissures to form, including volcanic fissures in case of incremental caldera formation (Askja, Iceland, Silali, Kenya).

4.6 Subsurface geology

Look for clues to subsurface geology. Take into account the possibility of low permeability near surface layers (espec. alluvial, lacustrine or mud flow deposits) that might divert water flow laterally.

4.7 Geological hazard factors

Be aware of geological hazard factors such as rock slides, potential flooding, ground fissuring, type and place of volcanic eruptions and their distribution in time. In Krafla and Námafjall, Iceland several

boreholes were clogged by basaltic melt during the Krafla volcanic episode in the 1970's. Also the geothermal system was partly rendered unexploitable temporarily by influx of volcanic gases. Two recent examples of fatal disasters can be mentioned (Muffler and Duffield, 1995). In Ahuachapan, El Salvador, a hydrothermal eruption occurred in 1990 resulting in 25 fatalities. At Zunil, Guatemala, a landslide buried a drilling pad and killed 23 people.

5. TYPES OF VOLCANIC GEOTHERMAL SYSTEMS IN RIFT ZONES

Eburru, Kenya – stratovolcano with large geothermal area extending over 15 km N-S. Collapse structure likely. Erupts silicic rocks (trachytes and rhyolites) and subordinate basalts in central area but basalts along fissure swarm to the north. Upflow may be limited to central volcanic area with outflow to north and south. Fissure swarm prominent with faults, and chains of craters.

Hengill, Iceland – shield volcano with large geothermal area extending 12 km NE-SW (surface manifestations). Lacks collapse structure, erupts mainly basalt, but silicic rocks occur in core area. Fissure swarm prominent with crater rows, faults and ground fissures. Main upflow follows dyke zones which fed Holocene and Late Pleistocene basaltic eruptive fissures.

Ahuachapan, El Salvador – complex stratovolcano with fumaroles at higher ground and hot springs at lower ground. Lacks collapse structure. E-W trending volcanic axis within back arc type graben. Aquifer primarily Plio-Pleistocene andesites at about 500-900 m depth in a laterally fed aquifer. Main upflow underneath volcanic ridge.

Olkaria, Kenya– rhyolite volcano with extensive geothermal field within large ring structure. Caldera most likely present now filled up. Eruptives mainly silicic rocks (rhyolitic) – about 13 km³ over about the last 20.000 years. (For comparison Menengai about 50 km³ over about the last 30.000 years). Fissure swarm is evident in the central area and in the northeast where possibly invaded by Eburru swarm?

Torfajökull, Iceland – rhyolite volcano, dead or dormant as an independent (primary) eruption system of its own. Invasion of basaltic magma from a distant volcanic system triggers faulting and mixed rhyolite/basalt eruptions. Last large eruption produced about 25 km³ about 80.000 years ago. Large caldera, gravity high, shadow zone, magma chamber, geothermal area ~140 km² based on surface manifestations.

Asal, Djibouti – close sub-aerial equivalent to oceanic ridge axis geothermal system. Shield volcano with geothermal system in central area and marginally to it in the direction of widening. Numerous NW-SE faults and crater rows. Recharge by sea water. Lessons to be learned from Reykjanes, Iceland? Perhaps drill shallow wells into steam zone which may already exist and become thicker in the future when production from deeper, water dominated part of the system comes about. Drilling into the steam zone will be difficult (to say the least) after it has developed further with pressures around 50-60 bar. Subsurface brine will get saltier with time as boiling off due to drawdown proceeds.

Reykjanes, Iceland – Small geothermal area from surface manifestations (1.5 km²) at centre of volcanic system. Numerous NE-SW faults and crater rows occur. Recharge by sea water. Best feed zones are dyke feeders of eruptive fissures. Boiling reservoir about 300°C. Production of geothermal fluid (corresponding to 100 MW electric) over a period of 18 months caused a drawdown of more than 200 m in the reservoir. Recharge slow despite open faults and fissures, probably due to sealing off of the geothermal reservoir (by anhydrite deposition)? Steaming ground, fumaroles and mud-pools have increased drastically indicating development of a shallow steam zone as a corollary of the drawdown. Such conditions may result in steam explosions if fissures open up. No such have occurred so far in Iceland as a consequence of drawdown. The obvious practice (in Iceland) to avoid disastrous consequences is to drill and exploit the steam zone for power generation.

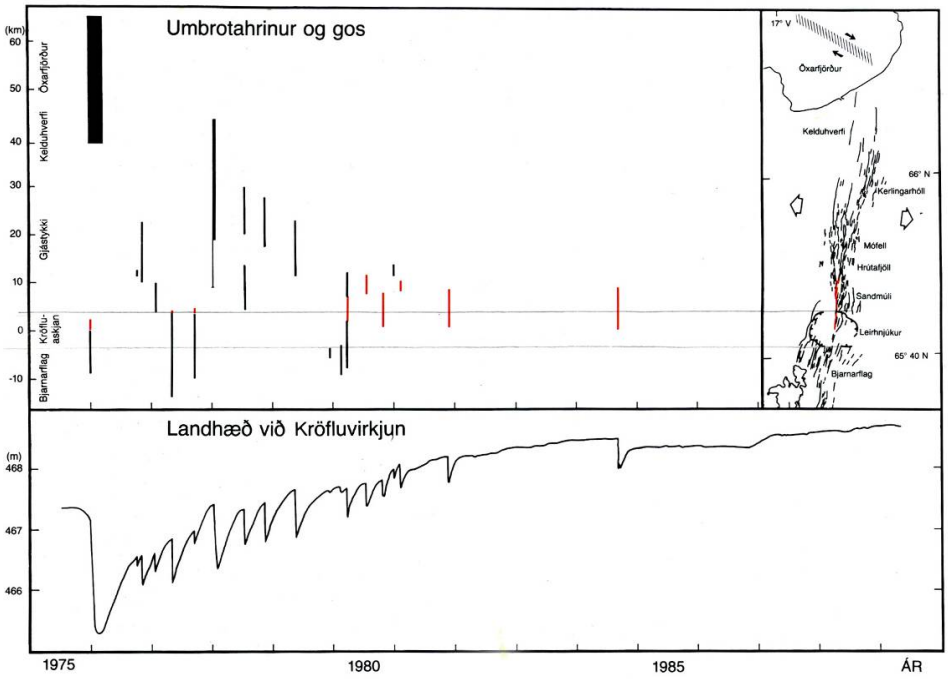

FIGURE 10: Krafla rifting episode of 1975-1984, course of events. Upper diagram: Dyking (black) and eruptive events (red). The bars indicate the part of the fissure swarm which were affected in individual events with reference to the map on the right. Their thickness is proportional to the time each event lasted. Lower diagram: elevation changes with time (Einarsson, 1991)

Krafla, Iceland – activity adjusted to slow spreading (half rate 1 cm/y). Rift episodes (Figure 10) occur at intervals of a few hundred years. Geothermal surface manifestations correlate with a preferred intrusion focus at centre of 8x10 km diameter caldera. Both have been extended in the direction of widening by about 1 km since the caldera formed 110.000 years ago. Magma chamber containing silicic melt in east central part of caldera. Rock composition basaltic to mixed basalt/rhyolite. A rifting episode occurred in 1975-1984. Precursory symptoms were earthquake activity starting a year before and elevation changes. Basaltic magma collected in magma chamber at 3-7 km depth. After filling and residence in magma chamber which took a few months, magma was expelled repeatedly as dyke intrusions with minor eruptions over a period of four and a half years. This was followed by further dyke intrusions and fissure eruptions occurring repeatedly over a period of another four and a half years (Figure 10). A total of about 1 km³ of basaltic magma was estimated to have been erupted and intruded as dykes. The widening of the fissure swarm amounted to max. 9 m on a 70 km segment of the fissure swarm. Geothermal power plant at Krafla produces 60 MW. A part of the geothermal system was contaminated and rendered unexploitable by a volcanic gas flux for about 15 years.

Dabbahu, Ethiopia – stratovolcano underlain by magma chamber. Abundant fumaroles at summit area of volcano extending from there towards north. Silicic rocks form the summit area, basaltic fissure eruptions on prominent fissure swarm. A rifting episode occurred in 2005. Precursory earthquake activity was followed by a minor mixed basaltic/silicic eruption and a major lateral magma flow at about 2-9 km depth 60 km to the SE. The intrusion event lasted less than a week. Dyke volume has been calculated about 2.3 km³. Widening of fissure swarm was about 6 m, with addition of several m throw to pre-existing fault scarps. There have been repeated rifting events after 2005, much less in size. These were not accompanied by inflation and deflation of central area. Possibly the explanation here is that dykes are fed from a lower crustal magma chamber.

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HIGH RESOLUTION AIRBORNE THERMAL INFRARED REMOTE SENSING STUDY, SILALI GEOTHERMAL PROSPECT, KENYA

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ABSTRACT

Airborne high-resolution thermal infrared (TIR) remote sensing has proven to be an effective method for mapping surface spatial temperature patterns. As geothermal energy continues to be a source of safe, reliable and renewable source of energy world over, TIR remote sensing has formed a key component of geothermal exploration. When combined with other spatial datasets, the TIR data showed areas of thermal influence resulting from geothermal activity associated with point, area and linear sources such as fumaroles, hot ground, fissures and faults. This paper describes the image acquisition and processing methodology, of high-resolution airborne thermography conducted over 2000 km^2 within the Silali geothermal prospect. The objective of the study was to characterize the geothermal features for further focused geothermal exploration studies.

1. INTRODUCTION

Thermal infrared (TIR) remote sensing provides data with synoptic coverage for investigating the surface manifestations of geothermal systems as applied to both geothermal energy exploration and also for more fundamental research and monitoring. TIR remote sensing provides a method for rapid mapping and quantifying surface geothermal features in support of exploration and assessment of new resources (Eneva et al., 2006; Kratt et al., 2006; Coolbaugh et al.,2007; Eneva et al., 2007; Rockwell and Hofstra, 2008; Kienholz et al., 2009; Littlefield and Calvin, 2009; Scherer et al., 2009; Taranik et al., 2009; Littlefield and Calvin, 2010; Haselwimmer et al., 2011; Reath and Ramsey, 2011).

Airborne thermal infrared remote sensing is a proven method of obtaining high-spatial resolution thermal imagery. Several applications using thermal imagery can be found in the literature. For example, Torgesen et al, 2001, used airborne thermal remote sensing to assess water temperatures in rivers and streams, related to fisheries habitat. Quattrochi and Luvall, 2003 presented several applications using airborne and satellite based thermal infrared applications to retrieve surface parameters and processes. This project was undertaken in Silali geothermal prospect in the Northern sector of the Kenyan Rift as shown in Figure 1. Previous integrated geophysical, geological and geochemical studies in the area (Lagat et al.,2010, Dunkley et al.,1993), indicated existence of a geothermal resource under Silali caldera which extends to the eastern flanks of the volcano.The results signified probable occurrence of a high temperature geothermal resource and recommended the prospect for further detailed investigations to determine its resource potential.

2. DATA COLLECTION

2.1 Description of the airborne remote sensing system

For this survey, a DigiTHERM thermal camera system was used (Figure 2). DigiTHERM is a camera developed for professional digital aerial thermography (IGI, 2013).

Its core component is an Infratec VarioCAM with 640 x 480 pixel field of view and 7.5 to 14 µm wavelengths and 30 mm focal length (InfraTec, 2013). With thermal resolution of 0.05K, the camera senses temperature in the range from -40°C to 1200°C. The uncooled microbolometer FPA-detector delivers thermal images in system-specific *.irb format. A graphical user interface allows real time preview and check of recorded thermal images.

The camera was mounted in a nadir looking position on a high–grade aluminum/carbon composite installed through a portal in the belly of a two engine Piper PA-31 Turbo Navajo aircraft chartered from Photomap International Ltd. (Andrea et al., 2012).

The thermal camera was operated via graphical user interface running on touch screen monitors (Figure 3) connected to the DigiCONTROL Sensor Management Unit (SMU). The raw thermal information was stored in 240GB Solid State Devices (SSD). For precise determination of position and altitude of the airborne sensor at the instant of exposure, the AERO control system used an Inertial Measurement Unit (IMU) for post acquisition georeferencing, orthorectification and mosaicking of the individual thermal images.

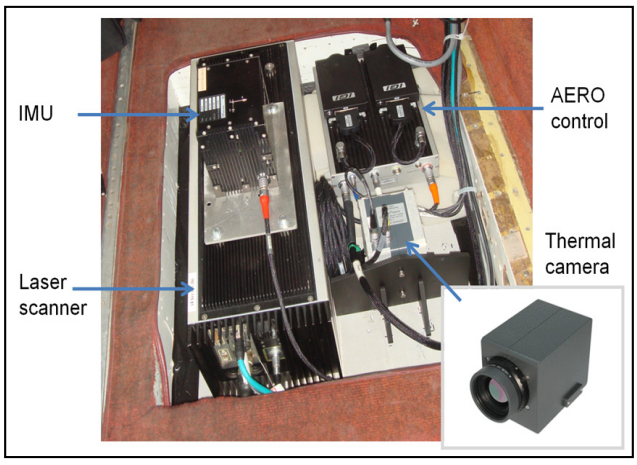

FIGURE 2: Thermal system equipment layout in the aeroplane

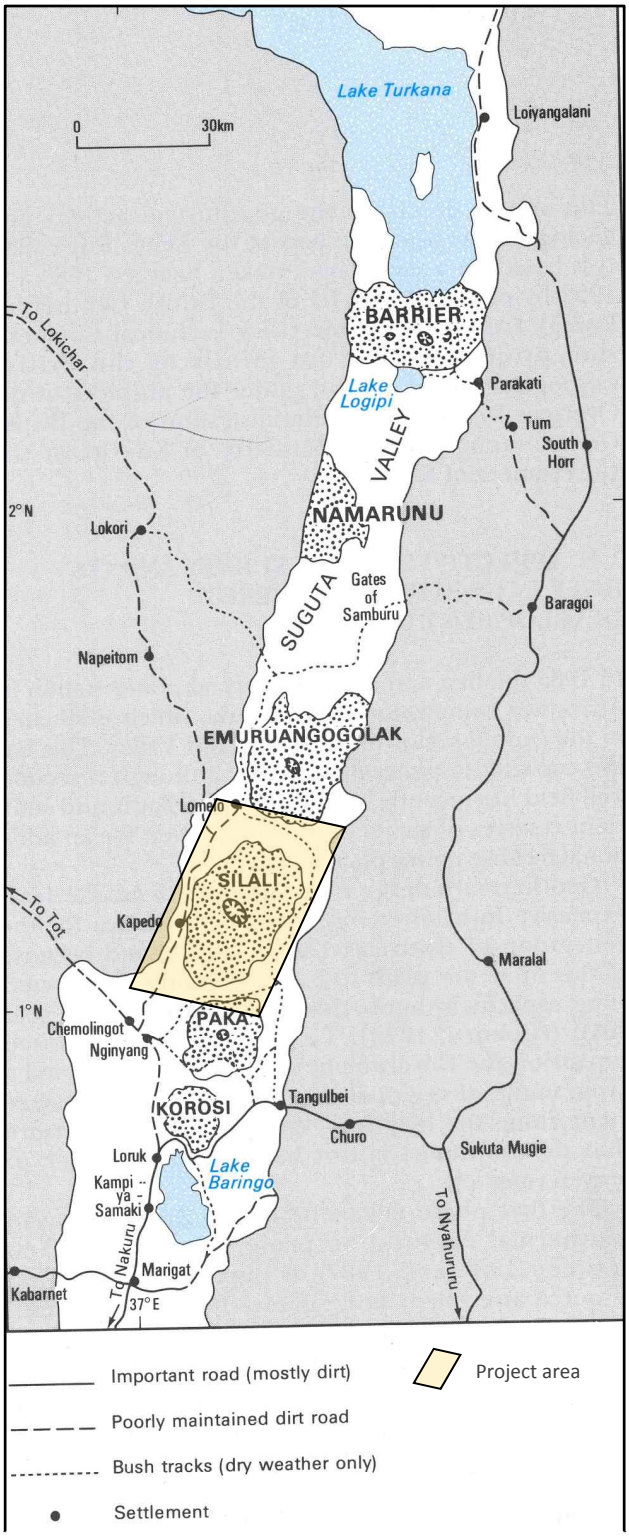

FIGURE 1: Map of the northern sector of the Kenya Rift showing the project area (modified from Dunkley et al.,1993)

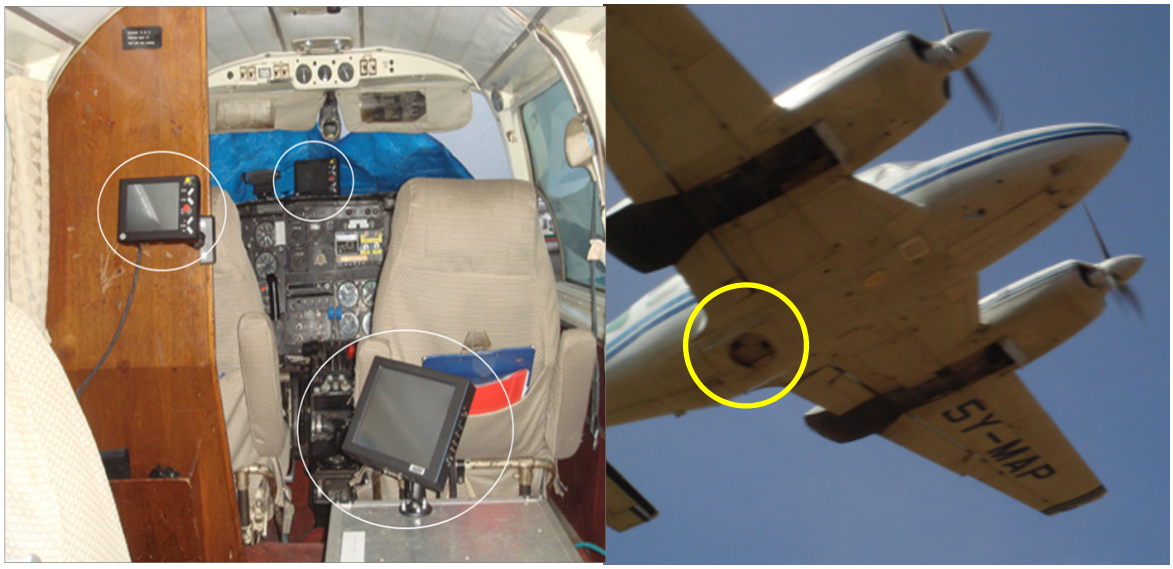

FIGURE 3: Touch screen monitors for operating the Thermal camera and the camera hatch as seen from below the aeroplane

2.2. Image Acquisition

High resolution thermal infrared images were recorded over an area of 2000 km^2 over the Silali geothermal prospect. A total of 32 flight lines each 50 km long where planned to ensure 25% side lap and 80% forward lap to guarantee complete coverage of the study area as shown in Figure 4. Other parameters are as outlined in Table 1.

TABLE 1: Key survey parameters

Survey parameters	Value
Altitude above ground	3,600 m
Flight altitude above mean sea level	4,500 m
Number of flight lines	32
Length of flight lines	50 km
Distance between flight lines	1,340 m
Distance between midpoints two thermal images	270 m
Mean GSD (ground sampling distance/ pixel size)	3 m
Field of view per image	1920 m by 1440 m
Number of triggered raw thermal images	6,236

In order to minimize influence of sun-dependent heating of the ground surface during daytime, the image acquisition over-flights were conducted during the second half of the night time hours (3:00 am to 6:00 am) and under clear sky conditions from 26th to 28th January 2012, This was to ensure that the thermal images are recorded at a time when the radiative cooling of the surface has been attained. Reference temperature thermal images and infrared thermometer measurements were carried out at Lake Baringo where surface water temperatures were recorded at hourly intervals on 28th January in the same site where a reference flightline of thermal images was also recorded.

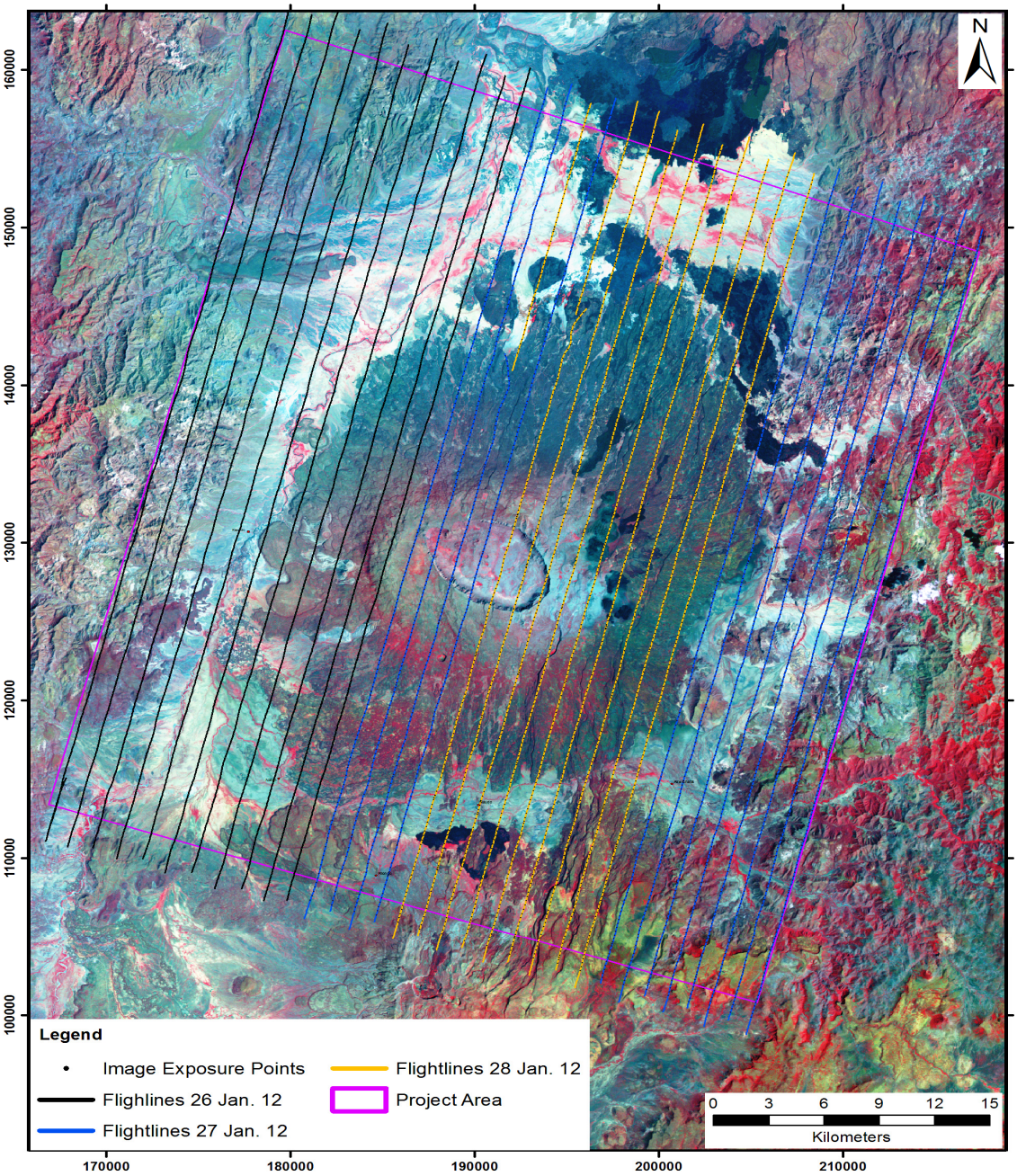

FIGURE 4: Landsat TM image (bands 421, RGB)

3. IMAGE PROCESSING

The individual spectral images from the DigiTHERM camera was stored in system specific format "*.irb" at a mean of 3-meter pixel resolution. Pre-processing was conducted for all the raw thermal images and calculation of orientation parameters for every single thermal image with IGI AERO office software with input data been the IMU records. After conversion of all raw thermal images to 8 bit and 16 bit *.tiff, direct geo-referencing of all single thermal images was done. This was followed the procedures outlined below:

a. Mosaicking of all 6,236 single ortho thermal images with automatic calculation of seam lines but without radiometric correction of camera lens' vignetting; resulted in ortho thermal image mosaic

(16 bit *.GeoTiff format) with visible seam lines. The mosaic was radiometrically unaltered and served as base for further temperature calibrations (step b),

b. From radiometrically uncorrected mosaic, the 16 bit digital number values of the mosaic's pixels were transformed to temperature ranges using temperature range function developed from relationship of image digital numbers and reference temperatures measurements (Figure 5). The result was a mosaic of thermal images, in which pixel values represented the surface temperatures.

c. In a parallel processing line, radiometric correction was applied in order to avoid visible seam lines. The output format was a 16 Bit GeoTiff. This mosaic showed a balanced grayscale distribution controlled by temperature relations but not absolute temperatures

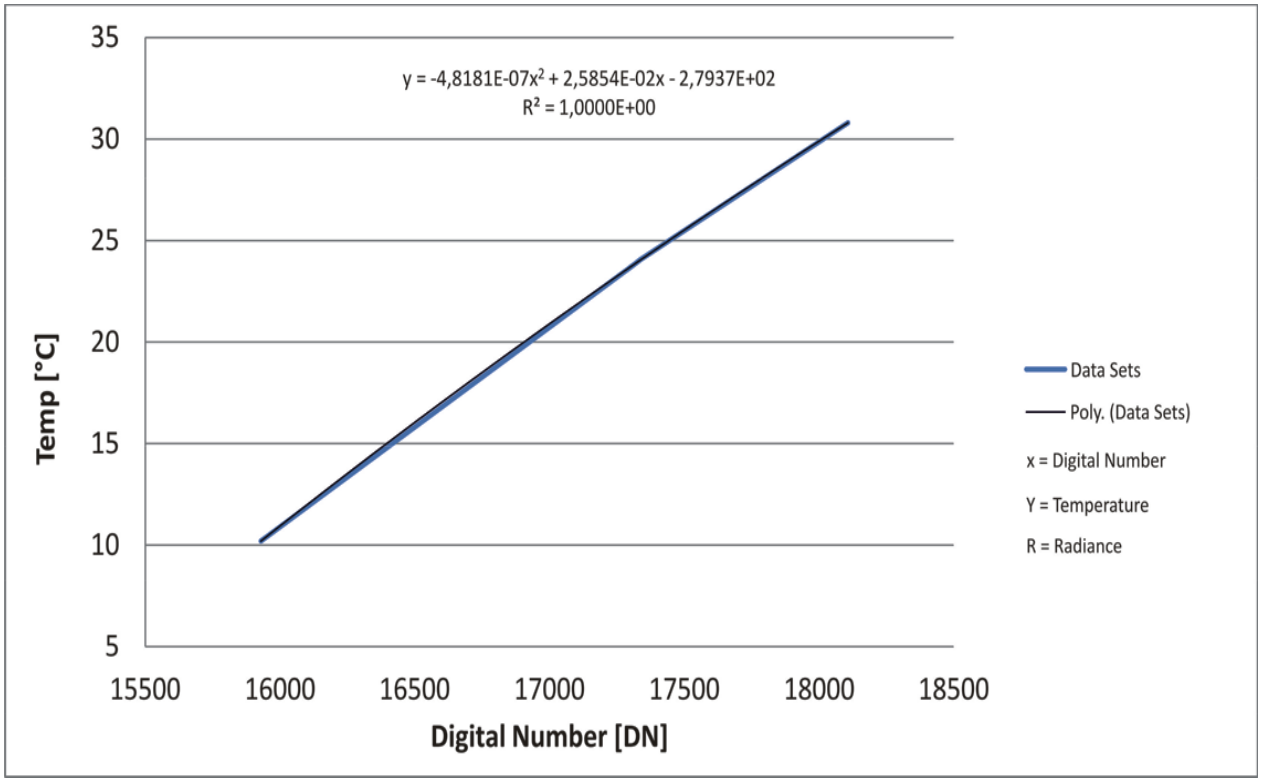

FIGURE 5: Temperature range function developed to convert 16 bit digital number values of pixels of single thermal images and of thermal mosaic to temperature values

4. RESULTS AND DISCUSSION

From the mosaicked thermal images more than 1000 thermally anomolous areas where identified from automatic screening. This outlined areas which were considered for further analysis of individual or smaller mosaics of thermal images and validated through field visits.

4.1 Analysis of single/mosaicked images of selected sites

Using the single thermal images or small scale mosaics of the anomalous areas as obtained from the automatic screening, detailed analysis gave more insights into these thermally anomalous areas as outlined below for areas A and B outlined in Figure 6.

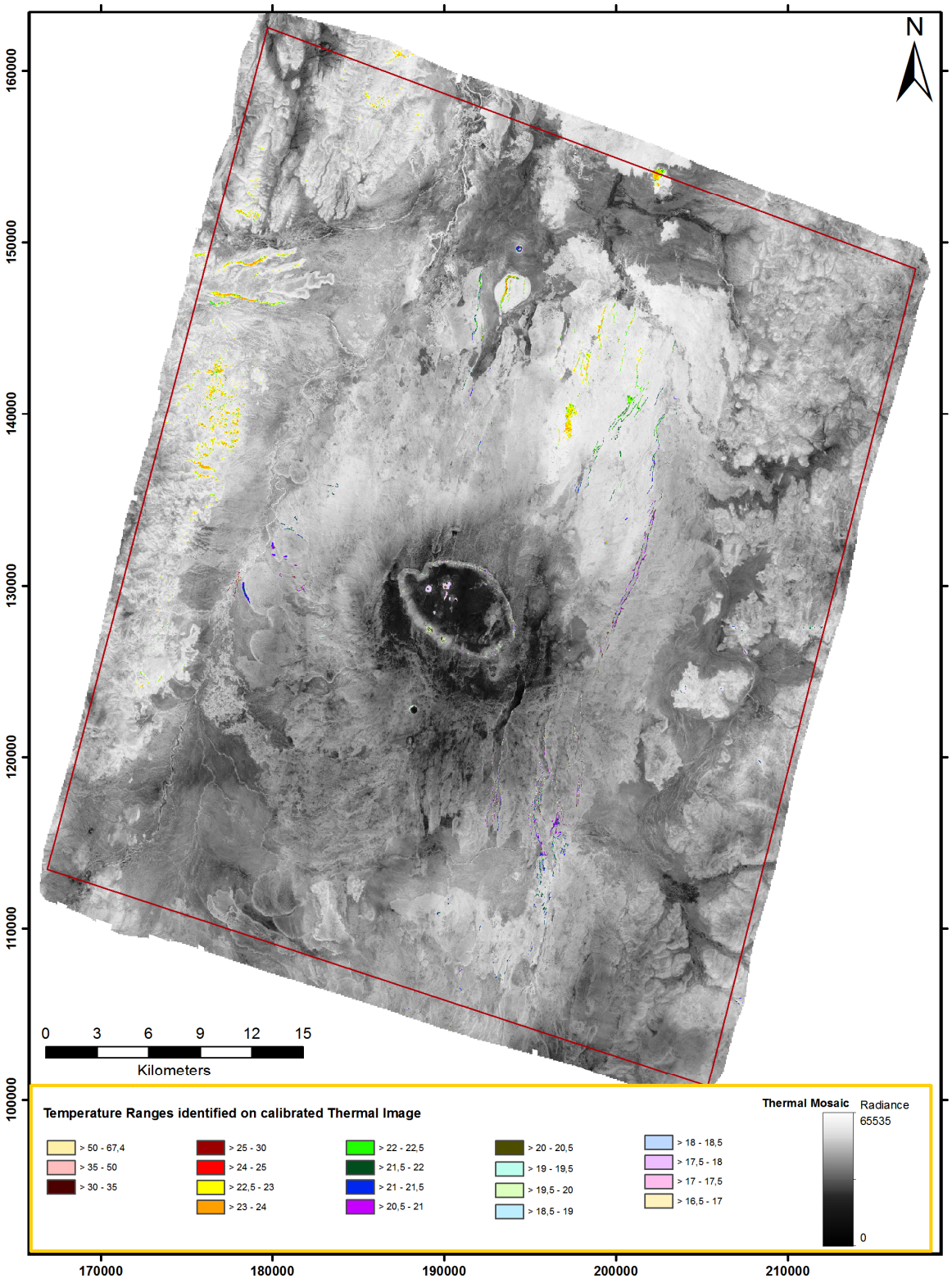

FIGURE 6: Thermal anomalies from the mosaicked image

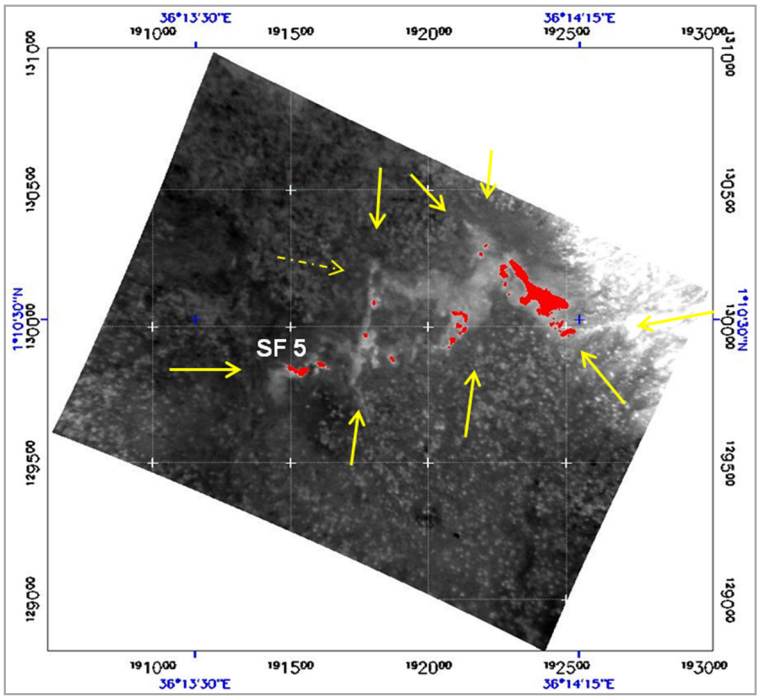

FIGURE 7: Thermal ortho-image of Area A

Fumarole field SF 5 before was known as single "hot spot". The measured temperature of fumarole SF 5 was 80°C, this showed the averaging of temperatures of the ground cells covered by pixel of a single thermal image. However, the thermal image revealed that SF 5 is a very complex system and not a single feature, most probably (Figure 7). Five nearly linear thermal features were recognizable on the thermal image (solid white arrows; dashed white arrows for indistinct lineament). The area of thermally anomalous temperatures is 1.0 km by 0.5 km wide. Highest pixel temperature of 18.15°C was recorded at E 191538 N 129837.General surface temperature of surrounding area was between 10 to 11°C. Areas with pixel temperatures higher than 14.20°C are highlighted on the thermal image and spot image (Figure 8) and show the whole extend of the system.

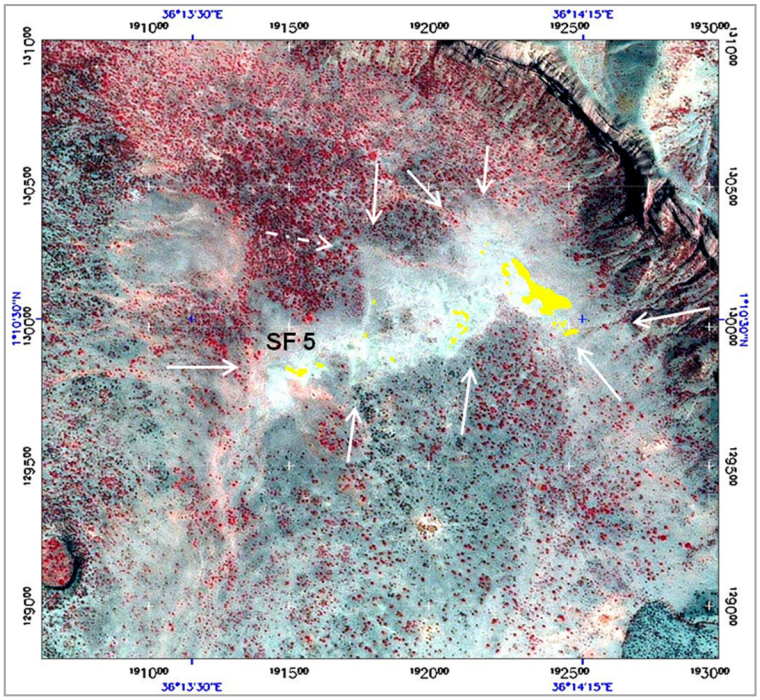

FIGURE 8: Thermal anomalies over Spot 5 image of Area A

The area marked on the thermal image (Figures 9 and 10) showed the highest pixel temperatures of 18°C and area marked b also showed elevated temperatures of 15°C to 16°C. The highest temperature was measured directly at a junction of two linear features (marked with B) and the others outlined by the arrows. The thermal anomalies followed the dense NNE-SSW trending fault lines and fissures in this area. Therefore, we suppose that the linear fault lines and fissures are the conduits of the recorded thermal anomalies in this region associated with magma at depth. This approach was applied for the different thermal anomalies identified after the thermal screening for in-depth understanding.

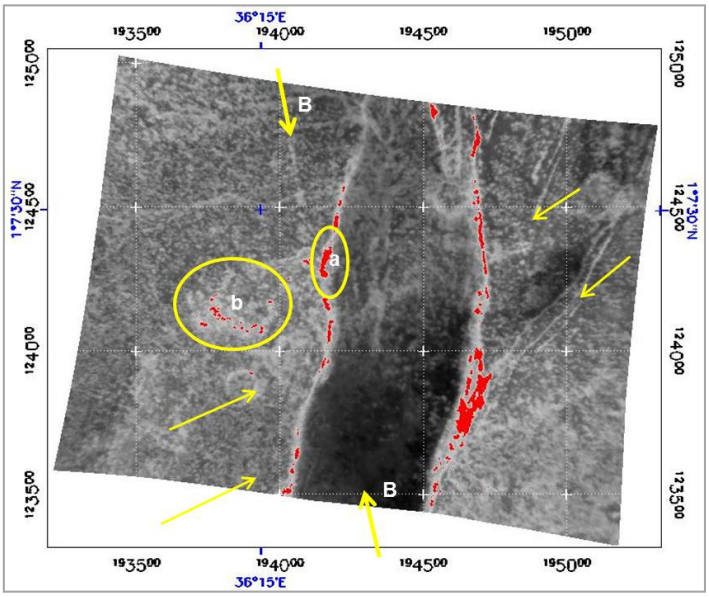

FIGURE 9: Thermal ortho-image of Area B

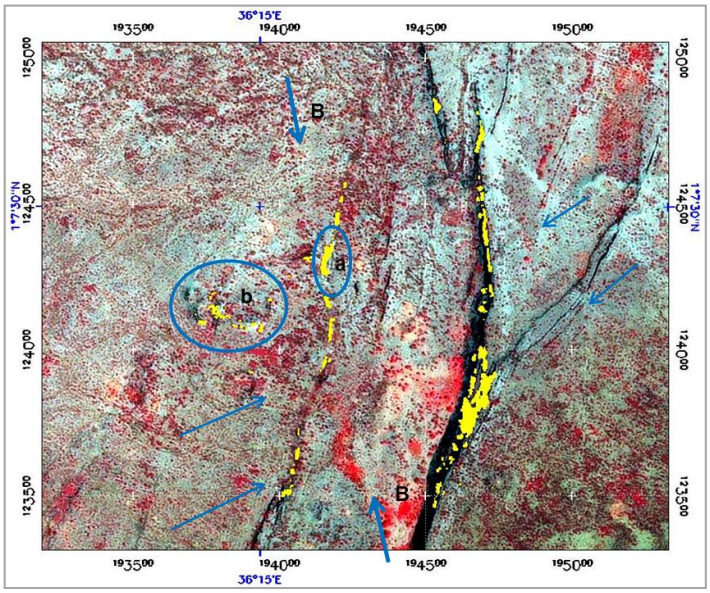

FIGURE 10: Thermal anomalies over Spot 5 image of Area B

5. CONCLUSIONS

Airborne thermal infrared remote sensing has the flexibility to provide imagery with reasonably high spatial resolution which was valuable in locating unidentified thermal anomalies in Silali geothermal

prospect. Thermal anomalies in the Eastern flanks of the caldera was mapped which was found to be related with the intense fissures and fault system in the area. Also already known fumaroles and hot grounds were revealed from the thermal survey that they covered extensive areas that known before. The discovered thermal anomalies complemented earlier exploration works in the area and helped in characterizing surface thermal anomalies and understanding of thermal relationships that were not known before. The use of high resolution TIR remote sensing was not separated from other aspects of science (geology, geochemistry, and geophysics). Therefore, TIR remote sensing provided a unique tool for qualitative and quantitative initial investigations contributing to detailed geothermal exploration surveys in geothermal exploration. The surface geothermal activity from TIR was also used to refine the interpretation and conceptualization of results from other exploration approaches. The obtained airborne TIR data will also be used to support long term monitoring of geothermal system in the prospect by providing repeatable method of inventorying surface geothermal features.

ACKNOWLEDGEMENTS

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INFRARED AND SATELLITE IMAGES, AERIAL PHOTOGRAPHY

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ABSTRACT

We will in the following mention a few remote sensing methods that are applicable in geothermal prospecting. Air photo interpretation has been practised in geology for 70-80 years. Infrared scanning became popular in the late nineteen fifties and satellite images followed in the seventies. Infrared sounds good as geothermal is concerned but its use has been limited. Satellite images have proved valuable in geology for recognizing all sorts of lineaments and also features have been discovered that were too large to be recognized from ground studies of conventional air photos. The Yellowstone caldera is an example. Several impact craters showed up around the world. In Iceland under-ice caldera volcanoes were detected. The stereoscopic view of air photos, however, is by far the most important for the geologist. Unfortunately access to them is limited in many countries as they are considered a kind of security information. Needless to say that ground check is needed to interpret the features correctly.

1. THERMAL INFRARED

Thermal infrared remote sensing (TIR) scans thermal surface activity, and difference in temperature (from tonal contrasts). Also heat loss through hot or warm ground by conduction can be calculated. The method requires temperature measurements in the topmost part of the soil to find the thermal gradient. This must be done at the same time as TIR. Changes in thermal areas can also be mapped and monitored by TIR. Infrared remote sensing of geothermal areas is preferably done from airplane before sunrise. At that time the contrasts come out best. The best conditions for application are in dry climate regions with minor cloud cover for days or weeks.

The method can be used also for mapping of thermal properties of different rock types. Then two flights are needed, one at about noon the other before sunrise. Sometimes considerable thermal radiation is found where no geothermal manifestations occur on the surface. In most cases this is due to insolation of dark rock. Obsidian flows are an example.

Two figures of the same area represent a sparsely vegetated and partly barren fumarole field and its surroundings at Hengill in SW-Iceland. Figure 1 shows thermal features above 25°C, from green to red (boiling). Lower than 25°C has been filtered out. The distribution, here NW-SE, correlates with a regional feature of that trend but of unexplained origin. A dominant NE-SW-fault pattern in this general area does not show up.

In Figure 2 the TIR has been superimposed on a geothermal map based on a ground survey. Here the pink spots mark hot ground (not hot springs as it says in the explanation), violet marks clayey alteration, and light brown marks low grade alteration. The latter two were defined as mainly cold. The ground survey would have been cheaper and it shows the alteration state of the ground. However, the TIR would make it possible to assess the heat loss, not done though for this small part of the geothermal field. On the other hand the natural heat output of 90% of the area of the Hengill geothermal field was calculated 470 MW from this survey.

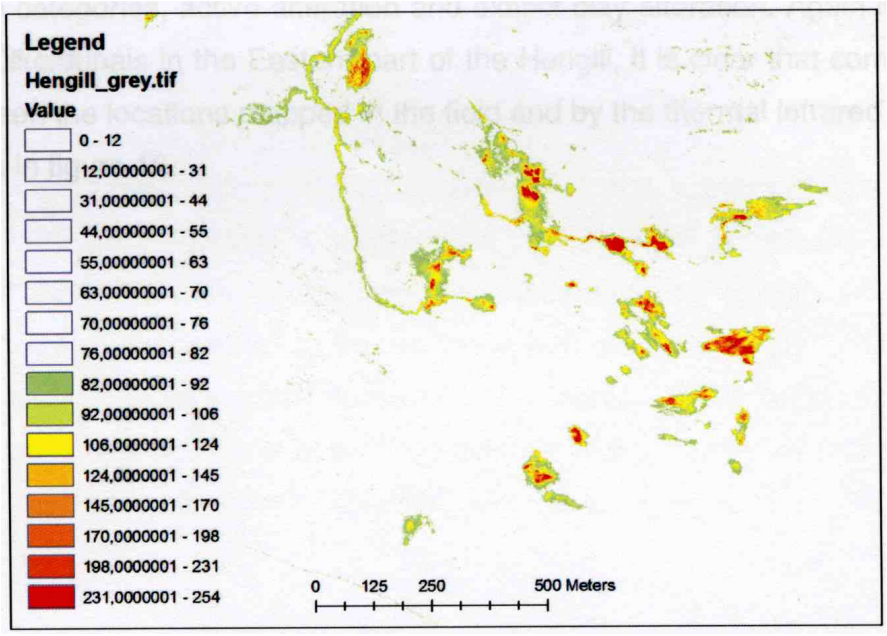

FIGURE 1: Thermal features of the Hengill area. The colours represent represent geothermal activity where the reflective temperature is above 25°C. Red represents the highest temperature. Temperatures lower than 25°C are filtered out

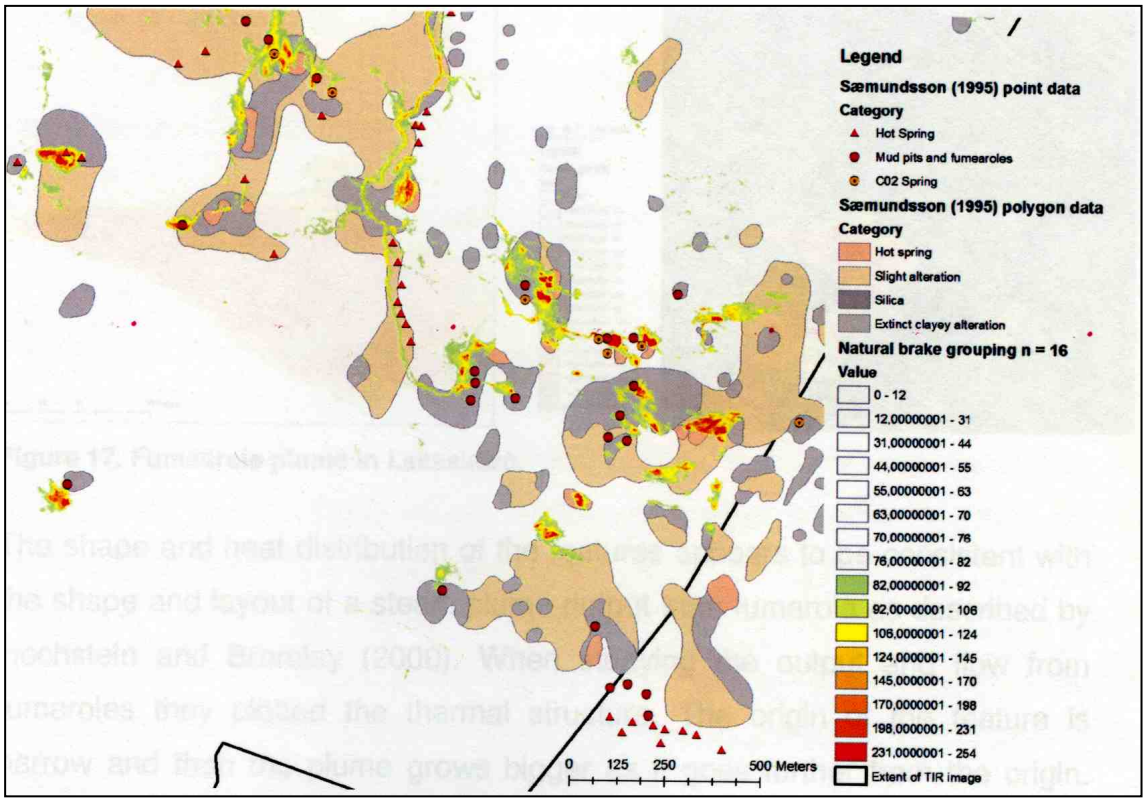

FIGURE 2: Comparison between geothermal mapping in the Hengill area and results from TIR imagery

Interestingly calculations of heat output have repeatedly shown that most of it is from the hot ground around the steam vents or mud pools.

2. SATELLITE IMAGES

Satellite images give a splendid overview where regional structures are prominent. Ground check and comparison with geological maps is important. The method has been successfully applied for over 30 years with increasing resolution from Erts, Landsat, Envisat to Spot-5 with resolution (pixels) down to 5 m. As an example the first ERTS-images of Iceland (in 1972) revealed several calderas in the ice-covered volcanoes up to then unrecognized (Figure 3).

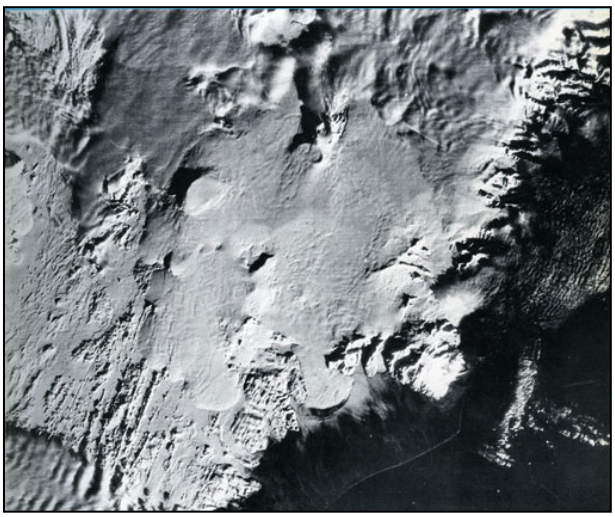

FIGURE 3: Vatnajökull glacier (9500 km²) is located in the smooth field in central part of the figure. Two central volcanoes with calderas were first recognized in its NW and SE part from this image. A third caldera to the north of these was also recognized here for the first time.

3. AIR PHOTOGRAPHS

Air photographs are an important aid for the geologist in geological mapping, especially as regards volcanic and structural features. There are several types of pictures, such as black and white, true colour, and false colour. In mapping of geothermal and volcanic areas the false colour photographs have proved superior to the others (Figure 4). Stereoscopic view is necessary.

Air photos reveal a wealth of surface features, primarily as regards structural elements. In geothermal areas also such features as are directly related to thermal activity show up. Among them alteration (light surface colours), slide on unstable slopes (clayey ground) hydrographic features (dominant trends) and lava flows with different vegetation cover (helps define relative age but roughness must be accounted for.

After locating a thermal manifestation - Role of the geologist:

- Define type: Fumarole, steaming ground, spring, seepage, CO_2 vent, alteration, type of surface clay (kaolinite or smectite). Type of efflorescence minerals. Temperature. Flow rate.
- Define local geological control.
- Correlate with ground temperature survey and soil gas survey if such is made.

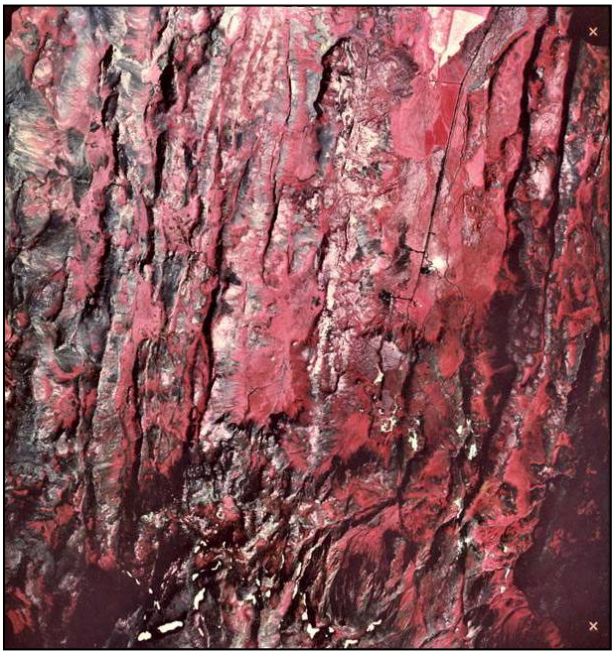

FIGURE 4: A false colour photograph of a 4x4 km area northeast of Hengill in SW-Iceland (northeast is up, vegetation is deep red (grass) and pale red (moss). Normal faults show up prominently. A zone of crater rows runs parallel to the faults through the upper two thirds of the photograph just east of the centre. This zone marks the main upflow of the geothermal system northeast of Hengill.

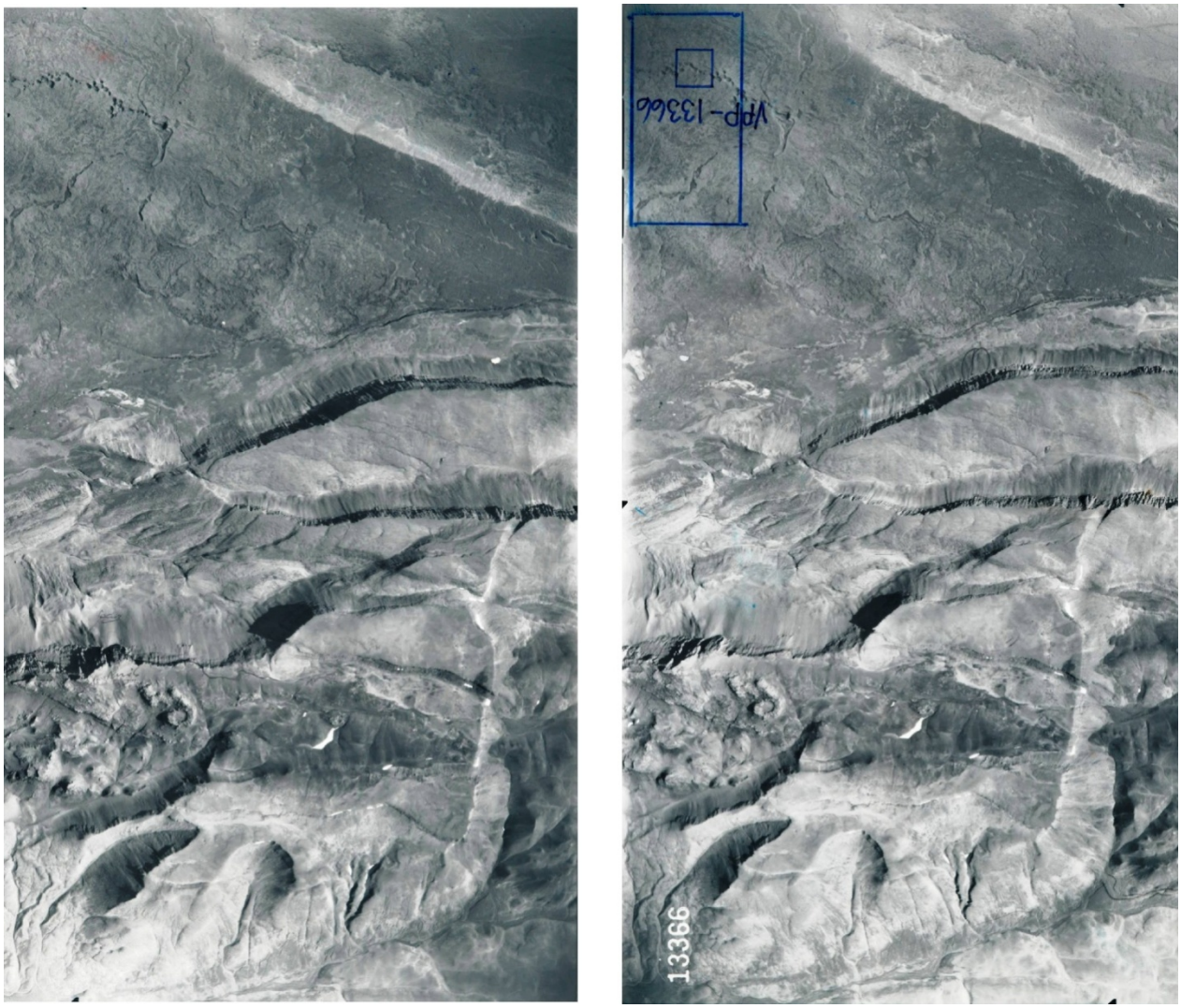

FIGURE 5: Stereopair of black and white air photographs. Large normal faults dissect the mountain complex in the lower two thirds of the pictures. A hyaloclastite ridge in lower one third overlies a tuya (subglacial lava shield) with glacial cirques. Holocene lava in upper one third. North is to the left.

4. InSAR

InSAR (synthetic aperture radar interferometry) is a powerful method of measuring mm scale crustal distortions from slight changes in the travel time of a radar beam played across the surface from a satellite. It is mainly used in surveillance of earthquake prone areas and volcanoes. It is also used to monitor ground level changes caused by exploitation (lowering of water level) of geothermal systems. Figure 6 shows an example from Askja, a central volcano in north Iceland.

An example is shown also from Reykjanes where drawdown of some 700 m the water level in the geothermal reservoir has caused subsidence. The mass extraction is about 400 l/s for a 100 MW power station over a period of 5 years. It is balanced partly by reinjection. InSAR observed a 5 cm subsidence of the ground during a four years interval (2005-2009) northeast of the main subsidence bowl. This agreed with a 12 cm subsidence at the production area shown by GPS between 2004 and 2010.

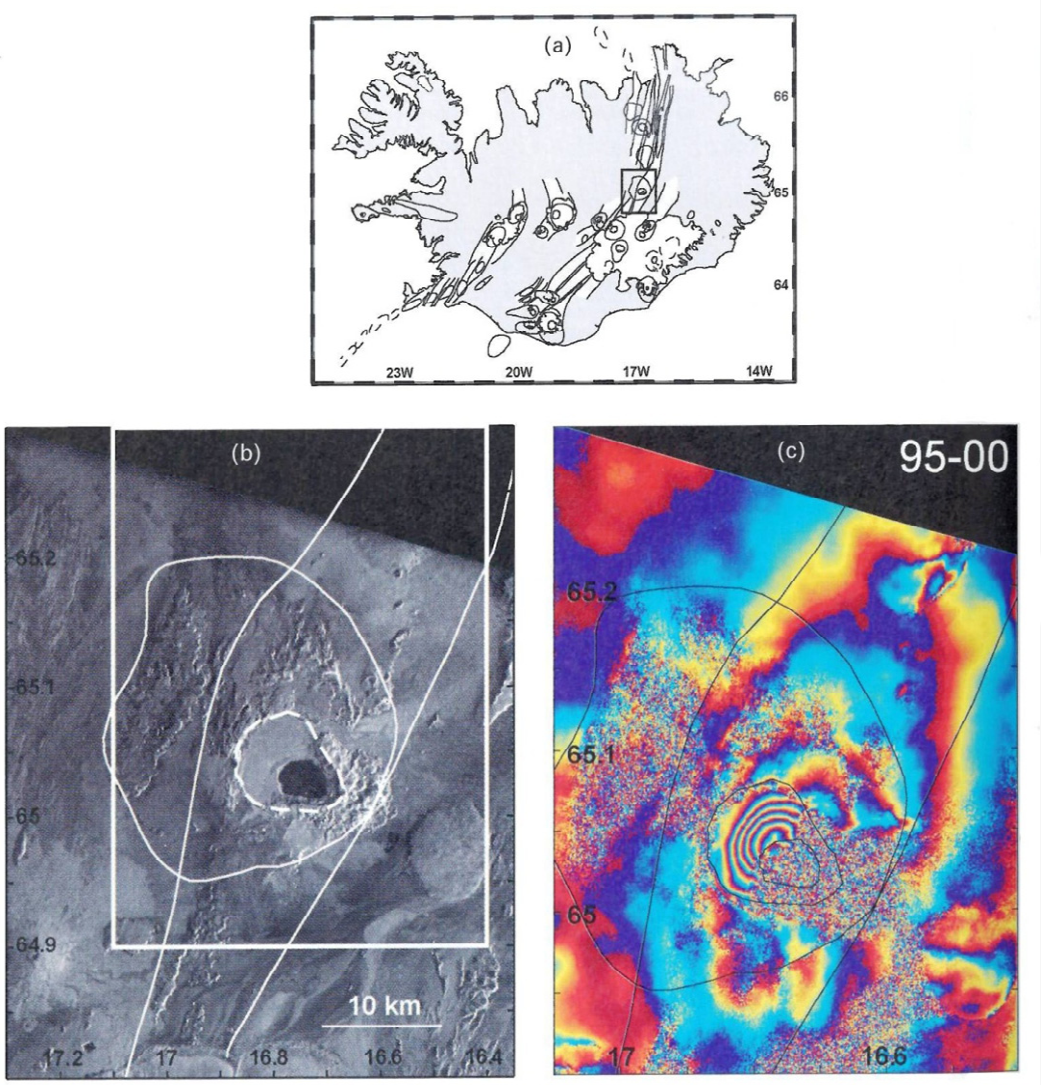

FIGURE 6: Askja volcano, Iceland and its calderas and associated fissure swarm. On the right: Interferogram spanning 1995-2000 shows subsidence centred on the main elliptical caldera. A full colour cycle corresponds to a change in range from ground to satellite of 2.8 cm (in total about 15 cm). Diffuse pattern is due to snow cover (F. Sigmundsson 2006: Iceland Dynamics. 209 pp. Springer).

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GEOLOGY AND GRADIENT WELLS

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ABSTRACT

Drilling of gradient wells is a method used in exploration of both high- and low-temperature geothermal fields. The applicability of the method depends on the permeability of the subsurface rock and the depth to groundwater. Low permeability is a prerequisite for the method to give reliable results because it is very important to avoid disturbance from internal flow of water inside wells. The drilling depth is accordingly anywhere from a few tens of metres to a few hundred metres. The latter may be necessary in areas of young or unaltered volcanics and low ground water level (such rocks are also as a rule costly to drill and secure from caving in). In fracture controlled low-temperature fields shallow boreholes come out best. This method has been applied also in high-temperature geothermal fields both as a regional survey and as testing the validity of indirect evidence (from geology or resistivity) of a potential. It is clear that knowledge of the hydrological conditions of the prospect area is needed, and also familiarity with the basic principles of hydrogeology.

1. THERMAL GROUND SURVEY

Drilling of gradient boreholes is in a way an extension of a ground temperature survey (temperature measured at 50-100 cm depth). In Iceland this method has been applied both in low-and high-temperature geothermal fields, partly with a different purpose in mind, however. In the low-temperature areas the method is used to outline the areal extent of an anomaly, its size and shape with the purpose of siting a hot water borehole. An example is shown from a left lateral fracture zone in South Iceland (Fig.1, 2 and 3). Warm springs in a bog with draining ditches indicated a thermal upflow. The ground survey suggested two parallel NE-SW trending fissures. Well number 1 was shallow but used for two decades. Well 2 was

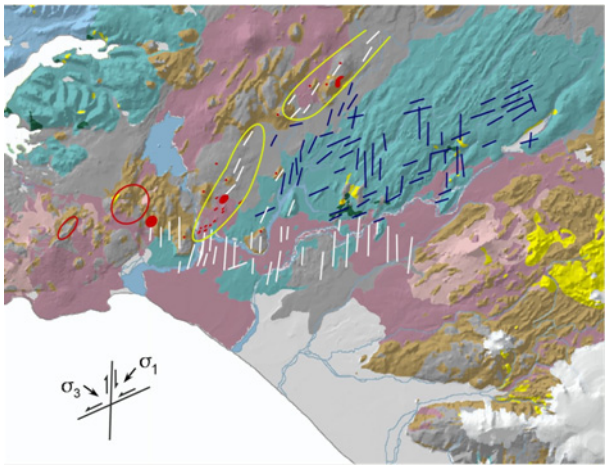

FIGURE 1: South Iceland Seismic Zone (a transform fracture zone) connects the two rift zones in South Iceland. It is characterized by a conjugate set of N-S and ENE-WSW faults. They are shown white where active and blue where extinct, indicating a former position north of the present location

unsuccessful. Well 3 struck a fissure and yielded plenty of 59°C water but the temperature was inverted at 115 m depth indicating lateral flow along the fissure system.

In high-temperature fields the method (ground temp. survey) has been applied only once in Iceland, in one of the smallest by area (Reykjanes) to estimate its thermal output. However, the main profit there was of a different kind, i.e. giving a basis to record changes, first decline of surface activity over a period of 40 years followed by a dramatic increase. This occurred after beginning of production on a large scale and thickening of a steam zone as a consequence of drawdown. A thermal ground survey of this kind was carried out in the Eburru and Olkaria geothermal fields at the early stage of prospection (Noble and Ojiambo 1975). It extended and outlined the shape of many fumarole fields in a clearer way than could be judged from the manifestations alone in a hot and dry climate at day time. No changes due to exploitation of the fields have been observed there.

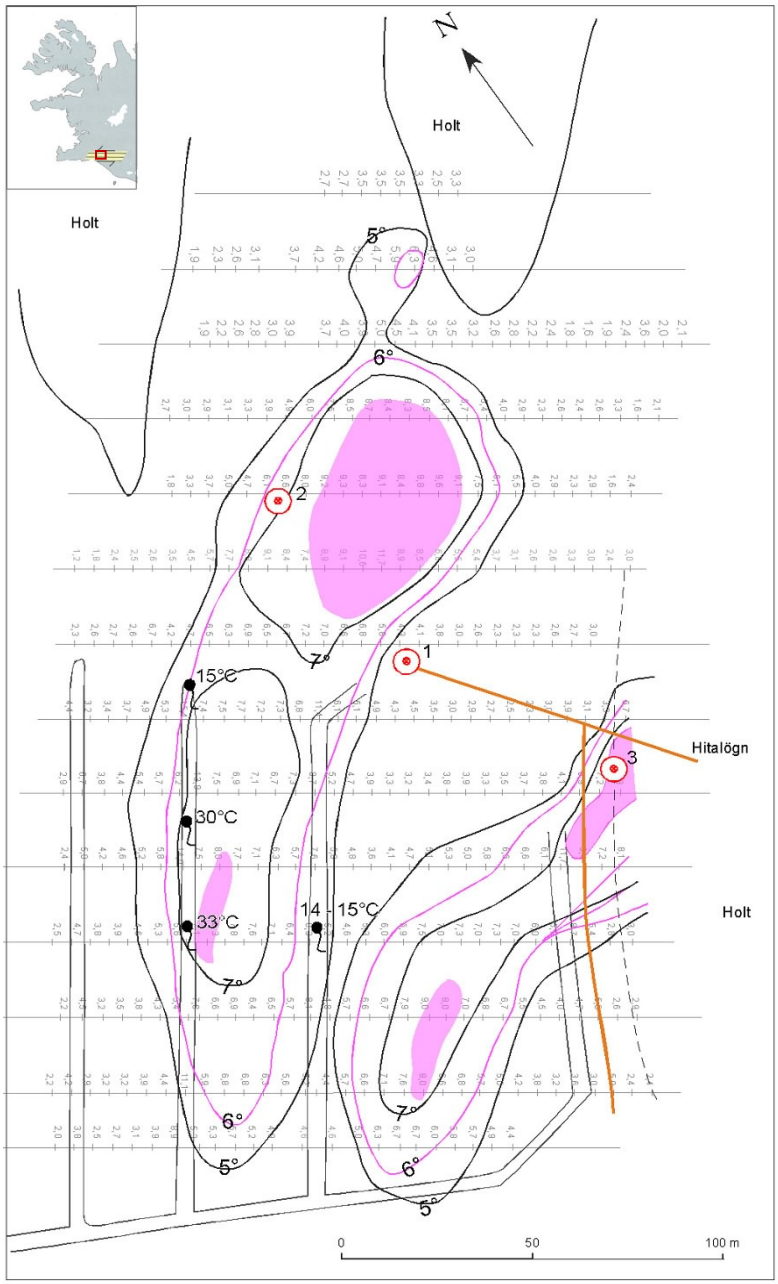

FIGURE 2: Example of a soil temperature survey. The locality is in the western part of the South Iceland Seismic Zone (SISZ). Warm springs are found in drainage ditches dug in a wet bog. Soil temperatures of over 10°C at 60 cm depth are shown in pink. Holt to the northeast and east are hills where Pliocene bedrock (basalt) is exposed. The survey was made in December. The trend of the thermal anomalies follows the trend of earthquake fissures which are the main targets for hot water drilling in the SISZ. Two en-echelon segments of a N-S main right lateral strike-slip fault were found

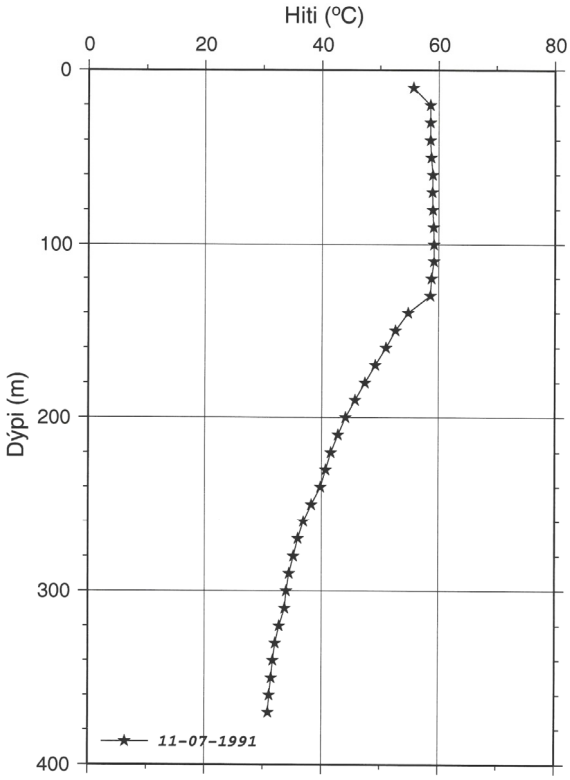

FIGURE 3: Temperature profile of SH-3 (of Figure 2). Plenty of 59°C hot water was found in a fissure from 70-120 m depth. The fissure was permeable down to ~250 m but the temperature inverted below 120 m, indicating lateral flow from higher ground to the North

2. LOW-TEMPERATURE GEOTHERMAL FIELDS

In low-temperature areas gradient boreholes need to be no deeper than 30-60 m if the permeability is low. The regional geothermal gradient must be known also as a basis for recognizing thermal anomalies. The greater the difference, the better are the prospects for success. The method has proved most useful in areas where the geothermal system is confined to a fracture of local extent. In Iceland many exploitable geothermal systems have been discovered by this method where there were no surface manifestations. Figures 4 and 5 from West Iceland are an example. The very high near surface gradients stem from a convective geothermal system. In this case it proved to be 85°C extending with constant temperature from 400 m down to at least 800 m (depth of production borehole). Fracture controlled

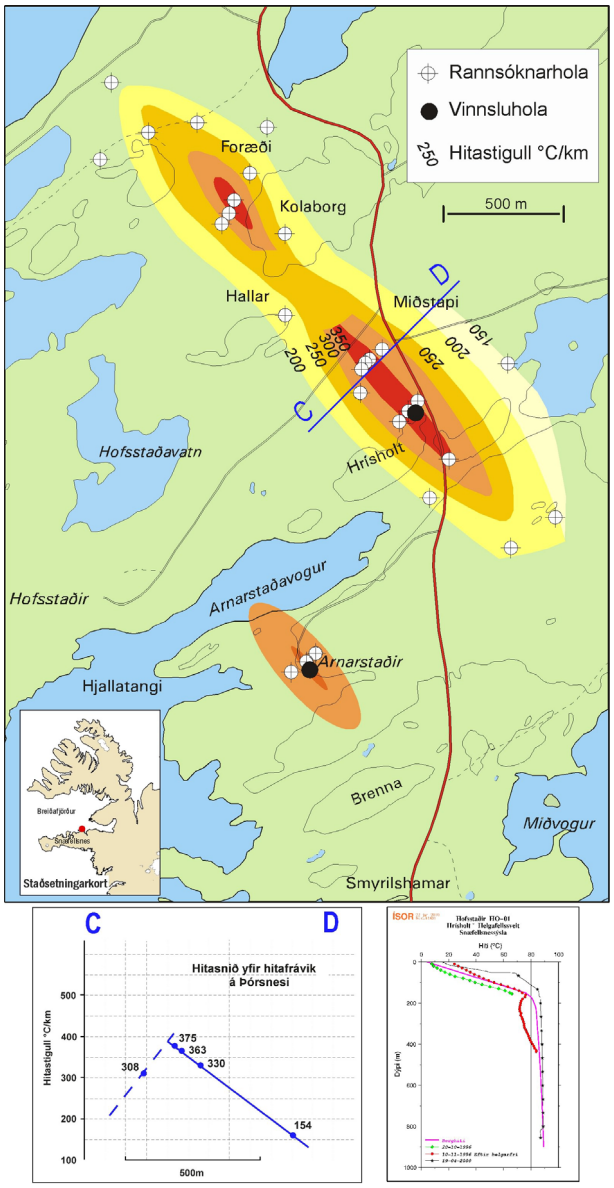

FIGURE 4: A regional thermal gradient survey was made of the Snaefellsnes Peninsula. An indication was found here in the first shallow borehole. This was followed up by further drilling of shallow wells (60 m deep, on average 2 were drilled per day). The outcome is shown on the map. A production borehole was drilled vertically into the peak of the larger anomaly. It produced about 20 l/s of 85°C hot water from a single fissure which was cut at 810 m depth. A second reinjection borehole was drilled 1500 m to the NW with the purpose of intersecting the same fissure. It was struck at 400 m depth with a similar yield and water temperature. Interference from a pressurization test occurred within less than 5 minutes

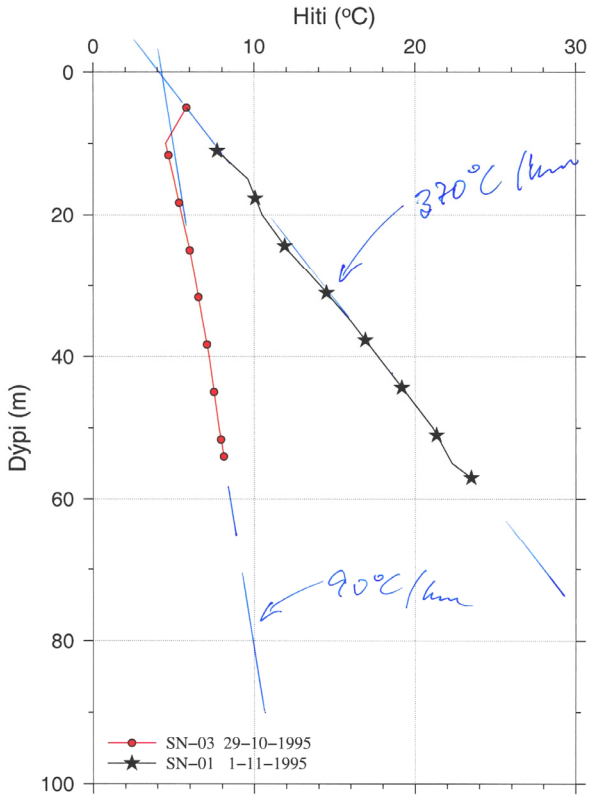

FIGURE 5: Thermal gradient in area of Figure 4. The bedrock there is zeolitized Miocene basalt lavas of very low permeability. Two shallow boreholes, 1500 m apart, show near surface regional gradient, versus local anomalously high gradient. Such high values as found in SN-1 can only be explained by an underlying geothermal system. There are no surface indications of a geothermal system in this area

geothermal systems can develop anywhere, also in areas of low geothermal gradients including the continental average of ~30°C/km.

Sedimentary basins are probably the most extensive hot water reservoirs. As regards those it would be sufficient to compile data on the sedimentary fill, permeability of the different sedimentary units and their facies changes. Many basins have been targets in oil prospection in particular molasse basins, but also sediment filled continental rifts.

The second main issue here is the geothermal gradient. The Hungarian basin e.g. gives high but variable values (50-70°C/km) (Rybach and Muffler, 1981). Basic information on such parameters often exists but may not be open as it is owned by private companies. Faults may add significantly to permeability and dilute a brine fluid (commonly found in basin fills) by recharge from precipitation.

2. HIGH-TEMPERATURE GEOTHERMAL FIELDS – FROM GRADIENT WELLS TO EXPLORATORY DRILLING

For interpretation it is important to know the basic character of a high-temperature geothermal system. Typically there is boiling groundwater at some depth from which steam and gas are boiled off to escape at the surface (fumaroles, solfataras, mud pots, hot ground). Sometimes the steam and gas get drowned in a (perched) near surface aquifer (in areas of sedimentary cover, Kaldakvísl). At low altitude the reservoir water may flow out forming flats of silica sinter deposited from boiling springs, often with geyser-activity (spout intermittently).

Drilling of gradient wells is sometimes applied in high-temperature areas. Gradient boreholes may be shallow or deep depending on the nature of the near surface rock. Preferably they should reach well down into near impermeable rock (due to alteration). Shallow boreholes (<100 m) in permeable rocks are not likely to yield temperatures much higher than 100°C, but they may show meaningful areal temperature variations and thus extend surface indications downwards (example from Djibouti, Stieltjes, 1976). In Iceland 40-60 years ago shallow wells were drilled in the midst of fumarole fields

in Námafjall, Hengill, Krýsuvík and Reykjanes, (Figure 6) using inappropriate equipment, and insufficient casing.

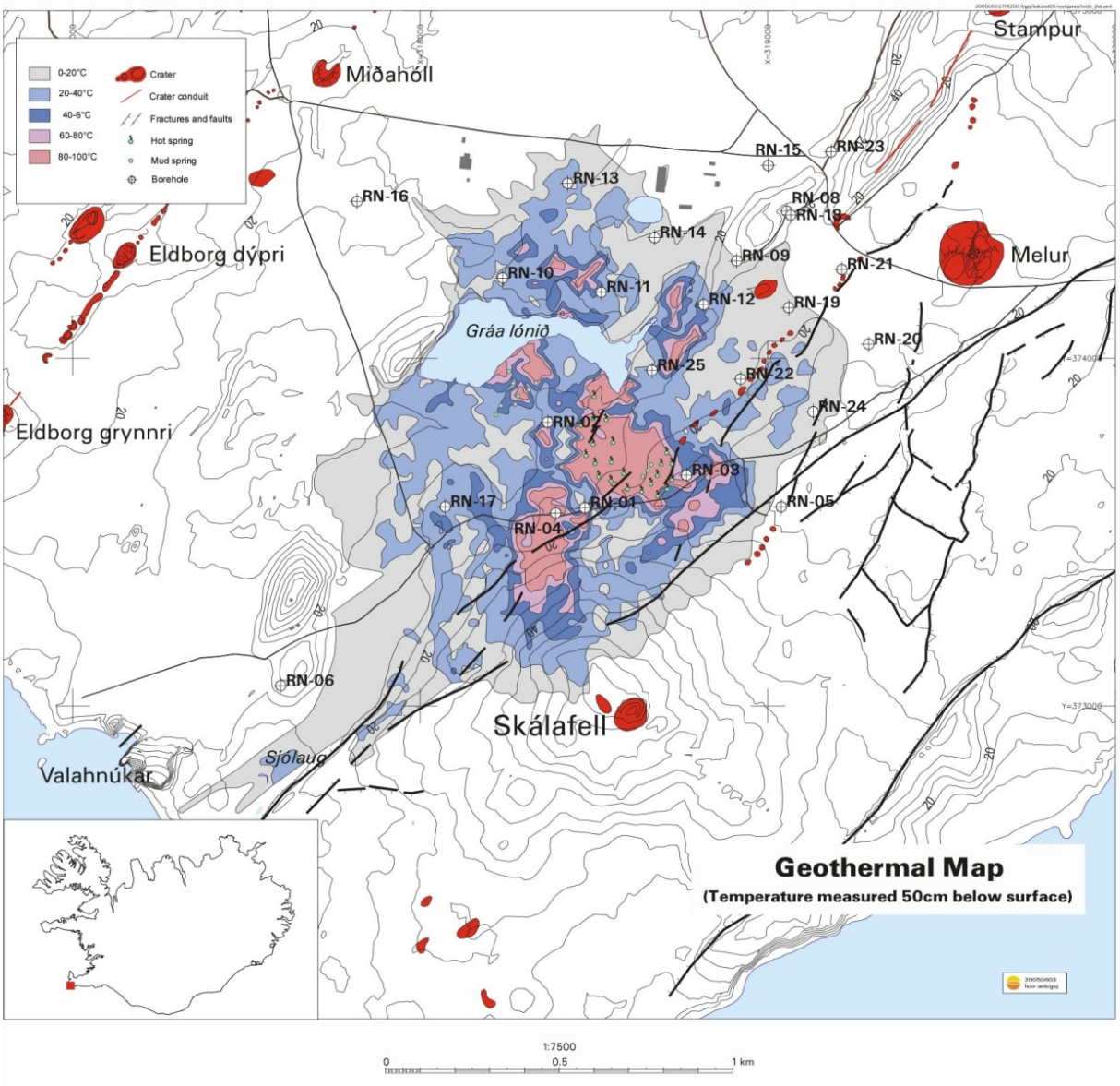

FIGURE 6: Ground temperature survey of Reykjanes, a high-temperature geothermal field at the tip of the Reykjanes Peninsula, SW-Iceland. The bedrock is Holocene basalt lavas. The first boreholes (RN-1-4) were drilled in the hottest part of the field. They all failed due to overpressure and insufficient casing (collapse). Borehole 5 was drilled to the east of the thermal anomaly. It failed also because of caving in of unaltered and unstable rock. It was drilled close to a fault and ended at 100 m. The first successful borehole (RN-8) was drilled into altered hyaloclastite 100 m northeast of the hottest area. The hyaloclastite is part of a NE-SW ridge system (constructional features show up in height contours). It proved later to be the main upflow zone of the field

The main purpose was to produce steam and locate a good production zone. Most of the boreholes ended in blow-up and/or collapse. Their depth varied from less than 100 m to over 300 m. Temperature logs were obtained only from the last ones drilled. Some of those boreholes have been blowing to this day. At Námafjall they emit dry steam and attract tourists not knowing how they came about. At that time a few boreholes, interestingly some of the first ones, were also drilled on more stable ground well away from the fumaroles (Krýsuvík). Those could be kept under control and they yielded valid information about subsurface temperature, in fact were useful gradient boreholes as

planned. Those early attempts failed because knowhow was insufficient to complete a shallow borehole into a steam zone underlying a highly active fumarole field. The subsurface extent and trend of such a field, however, could have been judged from the thermal gradient in boreholes drilled into altered rock some distance away.

Shallow gradient boreholes may give a misleading result. An example from Krýsuvík, Iceland (35 years back) is shown (Figures 7 and 8). Down to 300 m depth the results look promising, and no indication is seen of the temperature inversion, which occurs at greater depth. A recent example from Krafla is of interest. There a resistivity survey (Figure 9) was followed up by two shallow step-out boreholes (well away from the production area) and a third full-scale production hole where the prospects looked best - but proved the worst. One of the shallow boreholes showed the prospective resistivity anomaly to be cold the other to be hot as was inferred from surface geology. The latter was followed up by a production borehole, which was a success.

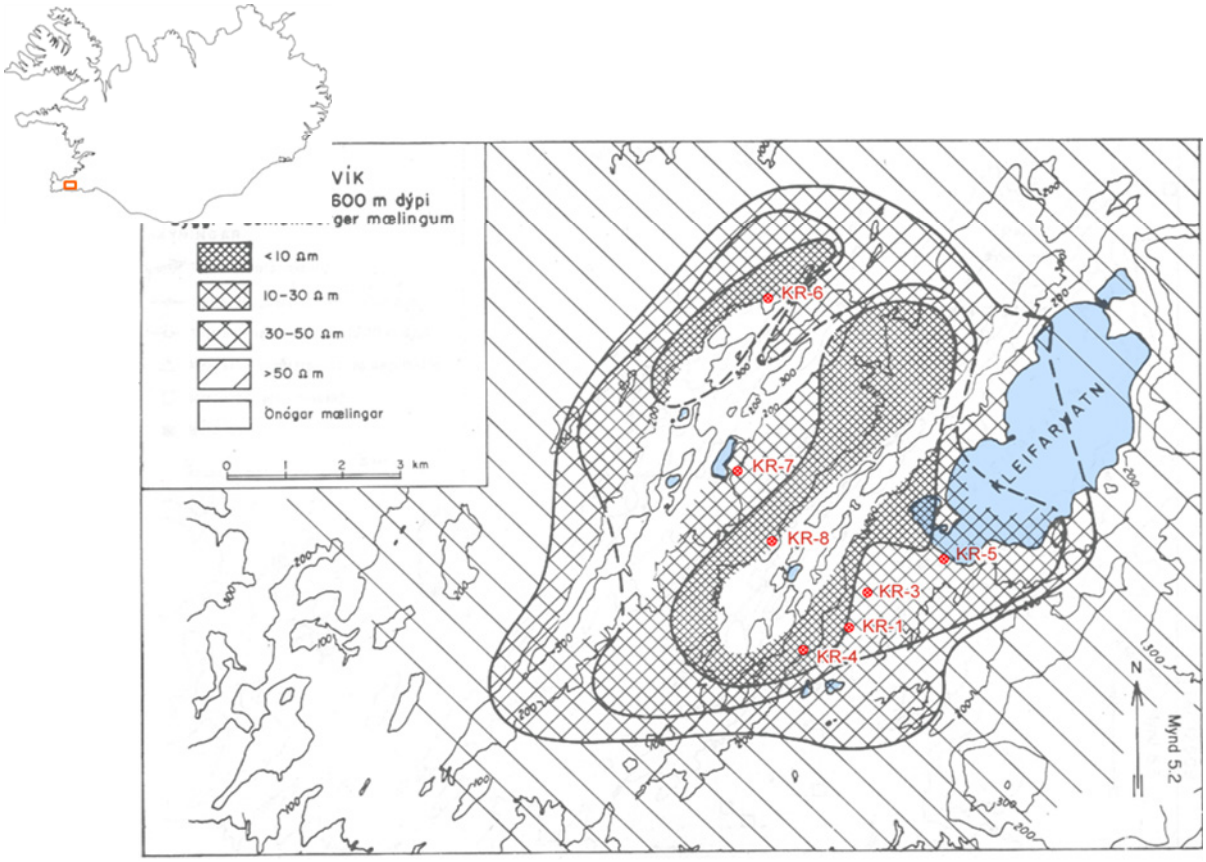

FIGURE 7: Krýsuvík. Resistivity at 600 m depth. Krýsuvík is the largest geothermal field by area on the Reykjanes peninsula, SW-Iceland. Geological structure, thermal manifestations and resistivity surveys indicate NE-SW trending prospective zones superimposed on a circular area, possibly a caldera. The markings show the location of moderately deep exploratory wells that were drilled 35 years ago. None of them found an upflow zone. Exploration by deep drilling is being taken up again these years concentrating this time about zones where eruptive fissure cluster

In Iceland the method (drilling of shallow gradient wells or medium depth exploratory wells) is not used as an early step in subsurface exploration, except where resistivity alone indicates a resource. Gradient boreholes or more often deep exploratory boreholes are drilled to follow up surface exploration if the results of the various methods correlate tolerably well.

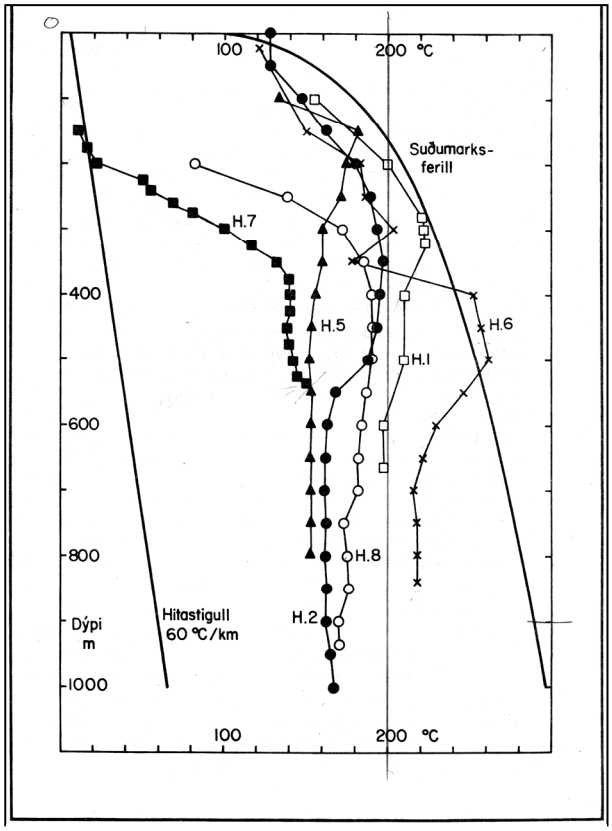

FIGURE 8: Temperature logs of exploration wells at Krýsuvík, shown in Figure 7. Down to 300 m depth none of the wells indicated the temperature inversion which occurred at greater depth. Gradient wells of 300 and in some cases 500 m depth would in this case have been misleading

A geothermal gradient map was compiled of the Campi Flegrei geothermal field, within a caldera west of Napoli, Italy, from 30 to 140 m deep water wells (Corrado et al. 1998) (Figure 10). High but variable gradients were found within the caldera. Correlation of the local anomalies with small magma bodies as suggested by the authors seems rather doubtful. Viewed against other information such as structural features, hydrology, and the occurrence of geothermal surface manifestations the map seems to add little to the deep structure of the field. On the other hand it is a good basis for monitoring changes both associated with natural unrest and exploitation if such come about (deep drilling has revealed temperatures of 300-400°C below 1500 m depth).

The lessons to be learned are that gradient or exploratory wells should be drilled down to at least 500-1000 m. Such wells are usually drilled vertically. Inclined wells in the deeper range would be appropriate in rift zones, especially for the purpose of testing the permeability of vertical (or near vertical) fissures and dykes. Such may act as high-permeability anomalies and optimal feed zones (Hengill, Eldvörp). The most important information to be gained would be a temperature profile of the prospect area as compared with the alteration state of the rock. A misfit (high alteration state but low rock temperature) may indicate cooling of the system (due to old age and exhaustion of the heat source) or a drop in water level (hydrostatic pressure) which might have occurred in the course of geological time. Think of pluvial periods (high lake stands) in low latitudes equivalent to glacial periods at high latitudes.

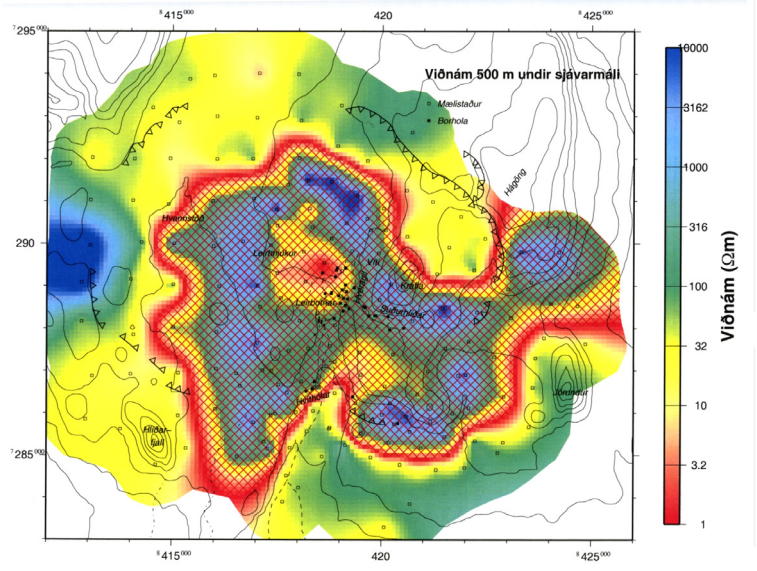

FIGURE 9: Resistivity map of Krafla at 900 m depth. The outline of the Krafla caldera is shown. Drilling of a gradient well into the anomaly east of the caldera proved it to be cold, probably an extinct part of the geothermal system from the time of its „youth“. A deep well drilled into the large anomaly which extends furthest south showed it to be a hot outflow zone. A sharp temperature inversion occurred below it, contrasting with high temperature alteration of the rock mass, but in accord with the high resistivity. The outflow is restricted to the uppermost permeable 500-800 m metres showing up as a low resistivity zone

It is important at an early stage of geothermal prospection to investigate the hydrology of the surrounding region such as precipitation, catchment area (for likely recharge), and depth to groundwater level, general flow direction and content of dissolved solids (get access to data from appropriate authorities). The last is an important issue to avoid locating deep wells in outflow areas too far off from upwelling geothermal plumes. The ground water level may be low (at several hundred metres depth) under large volcanic edifices which host a geothermal system. One way to get at them is by directional drilling.

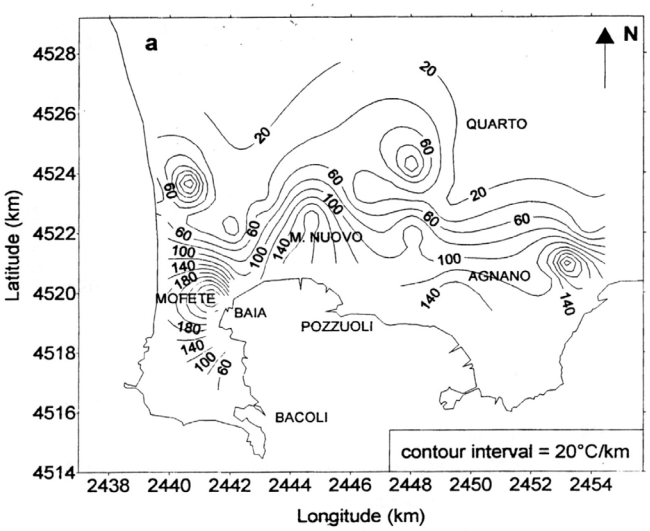

FIGURE 10: Geothermal gradient map of the Campi Flegrei high temperature geothermal field, Italy. The field is located in the northern half of a caldera. The map seems to be rather a blunt tool for concluding about deeper structure of the field, but may prove significant in volcano surveillance. Deep drilling (2000-2500 m wells have been drilled) revealed temperatures of between 300 and 400°C (From: Corrado et al. 1998).

Fumaroles are an indication of a boiling reservoir. Intensive fumarole activity and widespread hot ground (several hectares in extent) point to a steam zone at shallow depth (Figure 11, Námafjall). Such conditions call for precautions and an appropriate casing program when drilled into. In Iceland blowouts occurred under such conditions from time to time and are always time consuming and costly.

Temperature profiles are different in vapour dominated systems (nearly constant temperature and pressure with depth) versus water dominated systems where temperature increase is likely to more or less follow the boiling point curve at shallow depth. Temperature inversion commonly occurs, always indicating a marginal location or a mushroom character spread or outflow (Figure 11).

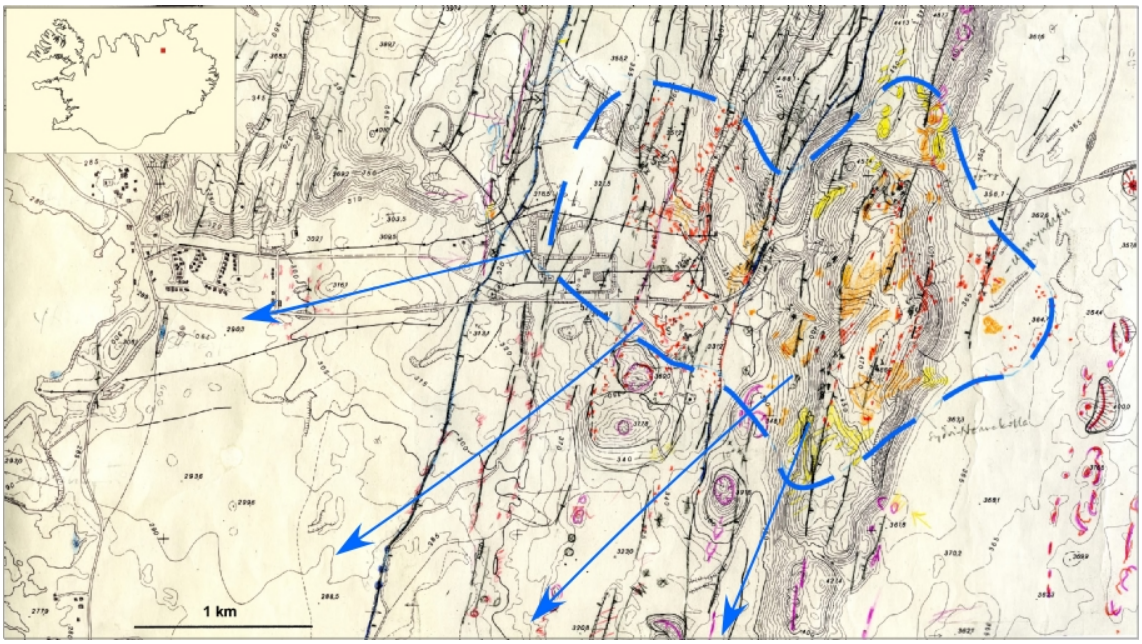

FIGURE 11: Geothermal map of Námafjall high temperature field in NE-Iceland

Námafjall high temperature field is 7 km south of Krafla on the same fissure swarm in NE-Iceland. As Figure 11 shows, Námafjall is traversed by a number of NNE-SSW faults and a few volcanic fissures. Hot ground and fumaroles depositing sulphur extend over large coherent tracts which follow the general fissure trend of the area. The first boreholes were drilled in the eastern part of the area 50 years ago. They struck into a steam zone and were difficult to keep under control. In the nineteen sixties 6 successful production boreholes were drilled in the western part of the field. They got plugged up by basaltic melt in 1977 (known because one of them erupted lava) when a dyke injection from Krafla intruded along the fissure swarm. The blue arrows (Figure 11) mark the outflow, which is 20-50°C hot at a distance of 1-2 km from the field.

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GEOHAZARDS IN GEOTHERMAL EXPLOITATION

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ABSTRACT

Geohazards need to be taken into account in harnessing of geothermal areas. This applies in particular to the high temperature type which is in one way or another related to volcanic or intrusive centres. The issues to be regarded include the type and history of volcanism, definition of segments with most active fault movements, earthquake activity including microseismicity, slope stability and possibility of flash floods. Gas fluxes from magma chambers or intrusive activity may cause corrosion problems of production wells. In geothermal systems of restricted recharge drawdown of the reservoir fluid causes thickening of the overlying steam zone and increased surface geothermal activity.

Hazards involved with exploitation of low and high temperature geothermal systems where hosted in sedimentary or thick pyroclastic deposits having limited recharge may cause ground subsidence and damage to buildings and roads.

1. INTRODUCTION

Geohazards in high temperature geothermal fields involve earthquakes, volcanic eruptions, fault movements, intrusions, gas fluxes emanating from intrusive bodies, and rock slides. Earthquakes and intrusions are not only hazardous; they may also prove beneficial for the geothermal systems by maintaining/stimulating secondary permeability. Magma movement is not always associated with volcanic eruptions. Monitoring of ground movements associated with production from the reservoir and latent creep or rifting episodes in extensional geological settings will be touched upon briefly.

For assessment of geohazards in the East African Rift it is necessary to collect information about former events. Reliable documentation of events there reaches back only about one and a half century as regards earthquakes and volcanic eruptions. As regards the latter, prehistoric eruptions can often be dated and also defined as to type (explosive or effusive) and volumes. The past is here the key to the present.

2. LARGE TECTONIC EARTHQUAKES

Large tectonic earthquakes are the most hazardous. Figure 1 shows earthquakes which occurred in East Africa in the period 1963-1989 (Kaban and Kuhanek 1991). The epicentres including aftershocks may define active faults underground. There have been 20 quakes of magnitude (M 6.5 to 7.4) in East Africa since 1970, all of them in the Western Rift. The depth of most is between 10 to 33 km (NEIC

catalogue) (Figure 2). Large earthquakes occur also in the Eastern Rift, but they are rare. The largest occurred in 1908 in Ethiopia. Earthquake swarms with hundreds of shocks occur (largest of M 4-5.5) but they do not cause much damage normally. They may define also some specific features such as intrusions or fracturing due to cooling in the periphery of existing shallow magma chambers.

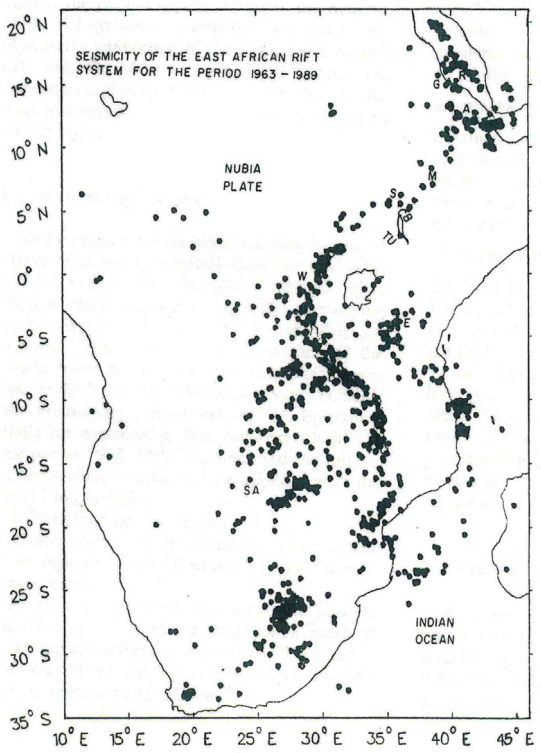

FIGURE 1: Seismicity of the East African Rift system and southern Red Sea for the period 1963-1989. Solid circles denote earthquake epicentres taken from National Oceanic and Atmospheric Administration (NOAA) catalogue. (From: Kbede and Kulhánek, 1991)

NEIC: Earthquake Search Results

U. S. GEOLOGICAL SURVEY

EARTHQUAKE DATA BASE

CAT	YEAR	MO	DA	ORIG TIME	LAT	LONG	DEP	MAGNITUDE
PDE	1973	08	28	150159.10	-0.19	-18.03	33	6.9 UKPAS
PDE	1975	10	07	082809.50	0.80	-26.77	33	6.7 MsGS
PDE	1979	08	25	084404	10.73	-41.69	10	6.6 MsGS
PDE	1982	01	03	140950.45	-0.57	-21.87	10	6.5 MsGS
PDE	1984	11	01	044850.27	8.19	-38.79	10	7.4 MSBRK
PDE	1985	06	06	024012.95	0.93	-28.43	10	6.6 MSBRK
PDE	1992	08	28	181846.44	-0.96	-13.56	15	6.9 MwGS
PDE	1992	12	26	195224.90	-0.56	-19.32	27	6.8 MwHRV
PDE	1994	03	14	043015.75	-1.28	-23.57	10	7.0 MwGS
PDE	1995	05	18	000627.46	-0.89	-22.00	12	6.8 MwHRV
PDE	1996	02	16	094458.41	-1.50	-15.28	10	6.6 MwHRV
PDE	1996	02	18	234928.16	-1.27	-14.27	10	6.6 MwHRV
PDE	1996	06	02	025209.55	10.80	-42.25	10	7.0 MwHRV
PDE	1996	12	10	083618.70	0.87	-30.04	10	6.7 MwHRV
PDE	2003	11	09	195236.82	-0.67	-19.69	10	6.6 MwHRV
PDE	2003	12	21	074045.83	-0.77	-20.60	10	6.6 MwHRV
PDE	2005	01	12	084003.65	-0.88	-21.19	10	6.8 MwGS
PDE	2007	08	20	224228.53	8.04	-39.25	6	6.5 MwGCMT
PDE	2008	02	08	093814.10	10.67	-41.90	9	6.9 MwUCMT
PDE-W	2008	04	24	121449.92	-1.18	-23.47	10	6.5 MwUCMT
PDE-W	2008	05	23	193534.94	7.31	-34.90	9	6.5 MwUCMT

FIGURE 2: Earthquakes of M 6.5 and larger in East Africa since 1970 (From: USGS)

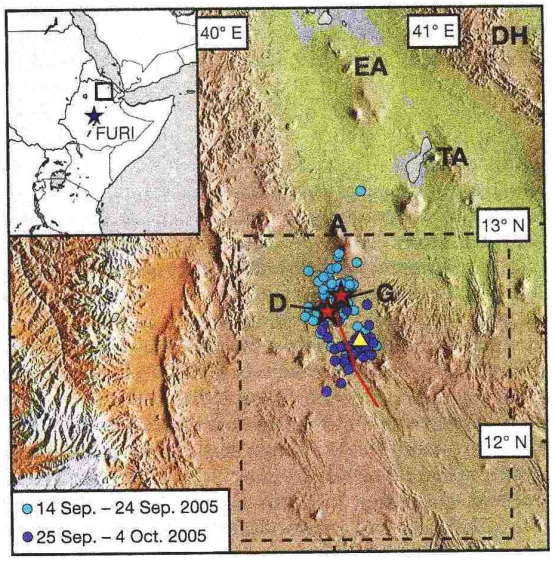

FIGURE 3: Red line shows location of dyke and red stars mark Dabbahu volcano. (From: Wright et al., 2006)

3. VOLCANIC ERUPTIONS

Volcanic eruptions in the Rift system are different as regards area and type. Basaltic fissure eruptions occur on elongate volcanic systems in the north, as in Djibouti (Ardoukoba 1978) and in Ethiopia (Dabbahu 2005-2008) (Figure 3). The Dabbahu episode may still be going on with repeated dyke injections from the magma chamber underneath Dabbahu into the fissure swarm. There have been 15 dyke injections so far including three fissure eruptions. In the south of the rift silicic rocks are more common, being erupted either as thick flows or domes restricted in area and volume, or as pyroclastic flows and surges. Air fall ash and pumice usually accompany the silicic eruptions, forming quite thick deposits in the vicinity of the eruption site, but dispersed far by winds. The only documented big explosive volcanic eruption in the Rift

occurred in Eritrea (Dubbi) in 1861. The volcano erupted trachytic pumice and ash flows in the initial phase, followed by basaltic lavas of over 1 km^3. Voluminous pyroclastic flows may spread over large areas and be followed by caldera collapses. Fortunately such events are rare but so far only few volcanoes have been investigated about their past paroxysmal eruptions.

In Kenya the histories of at least three major centres have been investigated in some detail: Menengai (Leat, 1984), Longonot (Scott, 1980), last eruption in 1863, and Suswa, but also Olkaria (Naylor 1972) (last eruption in 1770 according to Smithsonian). Figures 4-7 list the volcanoes of the Eastern Rift and when they were last active. Flows and surges may alternate in one and the same eruption. Surges do not spread as far as flows, little over 6 km from the source as a rule. Menengai and Longonot had their mega-eruptions and caldera collapses 10-30,000 years ago. Post caldera activity has been restricted to the calderas and their fissure swarms down the north and south flanks.

4. FAULT MOVEMENTS

Fault movements may create ground fissures in the epicentral areas of large earthquakes. In the Rift system they would presumably follow the trace of pre-existing normal faults. Earthquakes associated with magmatically driven rifting are not as strong, probably not much over M 5.5. They are associated with dyking. Ruptures associated with tectonic earthquakes would propagate at a rate of kilometres/second as against kilometres/hr for the latter which accompany dyke propagation. The fissures themselves would cause damage of surface structures where they cross pipelines or cut through boreholes. Needless to say that mapping of faults is important at the stage of site selection.

5. INTRUSIONS

Intrusions make themselves felt in two ways. We mentioned above that they may form dykes when magma is expelled laterally out of a magma chambers during rifting events. They may also form sheets in the roof of magma chambers both as irregular net veins or regularly inclined as cone sheets as a result of point source stresses. Dykes have made themselves felt when they cut through and clog boreholes. Examples are known from Krafla where a borehole erupted basalt and several were clogged as became evident from fresh glassy basalt being drilled through when cleaned.

6. GAS FLUXES

The magma chambers themselves have an aureole of magmatic gases such as CO_2, SO_2, Cl and F in a supercritical water phase around them. These may migrate off during times of unrest and pollute the geothermal system (lowering its pH), rendering it partly unexploitable for years, or even decades. The Krafla geothermal system is an example being situated in the caldera of a degassing volcano. An informative paper on volatile fluxes from volcanoes at rest is given by Brantley et al. 1993.

The sediment filled grabens of the Western Rift contain methane gas, which comes from organic material trapped in the lake. Reserves are well known in Lake Kivu and signs of it have been found elsewhere. Thus the western shore of Lake Tanganyika is leaking hydrocarbons (There is a Tanganyika oil company). Drilling into the rift floor needs to take notice of this.

Name	Elevation		Location	Last eruption
	meters	feet	Coordinates	
The Barrier	1032	3385	2.32, 36.57	1921
Central Island	550	1804	3.5, 36.042	-
Chyulu Hills	2188	7178	-2.68, 37.88	1855
Mount Elgon	4321	14178	-1.1, 34.5	
Elmenteita Badlands	2126	6975	-0.52, 36.27	Holocene
Emuruangogolak	1328	4357	1.5, 36.33	1910
Homa Mountain	1751	5745	-0.38, 34.5	Holocene
Mount Kenya	5199	17057	0°9'S 37°18'E	-
Korosi	1446	4744	0.77, 36.12	Holocene
Likaiu	915	3000	2.17, 36.36	-
Longonot	2776	9108	-0.914, 36.446	1863
Marsabit	1707	5600	2.32, 37.97	Holocene
Menengai	2278	7472	-0.2, 36.07	6050 BC
Namarunu	817	2680	1.9, 36.27	6550 BC
North Island (Kenya)	520	1706	4.07, 36.05	-
Nyambeni Hills	750	2460	0.23, 37.87	Holocene
Ol Doinyo Eburru	2856	9370	-0.63, 36.23	-
Ol Kokwe	1130	3707	0.63, 36.08	Holocene
Olkaria	2434	7985	-0.904, 36.292	1770
Paka	1697	5568	0.92, 36.18	6050 BC
Segererua Plateau	699	2293	1.57, 37.9	Holocene
Silali	1528	5013	1.15, 36.23	5050 BC
South Island (Kenya)	800	2625	2.63, 36.6	1888
Suswa	2356	7730	-1.175, 36.35	-

FIGURE 4: List of volcanoes in Kenya
(From: Wikipedia)

Name	Elevation		Location	Last eruption
	meters	feet	Coordinates	
Ardoukoba	298	978	11.58, 42.47	1978
Boina	300	984	11.25, 41.83	Pleistocene
Garbes	1000	3281	11.42, 42.2	Pleistocene
Tiho	500	1640	11.53, 42.05	Uncertain

FIGURE 5: List of volcanoes in Djibouti
(From: Wikipedia)

Name	Elevation		Location	Last eruption
	meters	feet	Coordinates	
Alid	910	2966	14.88, 39.92	Holocene
Asseb	910	2986	12.85, 42.43	Holocene
Dubbi	987	5331	13.58, 41.808	1861
Gufa	600	1969	12.55, 42.53	Holocene
Jalua	713	2339	15.042, 39.82	*unknown*
Mousa Ali	2028	6654	12.47, 42.4	Holocene
Nabro	2218	7277	13.37, 41.7	*unknown*

FIGURE 6: List of volcanoes in Eritrea
(From: Wikipedia)

Name	Elevation		Location	Last eruption
	meters	feet	Coordinates	
Adwa	1733	-	10.07, 40.84	1928
Afdera	1295	5686	13.08, 40.85	Holocene
Alayta	1501	4924	12.88, 41.57	1915
Ale Bagu	1031	3883	13.52, 40.63	Holocene
Alu	429	1407	13.82, 40.56	-
Alutu	2335	7661	7.77, 38.78	50 BC
Amoissa	1733	5684	10.069, 40.837	-
Asavyo	1200	3937	13.07, 41.6	Holocene
Asmara (volcano)	500	-	11.27, 41.52	Holocene
Ayalu	2145	7037	10.08, 40.7	1928
Beru	1100	3609	8.95, 39.75	Holocene
Bilate River Field	1700	5577	7.07, 38.1	Holocene
Bishoftu Volcanic Field	1850	6069	8.78, 38.98	Holocene
Bora-Bericcio	2285	7497	8.27, 39.03	Holocene
Borale Ale	668	2192	13.725, 40.6	Holocene
Borawli	875	2871	11.63, 41.45	Holocene
Borawli	812	2664	13.3, 40.98	Holocene
Boset-Bericha	2447	8028	8.558, 39.475	Holocene
Butajiri-Silti Field	2281	7484	8.05, 38.35	-
Chiracha	1650	5413	6.65, 38.12	Holocene
Corbetti Caldera	2320	7611	7.18, 38.43	-
Dabbahu	1442	4731	12.6, 40.48	Holocene
Dabbayra	1302	4272	12.38, 40.07	Holocene
Dalaffilla	613	2011	13.792, 40.55	-
Dallol	-48	-157	14.24, 40.3	1926
Dama Ali	1068	3504	11.28, 41.63	1631
Dendi	3260	10,692	9, 38	-
Dofen	1151	3776	9.35, 40.13	Holocene
East Zway	1889	6097	7.95, 38.93	-
Erta Ale	613	2011	13.6, 40.67	2006
Mount Fentale	2007	6585	8.97, 39.93	1820
Gabillema	1459	4787	11.08, 41.27	Holocene
Gada Ale	287	942	13.975, 40.408	Holocene
Gariboldi Caldera	1619	-	8.8, 39.69	-
Gedamsa Caldera	1984	6509	8.35, 39.18	Holocene
Groppo	930	3051	11.73, 40.25	Holocene
Hayli Gubbi	521	1709	13.5, 40.72	Holocene
Hertali	900	2953	9.78, 40.33	Holocene
Hobicha Caldera	1800	5905	6.78, 37.83	Holocene
Kone	1619	5312	8.8, 39.69	1820
Korath Range	912	2992	5.1, 35.88	Holocene
Kurub	625	2051	11.88, 41.208	Holocene
Liado Hayk	878	2881	9.57, 40.28	Holocene
Ma Alalta	1815	5955	13.02, 40.2	Holocene
Mallahle	1875	6152	13.27, 41.65	Holocene
Manda Hararo	600	1968	12.17, 40.82	Holocene
Manda-Inakir	600	1968	12.38, 42.2	1928
Mat Ala	523	1716	13.1, 41.15	Holocene
Mega Basalt Field	1067	3501	4.08, 37.42	Holocene
O'a Caldera	2075	6808	7.47, 38.58	-
Sabober	-	-	8.97, 39.93	-
Lake Shala	2075	6806	7.47, 38.55	-
Sodore	1765	5791	8.43, 39.35	Holocene
Sork Ale	1611	5285	13.18, 41.725	Holocene
Tat Ali	700	2297	13.28, 41.07	Holocene
Teppi	2728	8950	7.42, 35.43	Holocene
Tosa Sucha	1650	5413	5.92, 37.57	Holocene
Tullu Moje	2349	7707	8.15, 39.13	1900
Wonchi	3450	11,316	9, 38	-
Mount Yangudi	1383	4537	10.58, 41.042	Holocene
Mount Zuqualla	2800	9184	8.32, 38.52	-

FIGURE 7: List of volcanoes in Ethiopia
(From: Wikipedia)

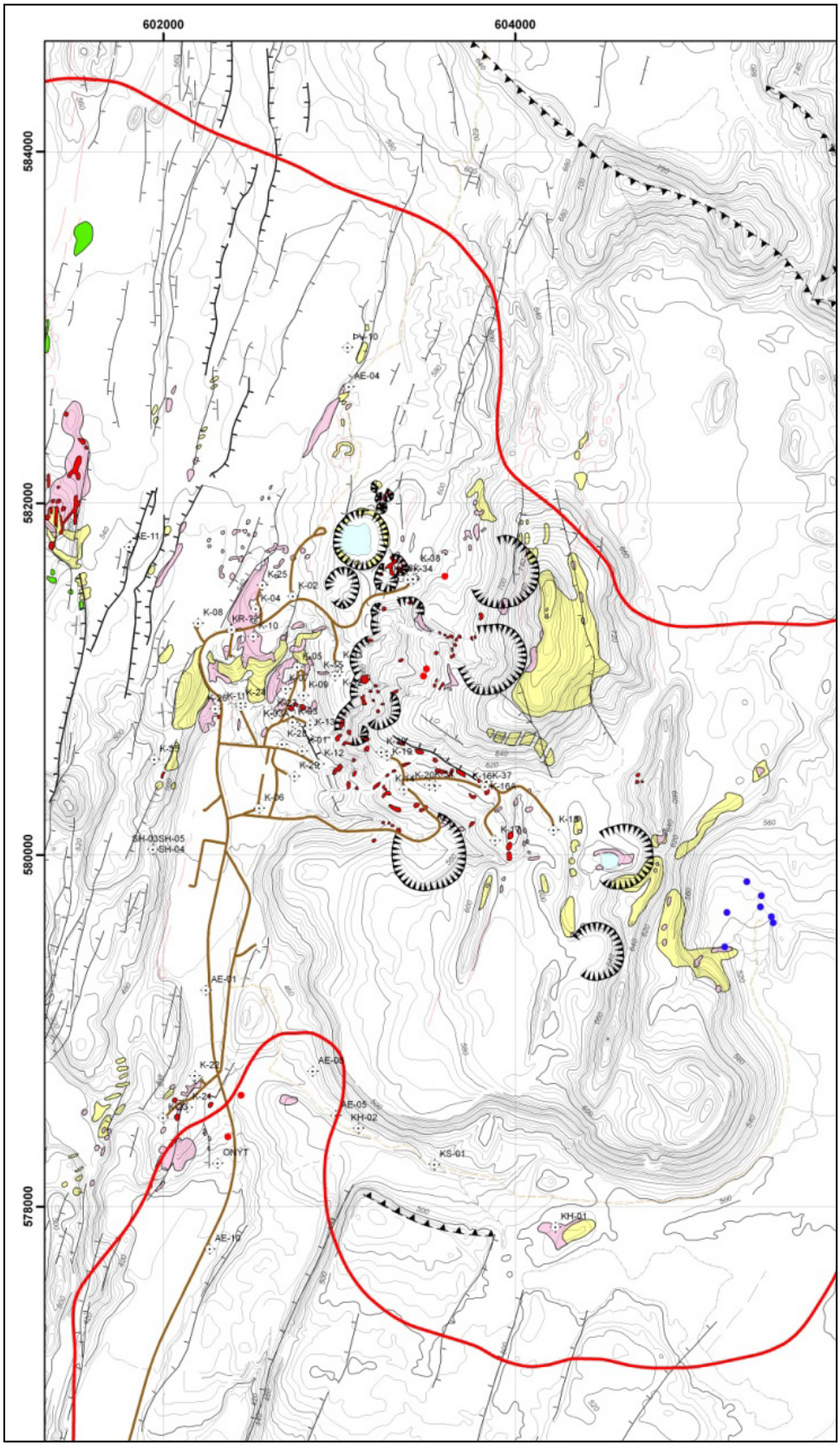

FIGURE 8: Explosion craters (circular) of Krafla geothermal area. Red line marks the outline of a high resistivity body at 600 m depth, enveloped by a low resistivity zone. Red dots are fumaroles. High grade surface alteration is pink. Low grade alteration is yellow. Normal faults are shown. Caldera margin is shown at upper right and lower centre
(From: ISOR database)

7. DRILLING INTO MOLTEN ROCK

Shallow depth to molten rock may cause problems. One possibility is a blowout, not known to have occurred for this reason yet. The reality of drilling into a basaltic melt came up fife years ago in Hawaii and in late 2008 at Krafla, Iceland, in both cases at about 2500 depth. At Krafla the yielding wells are located in an area of Late Pleistocene and Recent explosion craters (Figure 8). In our case the drill penetrated 50 m into the molten body (not recognized as such, because there had been a total loss of drill fluid which was water), then got stuck as circulation was stopped for a temperature log (showed 386°C at the bottom of the drill string) (Figure 9). The string was blasted above the hot part. The drill pipe broke well below. On pulling out, the lowest pipe was found to be plugged by fresh, silicic glass. Even though a feed zone just above the now recognized molten zone was plugged with cement, the well yielded low pH fluid which is corrosive. A well which was completed at Krafla end 2007 ran into a gas rich fluid at the same depth (Figure 10) (Thorhallsson et al., 2008). That particular feed zone was cemented off and the well is a moderately good producer. In summer 2009 again a research borehole which was scheduled for 4000 m depth ran into molten rhyolite at 2300 m and had to be abandoned. There was a large feed zone just above the melt. Due to excessive pumping of cold water into it the well is heating up slowly. It is not yet known whether the well will be usable. Figure 11 shows the location of the three wells that ran into molten rock and a gas rich aureole presumed to surround it.

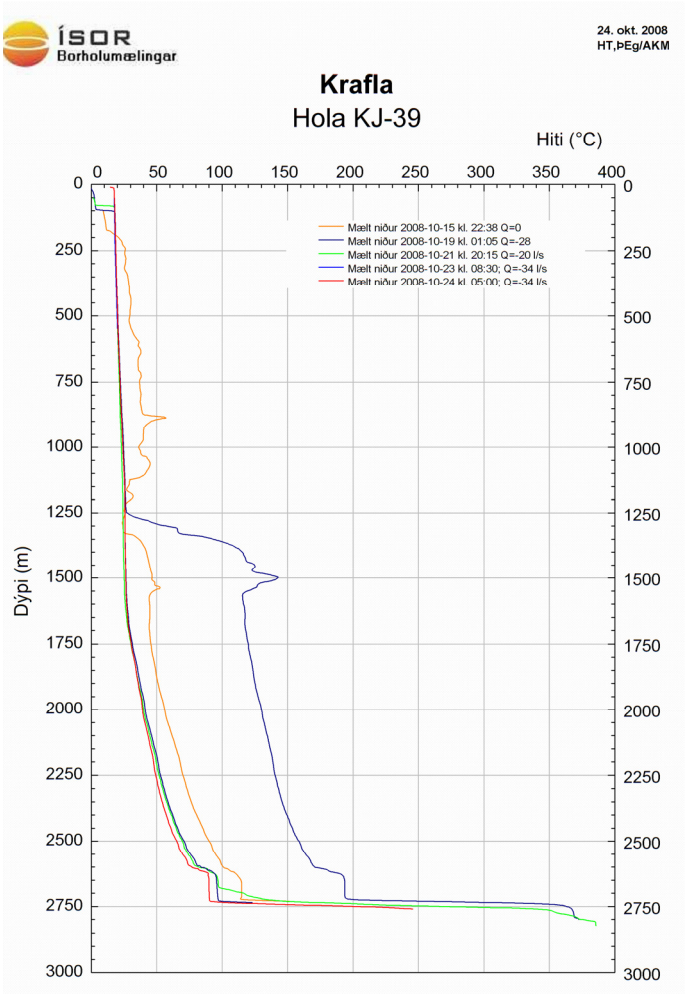

FIGURE 9: Temperature logs of well KJ-39
(From: ISOR database)

FIGURE 10: Well KJ-36 blowing
(From: Thorhallsson et al., 2008)

8. FLOODING AND SLIDING

Flooding and sliding involves a hazard in areas of steep topography, clayey ground (a common feature in high temperature geothermal fields) and heavy, in particular tropical, rain which may cause flash floods. The selection of drill pads, siting of buildings and layout and construction of steam pipes needs to be considered with regard to such hazard factors.

9. ELEVATION CHANGES

Elevation changes and horizontal displacements defined by GPS, inSAR and levelling measurements. Geophysics has the means of measuring accurately vertical and horizontal changes. It has been a common practice in volcanalogy for a long time to measure elevation changes on volcanoes as inflation may indicate magma accumulation. This is also important in surveillance of geothermal fields which may subside due to exploitation if recharge does not make up for fluid production. In recent years satellites have made it possible to register horizontal displacements also (Stamps et al., 2008).

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GEOPHYSICAL METHODS USED IN GEOTHERMAL EXPLORATION

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ABSTRACT

Geophysical methods are one of the three main disciplines applied on the surface to explore geothermal resources, including also geology and the chemistry of thermal fluids. The most successful methods are aimed at parameters that are directly influenced by the geothermal activity, such as resistivity methods and thermal methods, and are usually referred to as direct methods. Other methods explore the physical parameters of the host rock, including magnetic properties, density and seismic velocity, and are usually referred to as indirect or structural methods. Short description is given on the most important methods, their strength and limits discussed and examples given on their use.

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1. INTRODUCTION

Geophysical exploration of geothermal resources deals with measurements on the physical properties of the earth. The emphasis is mainly on parameters that are sensitive to temperature and fluid content of the rocks, or on parameters that may reveal structures that influence the properties of the geothermal system. The aim can be to:

- delineate a geothermal resource;
- outline a production field;
- locate aquifers, or structures that may control aquifers in order to site wells; or
- assess the general properties of the geothermal system.

The important physical parameters in a geothermal system are:

- temperature;
- porosity;
- permeability;
- chemical content of fluid (salinity); and
- (pressure)

Most of these parameters cannot be measured directly through conventional geophysical methods applied on the surface of earth. On the other hand, there are other interesting parameters that can be measured which are linked with the parameters above and may thus give important information on the geothermal system. Among these parameters are:

- temperature (°C);
- electrical resistivity (Ωm);
- magnetisation (Vs/m^2 or T);
- density (kg/m^3);
- seismic velocity (km/s);
- seismic activity;
- thermal conductivity (W/mK); and
- streaming potential (V).

A distinction is usually made between direct methods, and indirect or structural methods. The direct methods give information on parameters that are influenced by the geothermal activity, while the structural methods give information on geological parameters which may reveal structures or geological bodies that are important for the understanding of the geothermal system. The direct methods include thermal methods, electrical (resistivity) methods and self potential (SP), while the structural methods include magnetic measurements, gravity measurements, active seismic methods and passive monitoring of seismicity.

Different methods may be applied for the exploration of low-temperature fields compared to high-temperature resources. Furthermore, different methods are sometimes used from one country to another despite similar geothermal surroundings, based on the routines that have been developed at the different institutions. It is also important to combine different methods, as relying on the results of measurements of a single parameter usually does not give adequate information for good understanding of the geothermal system.

In the following sections the most important methods used in geophysical exploration of geothermal fields are described briefly, and examples given on their use. For a more thorough overview, see e.g. Hersir and Björnsson (1991) or Keary and Brooks (1992); and also Árnason and Flóvenz (1992).

2. THERMAL METHODS

Thermal methods include direct measurements of temperature and/or heat, and thus correlate better with the properties of the geothermal system than other methods. However, as a (near-) surface method they are limited to shallow levels. To measure temperatures close to the surface, in the uppermost metre or so, is fairly simple. Knowledge about status at deeper levels is based on the existence of wells, usually shallow gradient wells (e.g. 30-100 m deep), from which the thermal gradient can be calculated and possibly the depth to the exploitable geothermal resource. Drilling is though usually fairly expensive, and puts practical limits to the use of the method. Furthermore, shallow wells are not always adequate to get reliable values on the thermal gradient.

The heat exchange mechanism in the earth is important for interpretation of thermal methods. A distinction is made between:

- Conduction, which is based on atomic vibrations, and is important for transfer of heat in the earth's crust;
- Convection, which transfers heat by motion of mass, e.g. natural circulation of hot water; and
- Radiation, which does not influence geothermal systems.

The simplified geothermal relationship for thermal conduction is (conductive heat transfer only):

$$Q_{cond\text{-}z} = - k \ \Delta T / \Delta z$$

The parameter k, the thermal conductivity (W/m°C), is a material constant, which ranges between 1 and 5 W/m°C, with the low values usually associated with sedimentary formations and the higher for crystalline rocks. The thermal gradient, $\Delta T / \Delta z$, gives information on the increase of temperature with

depth, and its distribution can be important information for understanding and delineation of the geothermal resource, both on a regional scale and local scale. If the conductive hear transfer, Q, is 80-100 mW/m^2 or higher, it may indicate geothermal conditions in the subsurface.

For convection, a distinction is made between free convection, which is driven by density gradients in the fluid (due to a difference in temperature), and thus the heat is transferred, while forced convection is driven by an external pressure gradient, such as hydrostatic head. Convection is a much more powerful way of transmitting heat, but relies on the permeability of the rocks. High-temperature geothermal systems are based on the free convection of the geothermal fluids, while geothermal systems in sedimentary basins are based on conductive heat flow. However, geothermal systems are often of a mixed type.

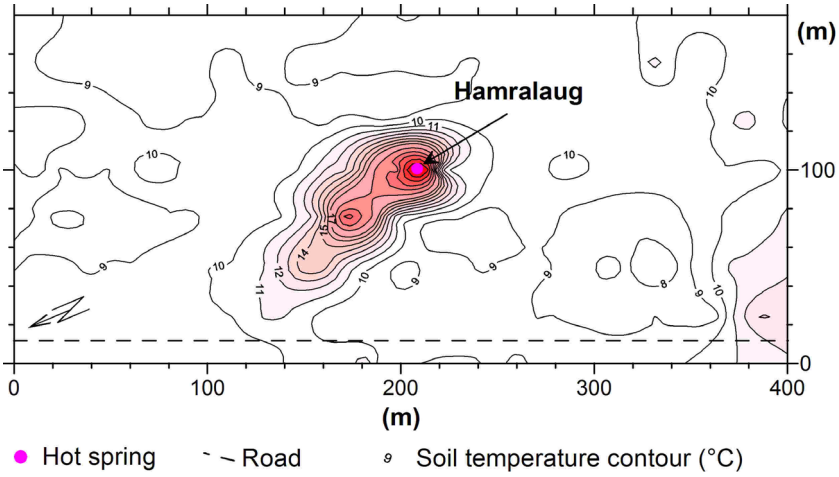

FIGURE 1: Soil temperature measurements at 0.5 m depth at Asgardur in Borgarfjordur, W-Iceland, where the temperature contours reveal a linear distribution, believed to be caused by a fracture (Ganbat, 2004)

Despite their limitations and their dependence on information from wells, thermal methods are important in geothermal exploration. They include the following:

- Mapping of thermal distribution at the surface, including:
  - Detailed geothermal surface mapping (GPS);
  - Soil temperature measurements in the uppermost metre or so (Figure 1);
  - Airborne IR survey.
- Temperature measurements in 20-100 m gradient wells, used to delineate regional or local gradient anomalies (Figure 2).
- Heat flow surveys for regional assessment for assessing thermal output of areas; here thermal conductivity measurements may be necessary and possibly terrain correction of the gradient survey.

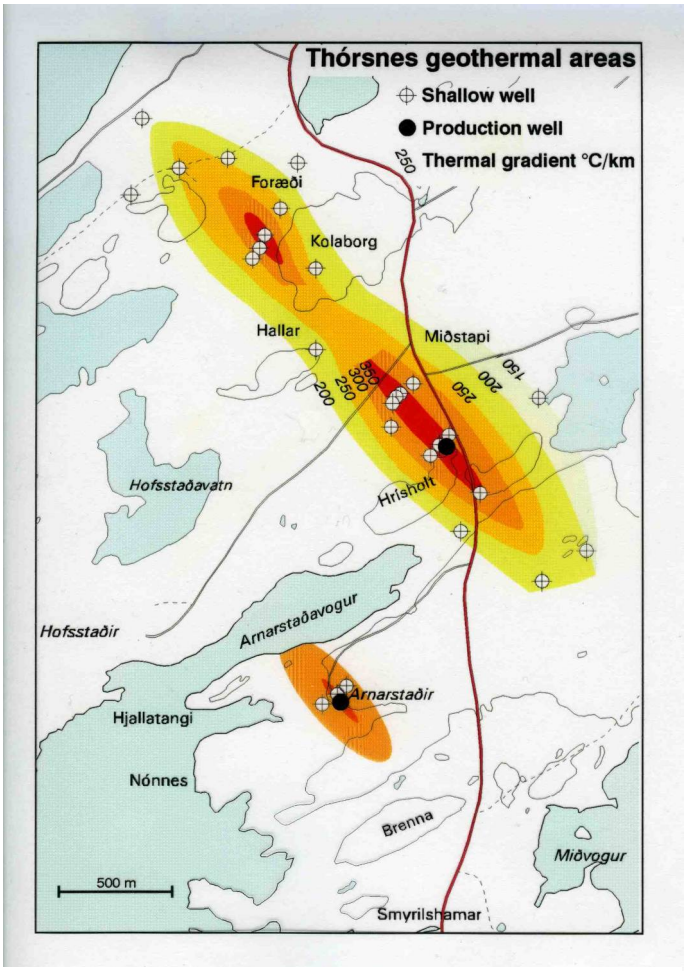

FIGURE 2: Gradient map of from the Thórsnes geothermal area, W-Iceland, where no geothermal activity was known on the surface; the gradient anomaly revealed two permeable fractures which proved very productive when drilled into (Saemundsson, 2008)

3. ELECTRICAL METHODS

3.1 Introduction

Electrical methods or resistivity methods are the most important geophysical methods in the surface exploration of geothermal areas, and as such the main methods used in delineating geothermal resources and production fields. The parameter of interest is the electrical resistivity of the rocks which correlates both with the temperature and alteration of the rocks which are key parameters for the understanding of the geothermal systems.

The main principle is that electrical current is induced into the earth which generates an electromagnetic signal that is monitored at the surface. The basic relationship behind resistivity measurements is the Ohm's law, which states that:

$$\mathbf{E} = \Delta \mathbf{j}$$

where **E** is the electrical field strength (V/m);
j is the current density (A/m^2); and
Δ is the *electrical resistivity* (Σm), which is a material constant.

For a unit cube/bar, the relationship for resistivity is defined as:

$$\Delta = V / I$$

The reciprocal of resistivity is c*onductivity* (S/m), thus it is also possible to talk about conductivity measurements. However, in geothermal, the tradition is to refer to electrical or resistivity measurements.

Electrical methods include many different types of measurements and varying setups or configurations for the different types. The most important types are:

- *DC methods,* where current is generated and injected into the earth through electrodes at the surface. The measured signal is the electrical field generated at the surface.
- *TEM,* where current is induced by a time varying magnetic field from a controlled source. The monitored signal is the decaying magnetic field at surface from the secondary magnetic field.
- *MT,* where current is induced by the time variations in earth's magnetic field. The measured signal is the electromagnetic field at the surface.

3.2 Resistivity of rocks

Electrical resistivity of rocks in geothermal surroundings is a parameter which reflects the properties of the geothermal system, or its history. Thus, a good knowledge on the resistivity is very valuable for the understanding of the geothermal system. This relates to the fact that *the resistivity of rocks is chiefly controlled by parameters that correlate to the geothermal activity*, such as:

- Porosity and pore structure, where distinction is made between:
  - Intergranular porosity such as in sedimentary rocks,
  - Fracture porosity, relating to tension, fracturing or cooling of igneous rocks,
  - Vugular porosity which relates to dissolving of material (limestone) or gas content (in volcanic magma);
- Alteration of the rocks, lining the walls of the pores, often related to as water-rock interaction;
- Salinity of the fluid in the pores;
- Temperature;
- Amount of water, i.e. saturation or steam content; and
- (Pressure).

The four listed first, namely fracture (secondary) porosity, alteration, salinity of the fluid, and temperature, are the most important ones, and basic parameters for a geothermal system. This explains why the parameter "*resistivity of the rocks*" is so important in geothermal exploration, and especially in volcanic surroundings, and hence the important role of resistivity soundings.

Generally, it can be said that electrical conduction is mainly through intercom-nected water-filled pores. If the rocks are fresh, the conduction is mainly through the water, while the alteration lining the walls of the pores is the decisive factor, when created at temperatures between 50 and 200°C, due to its very conductive properties. At higher temperatures resistive alteration takes over, changing the decisive conduction carrying mechanism again to the water. Figure 3 summarizes this and shows how the resistivity of water-bearing rocks changes with the alteration and temperature. High-resistivity core within a low-resistivity coat is typical for most high-temperature geothermal systems and has to do with the resistive alteration minerals that form at higher temperatures. Further discussion on resistivity of rocks and its correlation to the properties of geothermal systems will not be given here, but the reader is referred to Árnason et al. (2000) for further information.

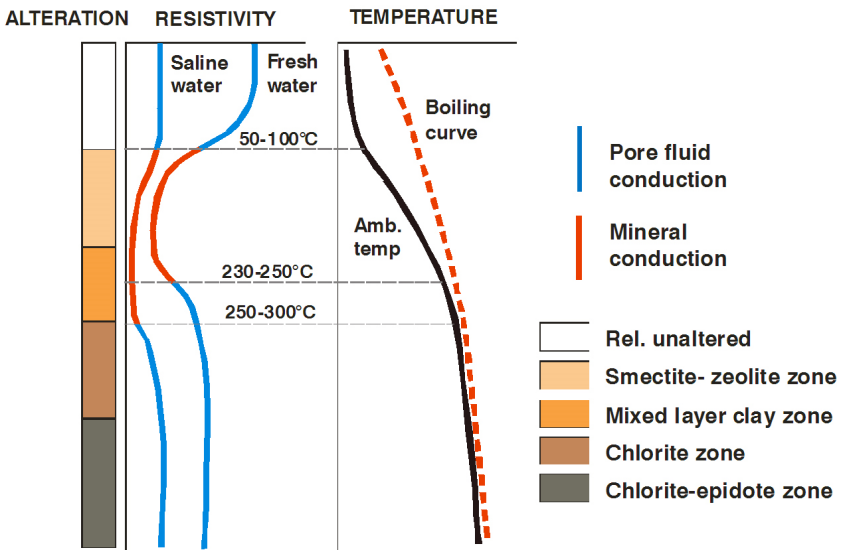

FIGURE 3: Resistivity of rocks and its association with alteration and temperature (Árnason et al., 2000)

3.3 DC-measurements

DC measurements are the oldest of the resistivity methods, at least as methods used for geothermal exploration and were the routine methods in the 1950s -1980s, but their application is not as common nowadays. Most of the configurations rely on *two pairs of electrodes* – one pair for current transmission and the other for measuring the potential difference. The geographical distribution defines the type. A distinction is made between sounding and profiling. A sounding, which is much more common to use, has a fixed centre and the varying of the electrode spacing is used for mapping resistivity changes with depth, while in profiling, the electrode distances are fixed, and the whole array moved along the profile line for mapping lateral changes. The most common configurations at least in geothermal exploration are:

- *Schlumberger sounding,* which has been widely used for a long time and is still the most popular one. The electrodes are on a line, and the set up is mirrored around the centre. The pair of potential electrodes is kept close to the centre, while the pair of current electrodes is gradually moved away from the centre, for the current to probe deeper and deeper into the earth.
- *Dipole sounding or profiling*; here various arrays exist, many used quite extensively in the 1970s into the 1980s.
- *Head-on profiling,* a successful method for locating near-surface vertical fractures or faults. It is really a variety of the Schlumberger profiling method with a third current electrode located far away at a right angle to the profile line.

Necessary equipment for DC soundings is a good current transmitter, a sensitive voltage receiver, wires on reels, electrodes, and a power source. By using (car) batteries as a source for the current

transmitter, the equipment is not very bulky, and usually possible to carry on foot for measurements in areas where access by car is not possible. Good DC equipment is marketed by many companies selling geophysical instruments.

The earth is not homogeneous so what we are looking at is a sort of average resistivity of the earth below the measuring site within a certain depth range. This "average" resistivity is usually referred to as *apparent resistivity*. For a sounding, apparent resistivity is plotted as a function of AB/2 (the length of the current arm) with increasing electrode separation, usually on a bilogarithmic scale, where the length of the current arm relates to the depth penetration. Schlumberger soundings are usually extended to a maximum current arm, AB/2, of 1-2 km. Much longer current arms have been used, but the long wires for longer distances can be difficult in practice. 1D interpretation is simple but 2D or even 3D interpretation of the resistivity bodies often necessary, and much more complicated.

Figure 4 shows a regional resistivity map from Husavik, N-Iceland based on Schlumberger soundings reflecting the resistivity at 500 m below sea level. It shows well a defined low-resistivity anomaly associated with the powerful Hveravellir low-temperature area.

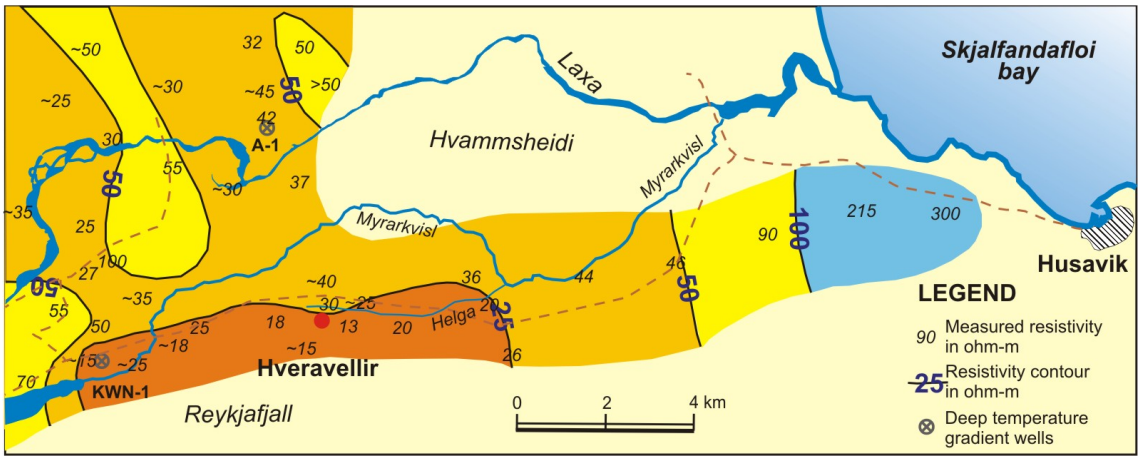

FIGURE 4: Resistivity map at 500 m depth b.s.l. from the Husavik area, N-Iceland, outlining the powerful Hveravellir low-temperature area (Georgsson et al., 2005)

3.4 TEM measurements

In the late 1980s, a new method started to make its impact in geothermal exploration and gradually it has replaced Schlumberger sounding as the routine method in the geothermal exploration of the uppermost 1-1.5 km of the earth. This is the TEM method (or Transient Electro-Magnetic method), which is an electromagnetic method which uses a controlled-source to create the signal to be measured. In the *Central loop TEM sounding method* (Árnason, 1989), referred to as TEM from now on, a constant magnetic field is built up by transmitting current I through a big loop (grounded dipole). Then the current is abruptly turned off. A secondary field is thus induced, decaying with time. This decay rate is monitored by measuring the voltage induced in a receiver coil in the centre of the loop on the surface. Current distribution and decay rate recorded as a function of time depend on the resistivity structure below the measuring site, and can be interpreted as such. The signal can also be based on a grounded dipole to create the primary magnetic field. TEM data are presented on a bilogarithmic scale as DC data, but here the apparent resistivity is plotted as a function of time after the current was turned off.

TEM equipment is sophisticated and relatively expensive, at least compared to DC equipment. Besides the receiver including a datalogger, a transmitter is required connected to a good electric generator able to generate high currents (the order of 10 A) and thus a strong magnetic field through the transmitting loop. The heavy generator makes it difficult to do measurements by carrying the

equipment on foot. In addition, a measuring coil and wires for the loops are needed with the current wires being able to carry heavy currents. In practice, the big transmitting loop is usually a square with a side of 150-300 m. With good conventional TEM equipment and a transmitter loop of 300×300 m, with TEM it is possible to study resistivity structures down to depth levels of 1-1.5 km.

TEM measurements have many advantages over Schlumberger measurements, such as in less need for manpower, both in data acquisition and interpretation, and in not being as sensitive for lateral inhomogeneities, and in improved resolution. Thus 1D interpretation of data is usually adequate, as the method is much more focussed than DC measurements.

Figure 5 shows a TEM resistivity cross-section from the large Hengill high-temperature area. The profile crosses an area where geothermal activity is not seen on the surface but the low-resistivity body with a high-resistivity core seen on its western (left) side indicates that this body has reached temperatures above 250°C, reflecting a suspected new production field. Figure 6 shows a TEM resistivity map of the Hengill area at a depth of 600 m b.s.l. The map delineates a wide spread low-resistivity layer but also the higher resistivities found in the central part of the geothermal system, indicating temperatures at or above 250°C in an area covering tens of square kilometres.

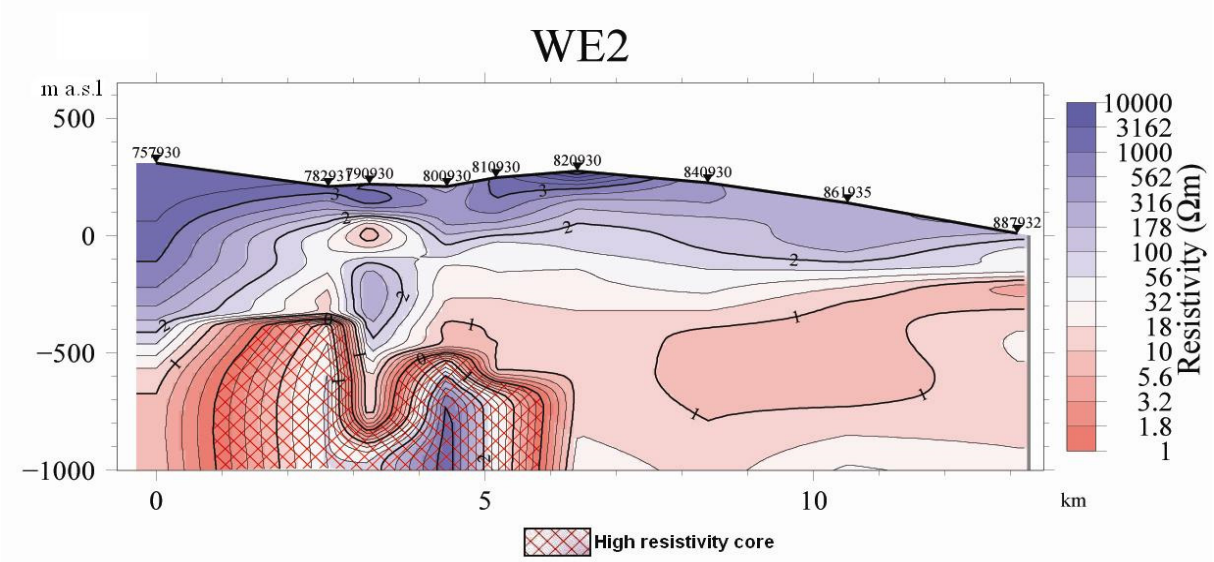

FIGURE 5: A W-E trending TEM resistivity cross-section from the southwest part of the Hengill high-temperature geothermal area, showing a resistivity anomaly that may indicate a new geothermal field where no geothermal activity is known on the surface (Tsend-Ayush, 2006)

3.5 MT-measurements

MT or natural-source electromagnetic use the earth's natural electromagnetic field as its power source. The variable natural magnetic field induces electrical currents in the conductive earth. By measuring the signal of the fluctuating magnetic field and the electrical currents (i.e. the electrical field) on the surface of the earth, it is possible to correlate this to the resistivity of the earth below the measuring site. The frequency of the signal relates to its probing depth, with low frequencies reaching deeper levels. Thus, frequencies of 0.00001 - 10 Hz are used for deep crustal investigations, while higher frequencies, like 10 - 1000 Hz, for the upper crust.

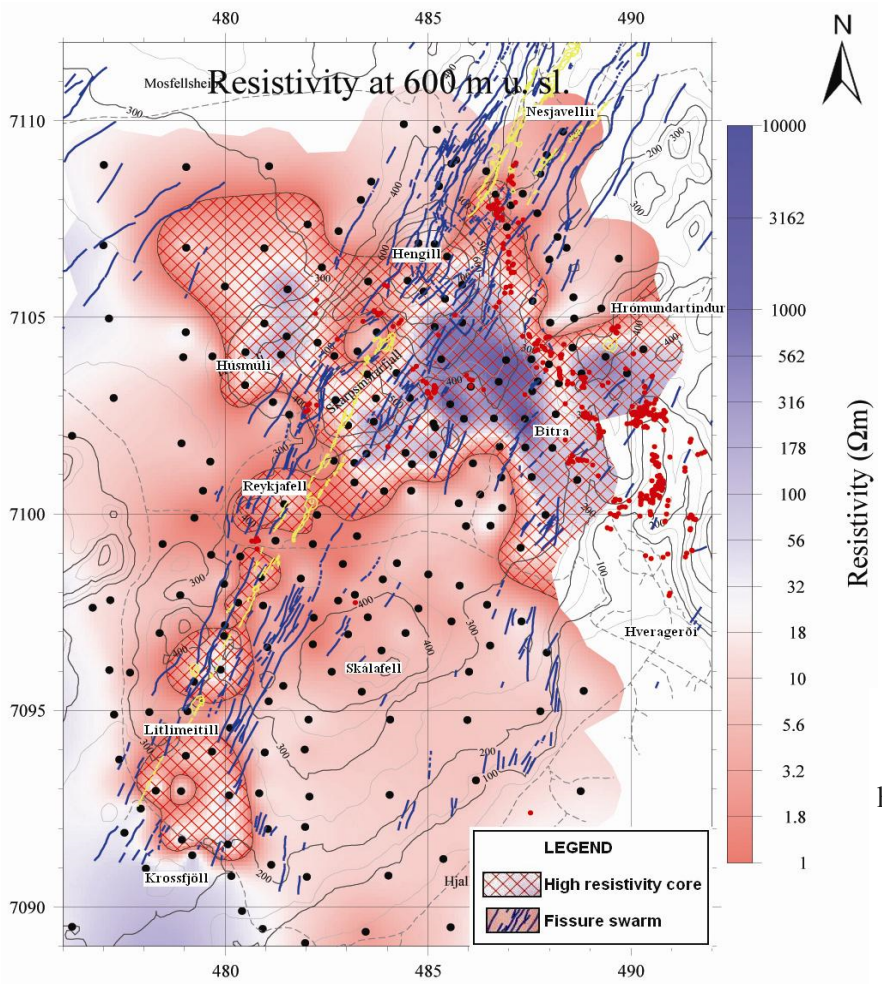

FIGURE 6: The Hengill high-temperature area, SW-Iceland, resistivity map based on TEM soundings showing the resistivity at 600 m below sea level (Tsend-Ayush, 2006)

The MT equipment is fairly simple and portable with the electromagnetic field monitored through magnetic coils and electric dipoles, through a data acquisition system, usually connected to remote-reference station for electro-magnetic noise.

MT is a powerful method to probe deep resistivity structures, which gives it an advantage compared to the other main electrical methods. The equipment is portable and the data collection is simple, involving measurement magnetic field components **B** and the induced electrical field **E**, both as a function of time for several hours, at each site. MT measurements are, however, quite sensitive to cultural noise (power lines etc.). Similarly, the measurements probe a large volume of rocks and are therefore sensitive to 3-D resistivity variations. Detailed interpretation can therefore be difficult and may require 3-D interpretation. More recently, the method has routinely been used in combination with TEM, with the TEM measurements used for mapping of the uppermost kilometre in detail in order to enhance the interpretation of the MT measurements and thus leading to better information at deeper levels. This way, good information on the distribution of the resistivity into the deeper parts of the geothermal system can be collected, reaching to 5-10 km depth.

Figure 7 shows a resistivity cross-section from the Menengai high-temperature geothermal system in Kenya down to about 8 km depth. It shows low resistivity in the uppermost kilometre inside the Menengai crater, but higher resistivity at deeper levels. Figure 8 shows a resistivity cross-section from the Krafla high-temperature system in N-Iceland. It reflects well the low resistivity close to the surface and the higher resistivity below associated with the exploitable geothermal reservoir at 1-4 km depth. Below that an extensive low-resistivity body may reflect partially molten magma.

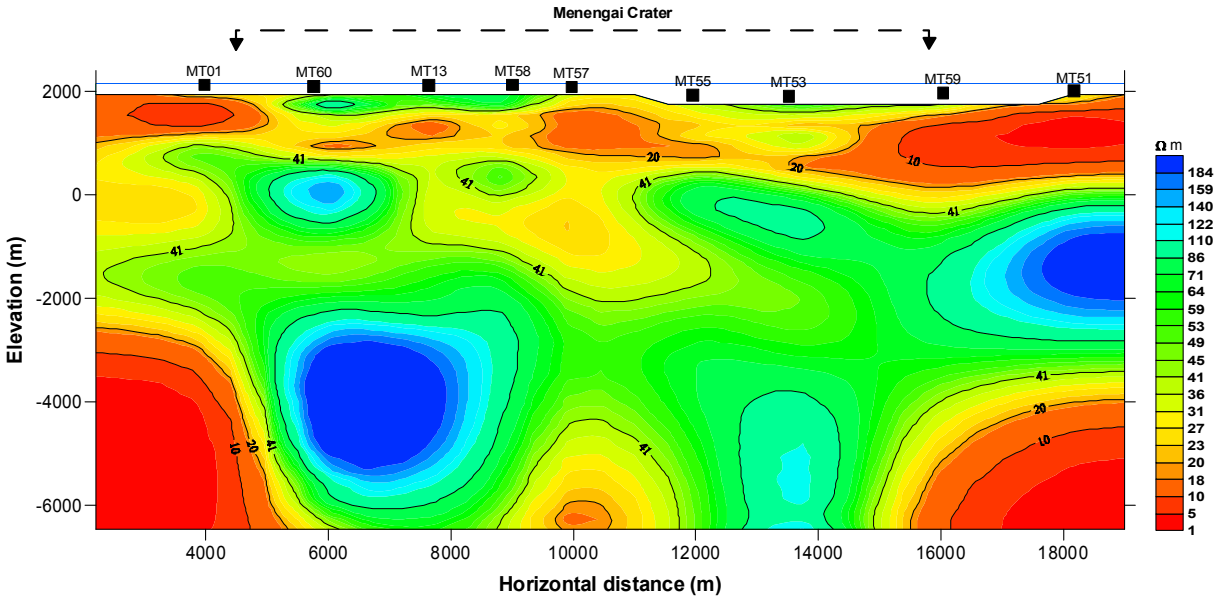

FIGURE 7: MT cross-section from the Menengai high-temperature area and crater in the Kenyan rift (Wameyo, 2005)

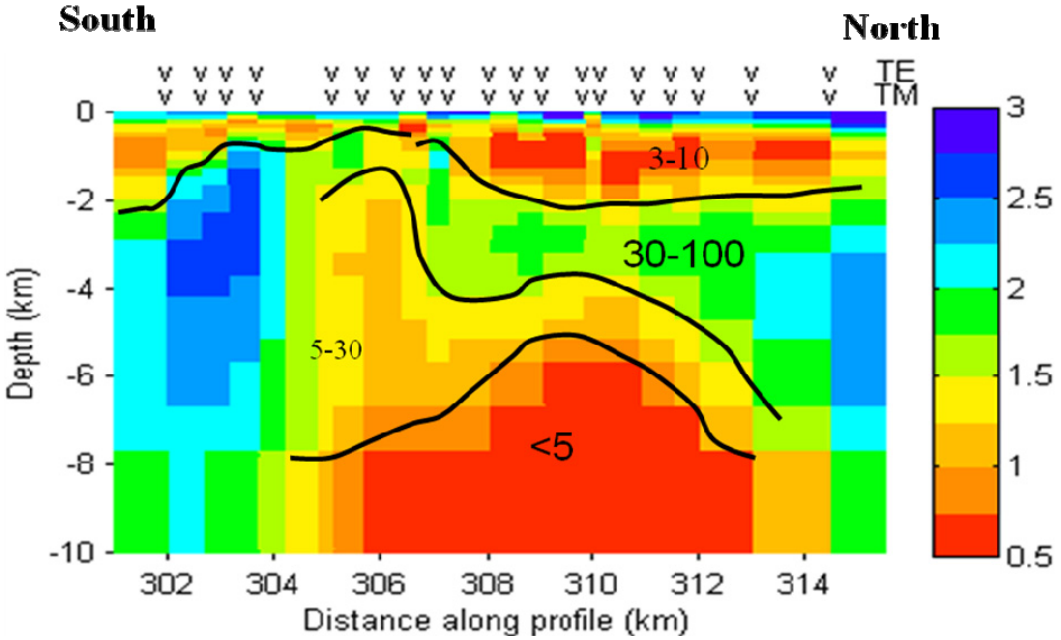

FIGURE 8: MT cross-section from the Krafla high-temperature field in N-Iceland (Árnason, 2007)

3.6 SP measurements

Self potential or SP is a special type of electrical measurements aimed at mapping the DC-component of the earth's natural electrical potential. Significant anomalies can be associated with geothermal activity. The anomalies may relate to temperature difference creating thermo-electrical potential, or fluid flow of hot or cold water, but may also be influenced by conductive mineral deposits or chemical variations in rock or pore fluid. The method is not widely used as the interpretation of the data is difficult to quantify, but it still can give important information. The most important applications are for reconnaissance studies, mapping boundaries and tracing faults. In Japan the method has also been used for reservoir monitoring especially for liquid-dominated geothermal systems, assuming that the main cause of the SP anomaly is streaming potential (Yasukawa et al., 2005).

4. MAGNETIC MEASUREMENTS

Magnetic methods are widely used in geothermal exploration, often together with gravity measurements and seismic refraction, in mapping geological structures. Magnetisation of rocks is of two types:

- Induced magnetisation M_i, which has the same direction as the ambient earth's field; and
- Permanent magnetisation M_p, which often predominates in igneous rocks and depends upon their properties and history.

A magnetic anomaly is a local or regional disturbance caused by a change in the magnetisation. It is characterized by the direction and magnitude of the effective magnetisation and the shape, position, properties and history of the anomalous body. The magnetic field strength is usually presented in γ (gamma) or nT (nanotesla). Magnetometers are fairly simple equipment and easy to use.

In geothermal exploration, magnetic measurements generally aim mainly at locating hidden intrusives and possibly estimating their depth, or at tracing individual buried dykes and faults. They may also aim at finding areas of reduced magnetization due to thermal activity. The measurements for local structures such as individual faults or dykes are done on the ground by regular measurements along parallel profiles or in a grid (Figure 9). Measurements aimed at larger anomalies such as mapping of deeper intrusions or outlining sedimentary basins are done through aeromagnetic surveys, where the height and spacing of the profiles relies on the preferred data density (Figure 10). In geothermal

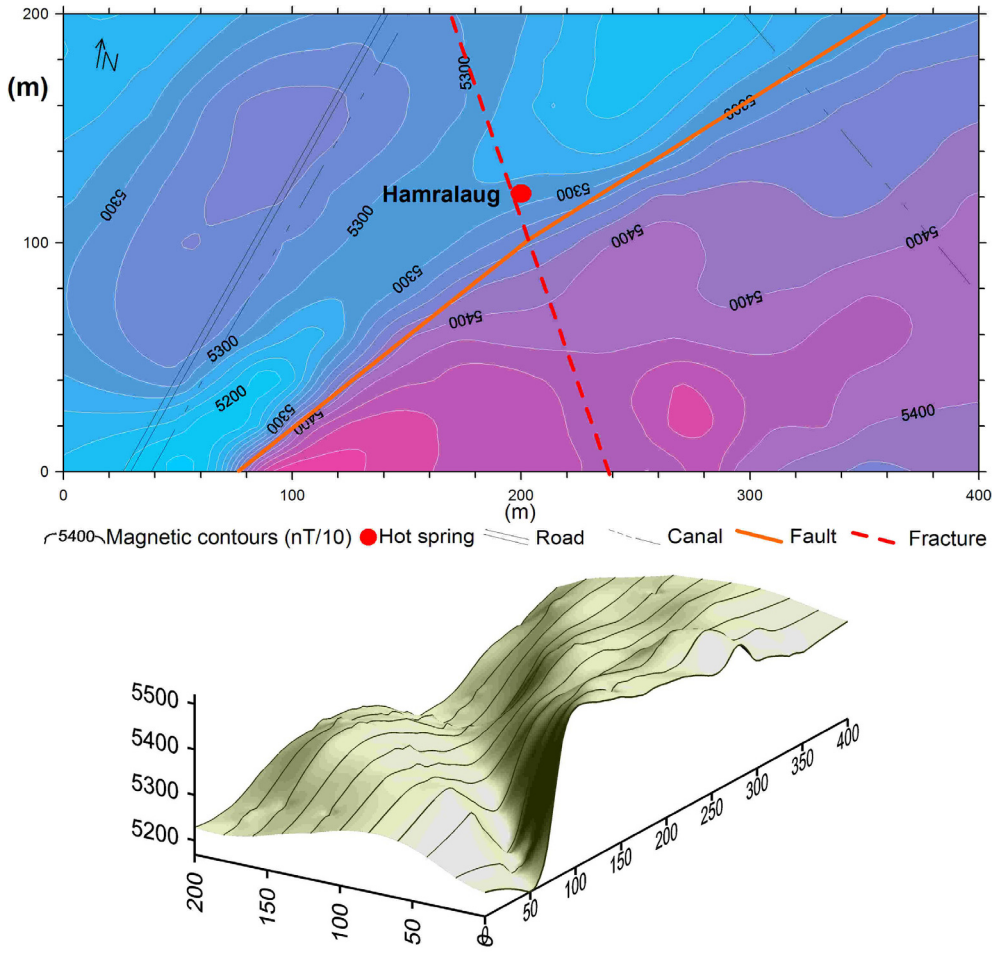

FIGURE 9: Magnetic measurements at the Ásgardur geothermal field in W-Iceland, presented both in a map and through 3D surfaces. The main anomaly is typical for a fault, resulting from different magnetization of the rocks on each side of the fault (Ganbat, 2004)

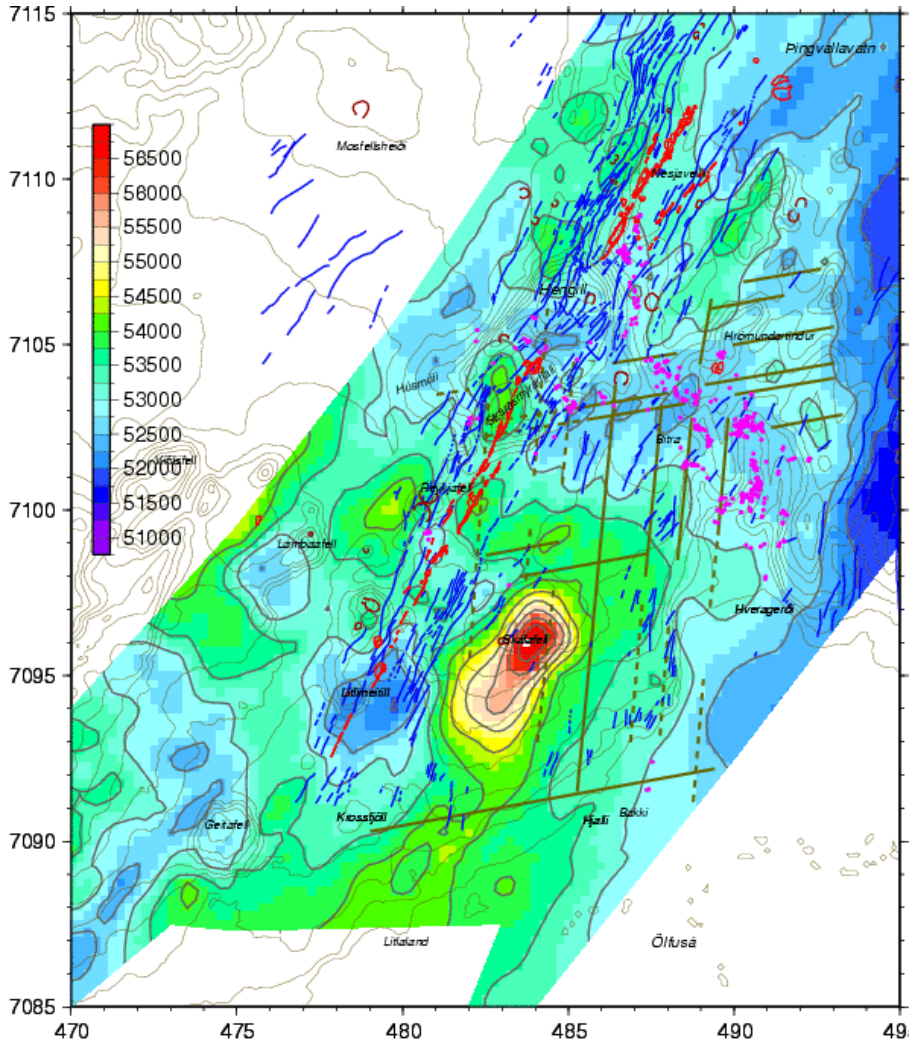

FIGURE 10: Magnetic map of the Hengill high-temperature area, showing also main tectonic features, Postglacial volcanic eruption sites, and the distribution of hot springs and fumaroles; the main geothermal activity correlates with low magnetic intensity (Árnason, 2007)

exploration an elevation of about 100 m above ground and 100 m spacing between profile lines is often used, but this is also influenced by the topography below. Data presentation is through contour maps or profile maps (Figure 9), and quite advanced filtering techniques can be used to distinguish anomalies in the data.

5. GRAVITY MEASUREMENTS

Gravity measurements are used to detect geological formations with different densities. The density contrast leads to a different gravitational force which is measured, and usually presented in mgal or 10^{-3} cm/s^2. The density of the rocks depends mainly on the rock composition and its porosity, but partial saturation of the rocks may also influence the values. Normally the density is between ~2 and 3 g/cm^3. Generally, sedimentary rocks are lighter than crystalline rocks. The raw data needs to be corrected for several factors. The results are usually presented or shown in Bouguer maps based on the Bouguer anomaly Δg_B, where corrections have been done on the measured value g_M for tidal effects, elevation, local topography, latitude and drift in the gravimeter.

Methods of data interpretation are quite similar to those for magnetic measurements. However, the gravity method is somewhat limited due to the ambiguity that theoretically an infinite number of

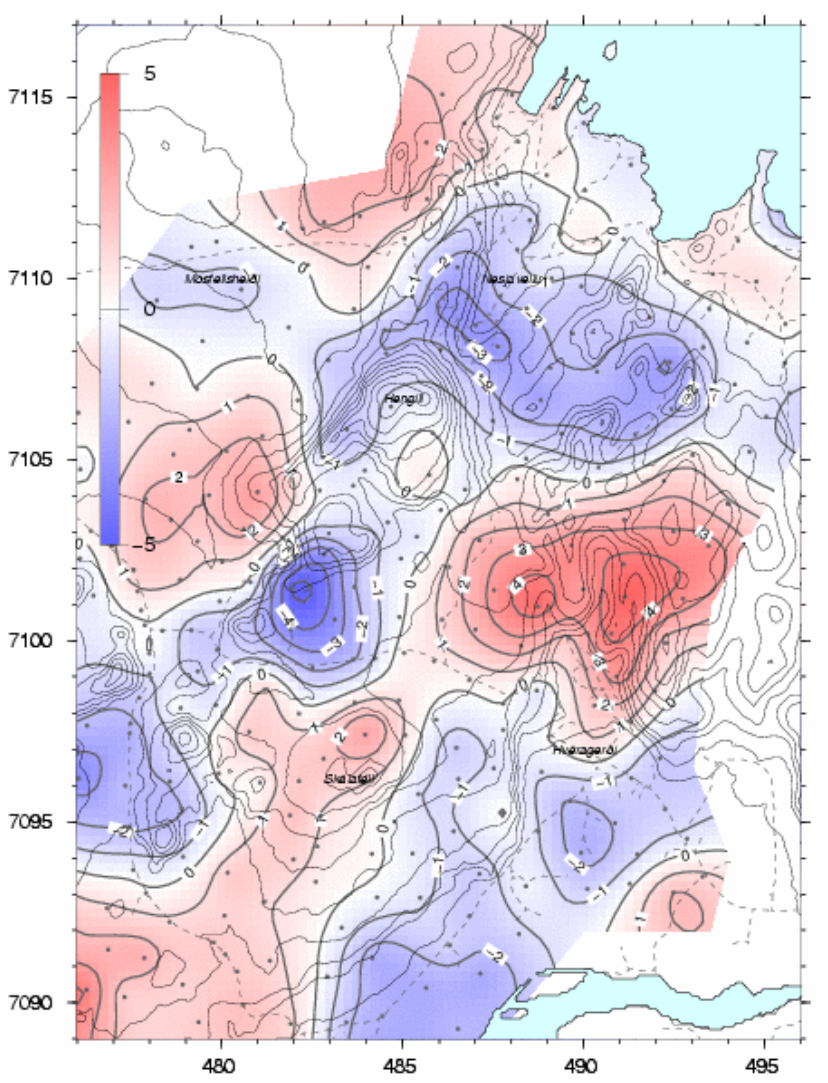

FIGURE 11: Bouguer gravity map of the Hengill high-temperature area; areas of high gravity may indicate intrusions at deeper levels (Árnason, 2007)

density distributions fits a given gravity field. Therefore, other information is needed to be able to fix values, e.g. thicknesses of formations etc.

Applications in geothermal exploration include mapping of: basement depth variations in sedimentary areas, intrusive rocks sometimes associated with a possible heat source, fault or dyke systems, and alteration/cementation due to thermal effects. Figure 11 shows a Bouguer gravity anomaly map of the Hengill area. An important additional application has been the use of precision gravity measurements for monitoring mass extraction in geothermal systems with production (Figure 12).

7. SEISMIC METHODS

Seismic methods measure sound velocity distribution and anomalies in the earth as well as attenuation of the sound waves. They are divided into two groups, active methods where an external source is used to create sound waves, such as explosions or hammer devices, while passive methods detect the seismic activity in the earth and use that to get information on parameters that may be influential for the geothermal system.

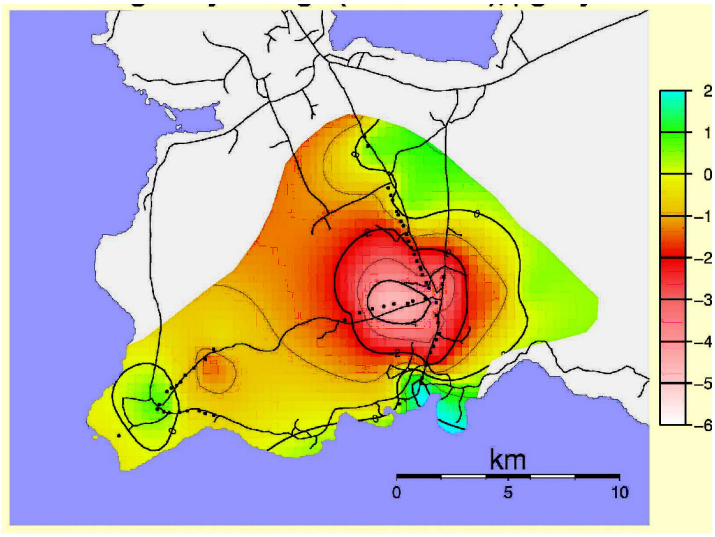

FIGURE 12: Map of the outer Reykjanes Peninsula, SW-Iceland based on precision gravity measurements showing the mean gravity change (reduction) in μgal/year from 1975 to 1999 due to production in the Svartsengi geothermal reservoir (Eysteinsson, 2000)

Seismic methods rely on elastic waves which have different velocities when travelling through different rock types, and are refracted or reflected at discontinuities in or between formations. There are two types of elastic body waves:

P-waves, or pressure waves, where the wave movement is in the travel direction; and
S-waves, where the material movement is perpendicular to the wave direction; due to the wave movement, S-waves do not penetrate through fluids, but only solid rocks.

In active measurements a distinction is made between refraction measurements and reflection measurements, depending on the procedures. Active measurements give information on the density of the formations, the porosity and texture, boundaries and discontinuities and fluid-filled zones and thus even temperature. The measurements are quite expensive, especially good reflection measurements. And despite being the most used of all geophysical methods as a key method in oil exploration, active seismic measurements, and especially reflection measurements, are not used routinely in geothermal exploration. High-temperature geothermal activity is mainly found within or at least associated with active central volcanoes, which are usually dominated by complicated bodies of crystalline rocks. The information can therefore be quite difficult to interpret and depth penetration not high, and the method thus not cost-effective. The strength of the active methods is in sedimentary surroundings (Figure 13) as is to be expected for the basic methods used for oil carrying formations.

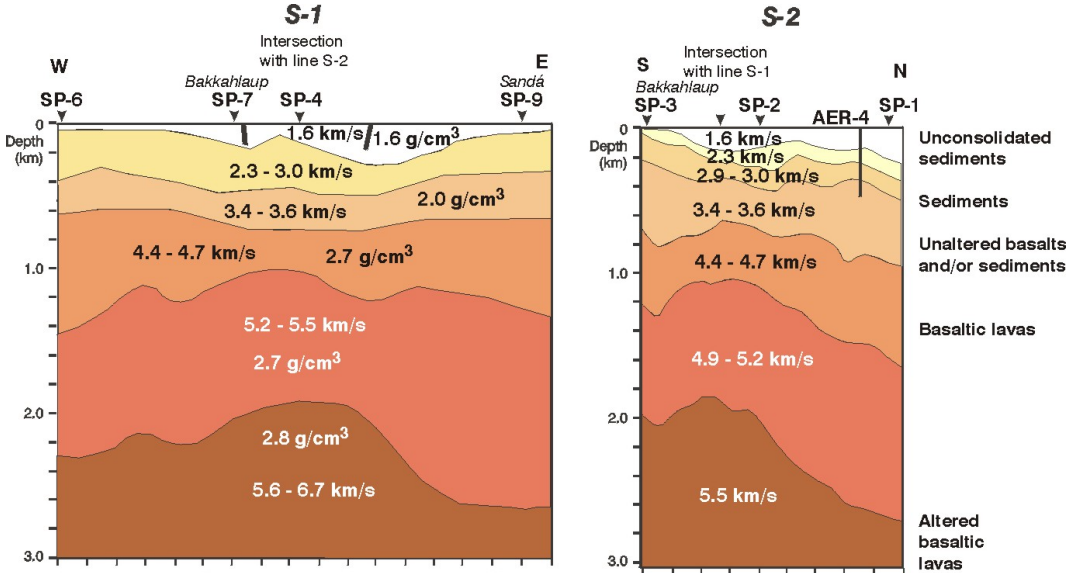

FIGURE 13: Cross-sections through the Oxarfjordur area in NE-Iceland, where geothermal activity is found in sedimentary surroundings, showing formation layers based on refraction measurements and gravity measurements. The up-doming of the high-velocity layers in the central part is the result of the geothermal activity (Georgsson and Fridleifsson, 2000)

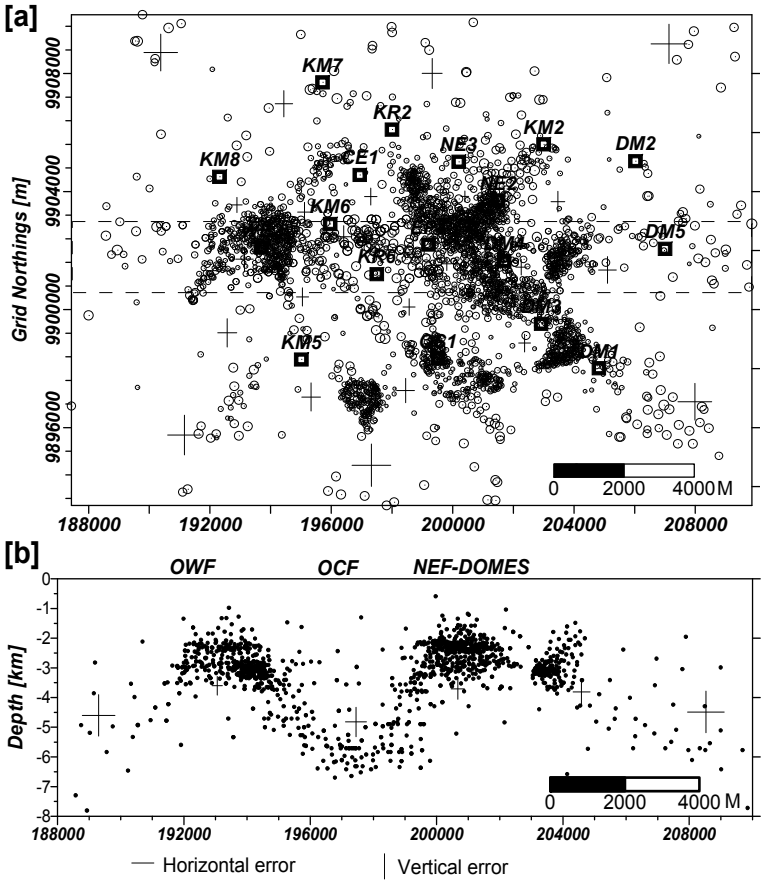

FIGURE 14: Distribution of earthquakes from the Olkaria field in Kenya. The cross-section below shows that the main production fields are associated with relatively high elevation of the brittle/ ductile boundary, indicating high temperatures and shallow depth to heat source (Simiyu, 2007)

Passive methods use the natural seismic activity to delineate active faults and permeable zones (shear wave splitting) or to locate the boundary between brittle and ductile crust, which can be indicative of depth to hear source. This can be important for the understanding of the geothermal activity in the measured area (Figure 14). Finally, S-wave shadows can be used to predict locations of bodies of partial melt, or magma chambers.

8. COMBINING MEHTODS

Good geophysical surveys are usually based on a combination of methods. It is necessary in order to get a better understanding of the geothermal system. Usually, routine methods are to be preferred, but if they do not suffice, then other methods or possibly improvised methods need to be taken into account. Figure 15 shows a simple model of the Asgardur geothermal system, based on the temperature measurements shown in

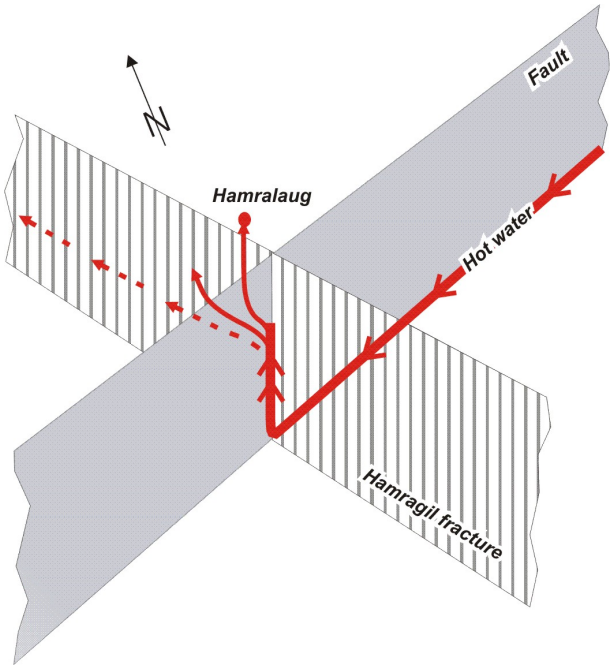

FIGURE 15: A simple model of the Asgardur low-temperature system in W-Iceland, based on the results of soil temperature measurements and magnetic measurements (Ganbat, 2005)

Figure 1 and the magnetic measurements in Figure 9. The NE-SW trending fault mapped by the magnetic measurements is believed to carry the water towards the geothermal field from the highlands, but the geothermal upflow (convection?) is at its intersection with a northwesterly fracture delineated through the soil temperature measurements.

Figure 16 shows maps of the large Hengill high-temperature area in SW-Iceland, where resistivity data has been combined with gravity data, information on active faults and the distribution of the geothermal activity. The maps have provided important information for understanding of the geothermal system and revealed possible new production fields.

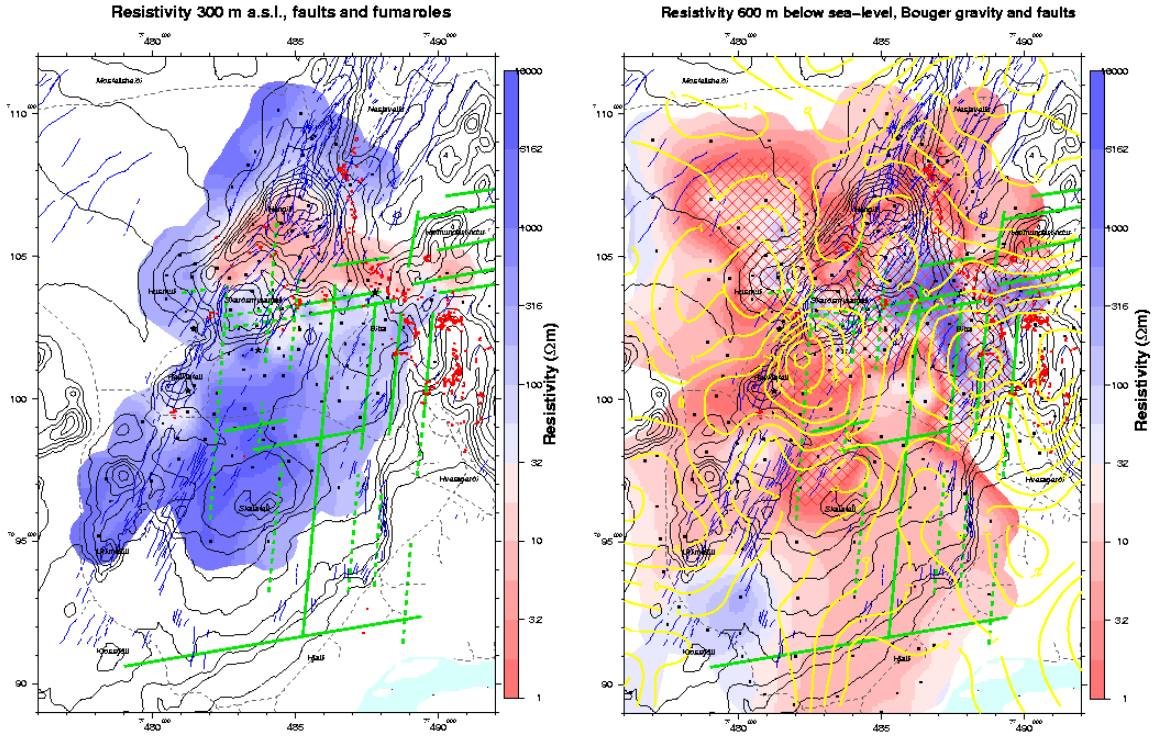

FIGURE 16: Resistivity maps at 300 m a.s.l. and at 600 m b.s.l. combined with the distribution of the geothermal activity, a Bouger gravity map and information on active faults from seismic measurements. The geophysical data have given important information on known production fields but also indicated new ones where no geothermal activity is seen on surface (Árnason, 2007)

9. FINAL REMARKS

Economic exploitation of a geothermal system is usually limited to the uppermost 1-3 km of the crust, and the actual target depth or the selection of a drill rig may be important for the selection of methods. It is sound to apply methods with which you are well acquainted if it is believed that they suit the purpose of the survey. However, it also important to have the knowledge and capacity to be able to improvise or adapt new methods if the conventional methods are not providing the information that is needed. Finally, the geophysicist must always remember that he does not stand alone. His results need to be integrated with information on the geology of the geothermal area and the chemistry of the geothermal fluids, for good understanding of the geothermal system.

A successful survey hopefully leads to the development of the resource, and if so, its success can be measured by the time, effort and money it has saved, for example by production of electricity or hot water for heating from a renewable energy source instead of oil or coal. Or if the measurements have managed to spare the drilling of one failed production well, they surely have saved a lot of money.

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RESISTIVITY OF ROCKS

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ABSTRACT

A brief summary of the importance of the electrical resistivity of rocks in geothermal exploration is given as well as some of its main relationships with some of the characteristics of geothermal reservoirs. Special emphasis is on the resistivity of rocks in high temperature geothermal fields where the dominant factor is the hydrothermal mineral alteration and how it relates to temperature. This review is to a great extent based on experience and work done through the years by Iceland GeoSurvey and its predecessor the NEA. In this review it should be pointed out that an overview of geophysical exploration for geothermal resources was given in a UNU GTP publication (Hersir and Björnsson, 1991). Other important sources here are two more recent articles from the World Geothermal Congresses (Árnason et. al., 2000 and Flóvenz et al., 2005).

1. INTRODUCTION

Measuring the electrical resistivity of the subsurface is the most powerful prospecting method in geothermal exploration. Resistivity is directly related to the properties of interest, like salinity, temperature, porosity (permeability) and alteration. To a great extent, these parameters characterize the reservoir.

The specific resistivity, ρ, is defined through **Ohm's law.** The electrical field strength, **E** [V/m] at a point in a material is proportional to the current density, **j** [A/m^2]:

$$\mathbf{E} = \rho\mathbf{j}$$

The proportional constant, ρ depends on the material and is called the (specific) resistivity, measured in Ωm. The reciprocal of resistivity is conductivity (1/ρ=σ).

Resistivity can also be defined as the ratio of the potential difference, ΔV [V/m], to the current, **I** [A], across material which has a cross-sectional area of 1 m^2 and is 1 m long.

$$\rho = \frac{\Delta V}{I}$$

Electrical conductivity in minerals and solutions takes place by movement of electrons and ions. Most rocks near the earth's surface have low conductivity. Conduction of electricity is mostly through

groundwater contained in pores of the rocks and along surface layers at the contact of rocks and solution. The case of altered rocks in high temperature areas will be discussed separately.

The common principle of all resistivity sounding methods is to induce an electrical current into the earth and monitor signals, normally at the surface, generated by the current distribution. In conventional direct current soundings such as the Schlumberger soundings, this is done by injecting current into the ground through electrodes at the surface and the signal measured is the electric field (the potential difference over a short distance) generated at the surface. In magnetotellurics (MT) the current in the ground is induced by time variations in the earth‘s magnetic field, and the signal measured is the electric field at the surface. In transient electromagnetics (TEM) the current is also induced by a time-varying magnetic field, but in this case the current source is not the natural field, the source is of a controlled magnitude generated by current in a loop or a grounded dipole and the monitored signal is the decaying magnetic field at the surface.

2. CONDUCTION IN SOLUTIONS

In aqueous salt-solution the ions of the solid separate and are free to move independently in the solution. In an electric field cations are accelerated to the negative electrode and the anions to the positive one. A viscous drag force limits the velocity of the ions. The mobility (terminal velocity/electrical field) of the ions depends on temperature (viscosity) and on concentration.

Groundwater may have a variety of salts in the solution. Therefore equivalent salinity is defined as the salinity of a NaCl-solution with the same resistivity as the particular solution. Mobility of the ions does not vary widely and equivalent salinity is therefore close to true salinty. The right part of Figure 1 shows the nearly linear relationship between the salinity of electrolytes and conductivity ($\sigma \approx C/10$, where C [g/l] is the concentration of NaCl).

At moderate temperatures, 0-200°C, resistivity of aqueous solutions decreases with increasing temperature. The reason is increasing mobility of the ions caused by a decrease in the viscosity of the water. Dakhnov (1962) has described this relationship:

$$\rho_w = \frac{\rho_{wo}}{1 + \alpha(T - T_0)}$$

where ρ_{wo} = resistivity of the fluid at temperature T_0;
α = temperature coefficient of resistivity,
$\alpha \approx 0.023\ °C^{-1}$ for $T_0 = 23°C$, and $0.025°C^{-1}$ for $T_0 = 0°C$.

At high temperatures, a decrease in the dielectric permittivity of the water results in a decrease in the number of dissociated ions in the solution. Above 300°C, this starts to increase fluid resistivity (Quist and Marshall, 1968) as seen in Figure 1.

3. ELECTRICAL RESISTIVITY OF WATER-BEARING ROCKS

In most rocks near the earth‘s surface, the conduction is dominated by electrolytic conduction in aqueous solution of common salts distributed through the pores of the rock and/or at the rock-water interface. The rock matrix itself is normally an insulator. The electrical resistivity of rocks depends on:

- Porosity and the pore structure of the rock
- Amount of water (saturation)
- Salinity of the water
- Temperature

- Water-rock interaction and alteration
- Pressure
- Steam content in the water

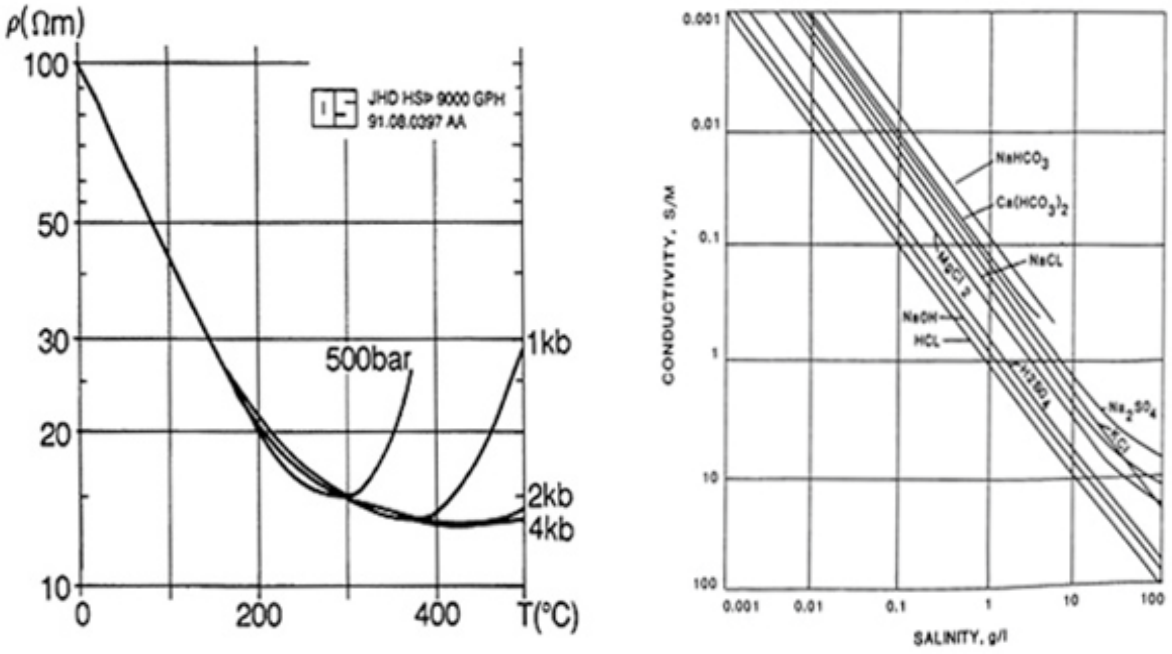

FIGURE 1: At left - electrical resistivity as a function of temperature at different pressures (taken from Hersir and Björnsson, 1991); at right - conductivity as a function of salinity

The most important factors are the porosity, temperature, salinity and water-rock interaction. In geothermal areas, the rocks are water-saturated. Ionic conduction in the saturating fluid depends on the number and mobility of ions and the connectivity of flowpaths through the rock matrix. Usually, the saturating fluid is among the dominant conductor in the rock and the degree of saturation is of great importance to the bulk resistivity. The pressure dependence is negligible compared to the temperature dependence, provided that the pressure is sufficiently high so that there is no change in phase.

Porosity is defined as the ratio between the pore volume and the total volume of a material. There are primarily three types of porosity: *Intergranular*, the pores are formed as spaces between grains or particles in a compact material (sediments, volcanic ash). *Joints-fissures*, a net of fine fractures caused by tension and cooling of the rock (igneous rocks, lava). *Vugular*, big and irregular pores, formed as material is dissolved and washed away, or pores formed by gas (volcanic rocks, limestone). Pore spaces must be interconnected and filled with water in order that fluid conduction takes place. In all types of porosity there are larger voids, called storage pores, and finer connecting pores. Most of the resistance to electric current flow (and fluid flow) is met in the connecting pores.

It has been observed for many cases that resistivity of water-bearing rocks varies approximately as the inverse square of the porosity. This empirical law, called **Archie's law** (Archie, 1942) describes how resistivity depends on porosity if ionic conduction in the pore fluid dominates other conduction mechanism in the rocks.

$$\rho = \rho_w a \, \Phi_t^{-n}$$

where ρ = bulk (measured) resistivity;
ρ_w = resistivity of the pore fluid;
Φ_t = porosity in proportions of total volume

a = empirical parameter, varies from <1 for intergranular porosity to > 1 for joint porosity, usually around 1;

n = cementing factor, an empirical parameter, varies from 1.2 for unconsolidated sediments to 3.5 for crystalline rocks, usually around 2.

Archie's law is valid if the resistivity of the pore fluid is of the order of 2 Ωm or less, but doubts are raised if the resisitivity is much higher (Flóvenz et al., 1985). However, Archie's law seems to be a fairly good approximation when the conductivity is dominated by the saturating fluid (Árnason et al., 2000).

Conduction in the rock matrix is normally negligible. The main contributions to the conduction mechanisms are: Conduction by dissolve ions in the pore fluid, pore fluid conduction. Conduction by absorbed ions on the pore surface, surface conduction. Conduction in alteration minerals, mineral conduction. Figure 2 illustrates these main conduction mechanisms.

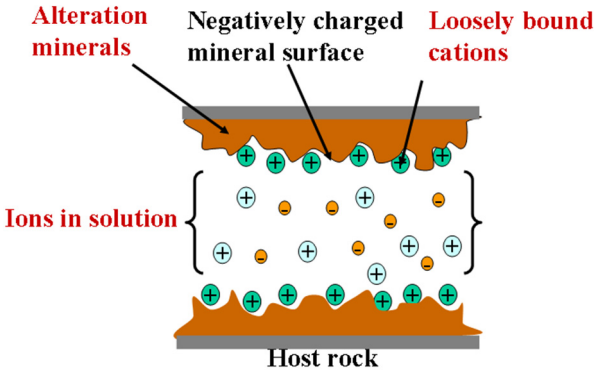

FIGURE 2: Conduction mechanisms

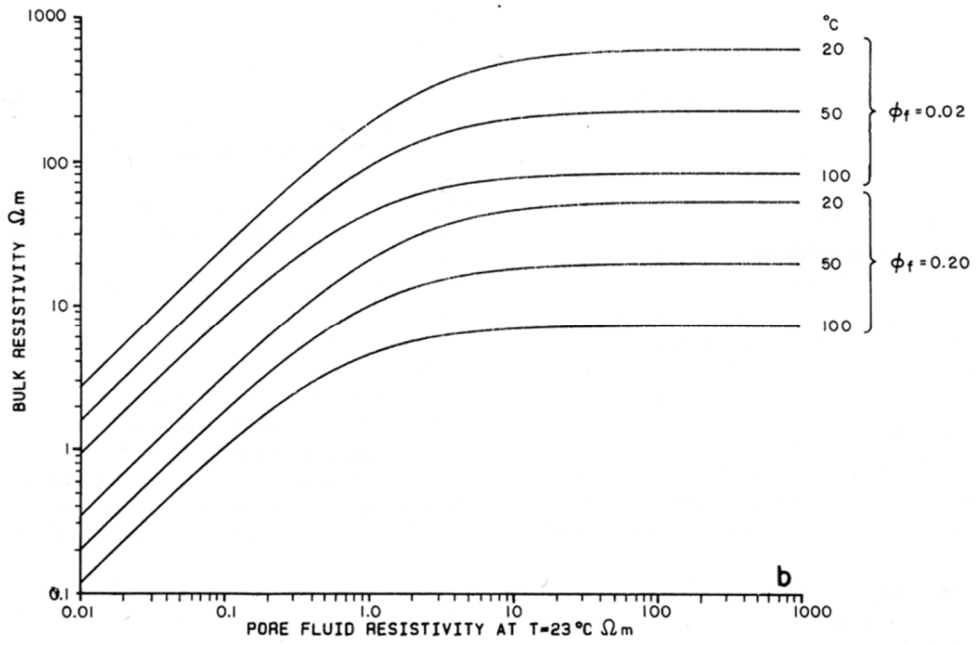

FIGURE 3: Bulk resistivity as a function of pore fluid resistivity for different temperatures and porosities (Flóvenz et al., 1985)

Figure 3 shows the relationship between the bulk resistivity and the pore fluid resistivity for different porosities and temperatures for rocks in the uppermost kilometer of the Icelandic crust outside the volcanic zone. It is based on a model put forward by Flóvenz et al. (1985). The model includes both electrolytic and surface/mineral conduction. For pore fluid resistivites less than 2 Ωm the dominant conductivity is pore fluid conductivity, Archie's law applies. For rocks saturated with fluids, having resistivity higher than about 2 Ωm and at room temperature, the bulk resistivity is practically independent of the resistivity of the fluid, but dependent on porosity and temperature, the dominant conductivity is mineral and/or surface conductivity.

4. RESISTIVITY STRUCTURE OF HIGH TEMPERATURE GEOTHERMAL FIELDS

All high temperature geothermal fields in Iceland and in general where the host rocks are volcanic not sedimentary, have a similar resistivity structure. They are characterized by some kind of a convex structure. At a certain depth, a low resistivity (conductive) cap or zone domes up (the outer margin of the reservoir) and is underlain by higher resistivity, a resistive core (see Figure 4). Not so many years ago most scientists found it hard to believe that the resistivity would increase at this depth since the temperature obviously increases with depth. This was a kind of a puzzle and many different theories were put forward. In Iceland it was not until a detailed multi-method DC resistivity survey was conducted in the Nesjavellir area, SW-Iceland in 1985 and 1986 that a reasonable explanation was put forward. The joint 2D interpretation of the different datasets showed a detailed picture of the resistivity structure in the uppermost 1 km under Nesjavellir, SW-Iceland that could be compared to data from nearby boreholes (Árnason et al., 1987 and 1987b).

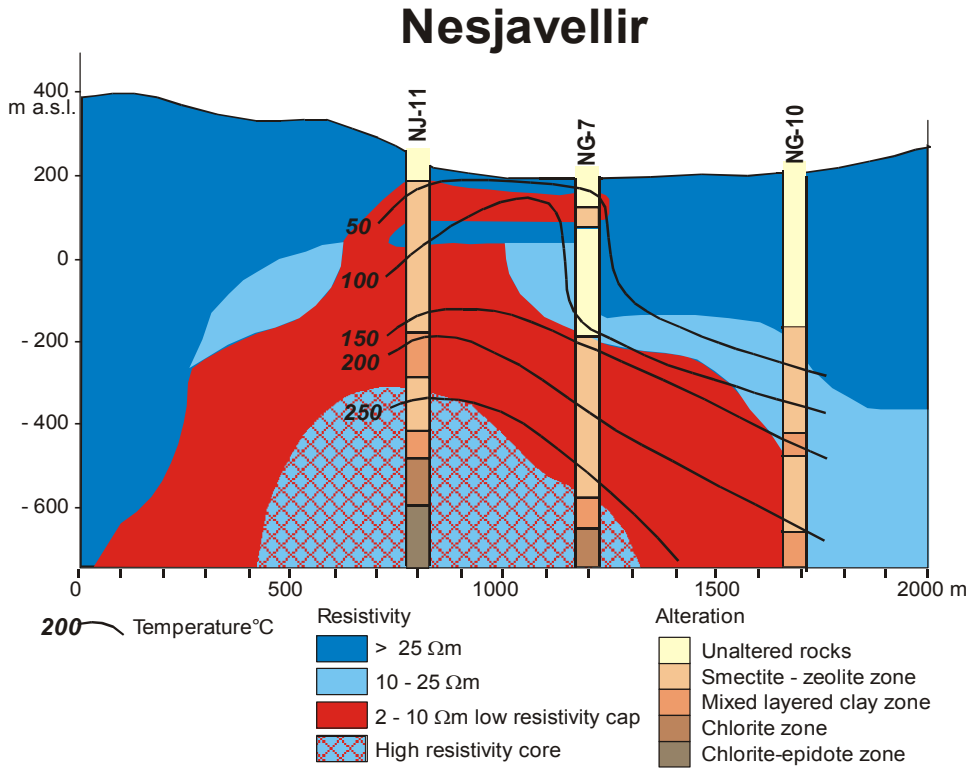

FIGURE 4: Resistivity cross-section from Nesjavellir geothermal field, SW-Iceland, alteration zoning and temperature (Árnason et al., 1987)

The resistivity structure at Nesjavellir was compared to lithology, alteration mineralogy and temperature. The resistivity was not found to correlate with the lithology, but a fairly clear and consistent correlation was found with the alteration mineralogy. Figure 4 shows a simplified resistivity cross-section from Nesjavellir and the zones of dominant alteration minerals and temperature in nearby wells. The figure shows that the resistivity is high in the surrounding cold unaltered rocks. At temperatures of 50-100°C pronounced geothermal alteration sets in with smectite and zeolites as the dominant alteration minerals and the rocks become conductive. At higher temperature, in the range of 220-240°C, smectite and zeolites are gradually replaced by chlorite as the dominant alteration mineral in the so-called mixed layered clay zone (Kristmannsdóttir, 1979) and the resistivity increases again. At still higher temperatures epidote becomes abundant.

An overview of this relationship between alteration and temperature is given in Figure 5. The smectite and the zeolites minerals have loosely bound cations that make these minerals conductive, while in the

chlorite mineral these ions are bound in a crystal lattice (Deer et al., 1962), which makes the mineral more resistive. Similar correlation has been found in all the explored and drilled high-temperature geothermal fields in Iceland as well as in many high-temperature areas in other countries (Árnason et al., 2000).

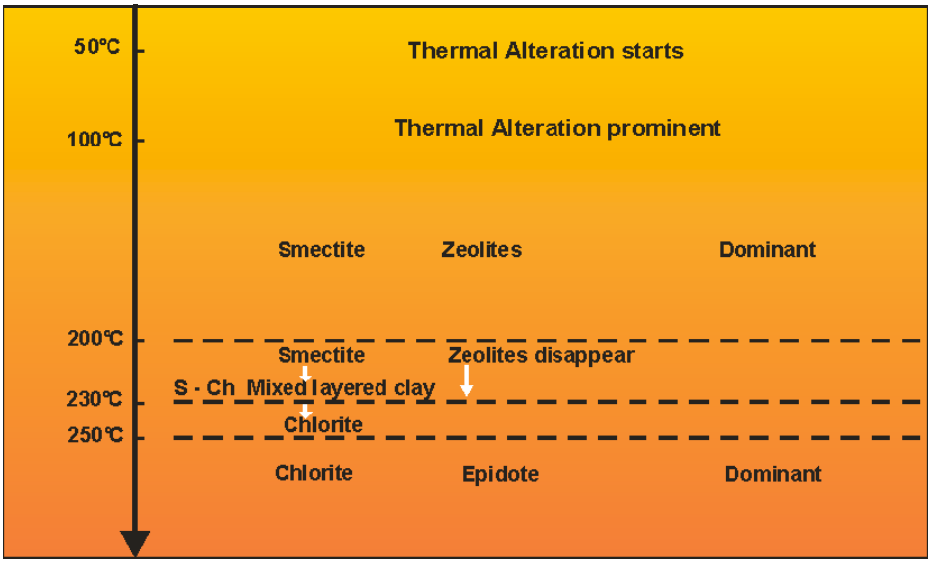

FIGURE 5: Alteration mineralogy and temperature

Figure 6 shows measured normalised sample conductivity as a function of pore fluid conductivity for different salinity from different alteration zones in Iceland. This study was done in cooperation between scientist at Iceland GeoSurvey and GFZ in Potsdam, Germany (Flóvenz et al., 2005). For unaltered rocks the conductivity is dominantly pore fluid conductivity for all salinities. On the other hand for smectite altered rocks the figure shows near constant values of conductivity for different salinities (except for one sample), showing dominantly mineral conduction. In the case of chlorite alteration, the conductivity curve is between these two, showing dominantly pore fluid and surface conduction. This is also in good agreement with the result in figure 4 showing the correlation between the subsurface resistivity and hydrothermal alteration minerals as revealed in cuttings from boreholes.

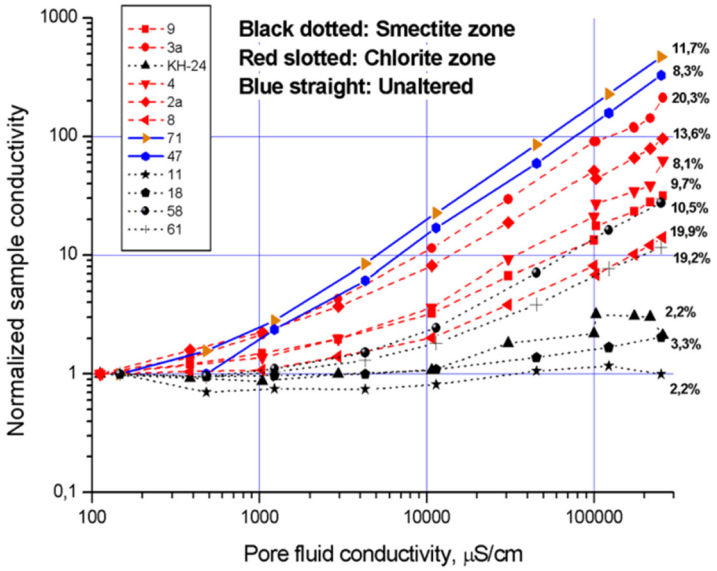

FIGURE 6: Normalized resistivity as a function of saturating fluid conductivities for different alteration zones in Icelandic rocks (Flóvenz et al., 2005)

Figure 7 shows the general resistivity structure of the basaltic crust in Iceland based on in-situ measurements and laboratory data. The uppermost and unaltered part has relatively high resistivity and the conduction is mainly pore fluid conduction. The resistivity decreases as the smectite-zeolite zone is reached and mineral or surface conduction becomes the dominant conduction mechanism. Because of increasing temperature and increasing alteration at greater depth, the resistivity decreases furthermore. Below, the mixed clay zone becomes dominant and the resistivity increases again, most likely due to strongly reduced cation exchange capacity of the clay minerals in the mixed clay and chlorite zone. Here the surface and pore fluid conduction probably dominate as the mineral conduction is diminished. The transition from smectite to mixed layer clay happens at a temperature around 230°C. At still greater depths the resistivity decreases slowly which is considered to be caused by slowly increasing temperature with depth in the reservoir.

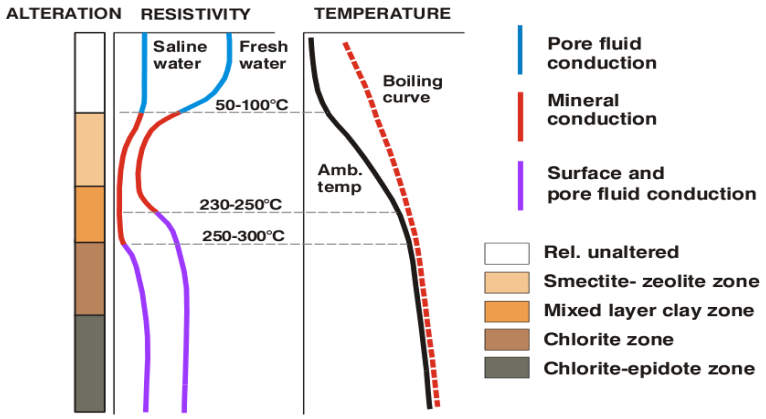

FIGURE 7: The general resistivity structure of the basaltic crust in Iceland summarized (taken from Flóvenz et al., 2005); the depth scale is arbitrary

The subsurface resistivity structure in high temperature geothermal fields therefore reflects the hydrothermal alteration. The primary minerals in the host rock matrix are transformed into different minerals because of water-rock interaction and chemical transport by the geothermal fluids. Alteration minerals depend on the type of primary minerals and the chemical composition of the geothermal fluid but mainly on temperature, but porosity and premeability also control the intensity of the alteration. If the alteration and temperature are in equilibrium the subsurface resistivity structure reflects not only the alteration but also which temperature to expect. This was an important finding, because if the temperature that produced the alteration mineralogy prevails, the resistivity structure can be used to predict the temperature. But if cooling occurs, the alteration remains and so does the resistivity structure. The resistivity structure can therefore in most cases be regarded as a "maximum thermo-meter". However, it has occurred that alteration minerals have indicated lower temperature than measured in the wells. This has been interpreted as being due to a young system being heated up and the alteration is lagging behind, still not in equilibrium with the temperature.

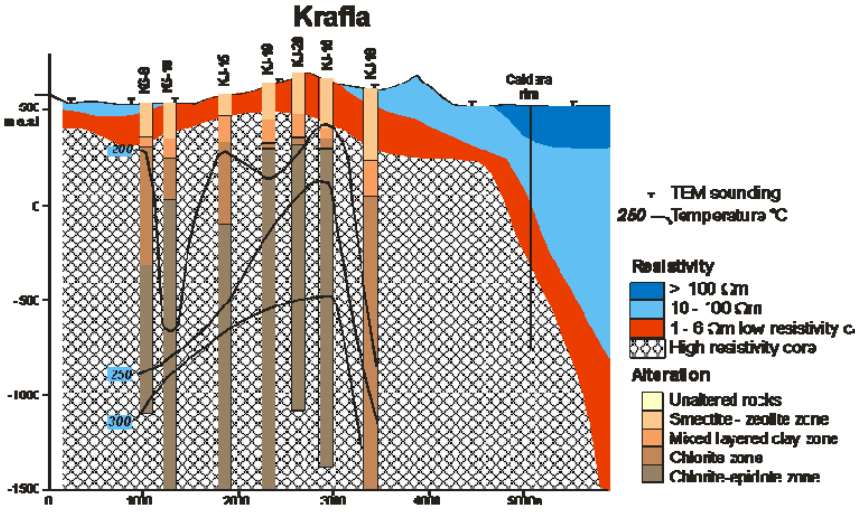

FIGURE 8: An example of cooling - resistivity cross-section from Krafla geothermal field, NE-Iceland, with alteration zoning and temperature (Árnason and Karlsdóttir, 1996)

Figure 8 shows a fine correlation between the subsurface resistivity and alteration zoning for all bore holes on a profile from Krafla geothermal

field, NE-Iceland. Correlation with temperature is fair as well except for boreholes KG-10 and KJ-18. It has been proposed that 2000 years ago, a dyke was injected and blocked the flow of geothermal fluid resulting in considerable cooling around well KJ-18 (Sæmundsson, 1991; Árnason and Karlsdóttir, 1996). Therefore great care should be taken when predicting the temperature from the subsurface resistivity structure.

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RESISTIVITY METHODS - DC AND TEM WITH EXAMPLES AND COMPARISON FROM THE REYKJANES PENINSULA AND ÖXARFJÖRDUR, ICELAND

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ABSTRACT

Resistivity methods have for a long time been proven as the most successful method in geothermal exploration, due to the resistivity of rocks in geothermal environment being chiefly controlled by parameters that correlate to the geothermal activity. The most important method for measuring the resistivity in the uppermost kilometre was for a long time the DC resistivity method, especially with the Schlumberger configuration. It was in the 1990's replaced by the TEM method, more specifically the central loop TEM sounding method, as the routine method for the exploring the uppermost kilometre. Description is given of both methods and their differences discussed. Then examples are taken from two geothermal areas in Iceland, the outer Reykjanes Peninsula and the Öxarfjördur area, where surveys using both methods have been done. The results are discussed and conclusions drawn that confirm the advantage of TEM over the DC method.

1. INTRODUCTION

Resistivity methods have been used in geothermal research since the 1940s and since the 1960s they have been the most important geophysical methods in the surface exploration of geothermal areas, and as such key methods in delineating geothermal resources and production fields. The parameter of interest is the electrical resistivity which in geothermal areas gives information on temperature and alteration of the rocks with depth which are major parameters for the understanding of the geothermal systems.

The main principle is that electrical current is induced into the earth which generates an electromagnetic signal that is monitored at the surface. There are many different methods and varying setups or configurations for the different methods. The most important methods are:

DC methods, where current is injected into the earth through electrodes at the surface generating an electric field at the surface. The electrical field is measured. Based on that and the geometry of the set-up, the electrical resistivity of the rock structures below is calculated. The DC methods can be grouped into several types and in addition there can be different geometrical configurations.

TEM methods, where current is induced by a time varying magnetic field from a controlled source , thus secondary magnetic field is created that consequently creates secondary currents in the earth. The monitored signal is the voltage induced at surface in a receiver coil due to the decaying secondary magnetic field. Here there are also different possibilities in the set-up.
MT or Natural-source electromagnetics, where the current is induced by the time variations in earth's natural magnetic field, and the signal measured is the electromagnetic field at the surface.

Distinction is made between **soundings**, which are used for mapping resistivity changes with depth, and **profiling** where the whole array is moved along profile lines for mapping lateral changes of the resistivity.

In this paper the DC and TEM methods are presented with emphasis on the Schlumberger method (DC) and the Central loop TEM method. The basis is the experience gained in Iceland through the years in using these methods, with DC methods having been used in geothermal exploration from its infancy in the late 1940s and TEM from the late 1980s. For further information see e.g. Hersir and Björnsson (1991), Árnason and Flóvenz (1992) and Keary and Brooks (1992).

2. RESISTIVITY OF ROCKS

Electrical resistivity of rocks in geothermal surroundings is a parameter which reflects the properties and history of the geothermal system. Thus, a good knowledge on the resistivity is very valuable for the understanding of the geothermal system. This relates to the fact that **the resistivity of rocks is chiefly controlled by parameters that correlate to the geothermal activity**, such as:

- Porosity and pore structure, where distinction is made between:
  - Intergranular porosity such as in sedimentary rocks;
  - Fracture porosity, relating to tension, fracturing or cooling of igneous rocks;
  - Vugular porosity which relates to dissolving of material (limestone) or gas content (in volcanic magma).
- Alteration of the rocks – often related to as water-rock interaction;
- Salinity of the fluid in the pores;
- Temperature;
- Amount of water, saturation or steam content; and
- (Pressure)

The four first, namely fracture porosity, alteration, salinity of the fluid, and temperature, are the most important ones**.** That also explains why the resistivity is so important in geothermal exploration, especially in volcanic surroundings, and the important role of resistivity soundings. Further discussion on resistivity of rocks and its correlation to the properties of geothermal systems will not be given here, but the reader is referred to Árnason et al. (2000) for further information.

3. DC METHODS – SCHLUMBERGER SOUNDING

The important relationship behind DC resistivity methods is the **Ohm's law:**

$$\vec{E} = \rho \vec{j}$$

where $\vec{E}$ is electrical field strength (V/m);
$\vec{j}$ is current density (A/m^2); and
ρ is electrical resistivity (Σm), which is a material constant.

For a homogenous earth and a single current source (Figure 1), the relevant equation for the electrical potential V, at a distance r from the current source I, becomes:

$$V_r = \Delta I / 2\pi r, \text{ or } \Delta = 2\pi r V_r / I$$

This is the key equation to calculate the resistivity for all the different DC configurations.

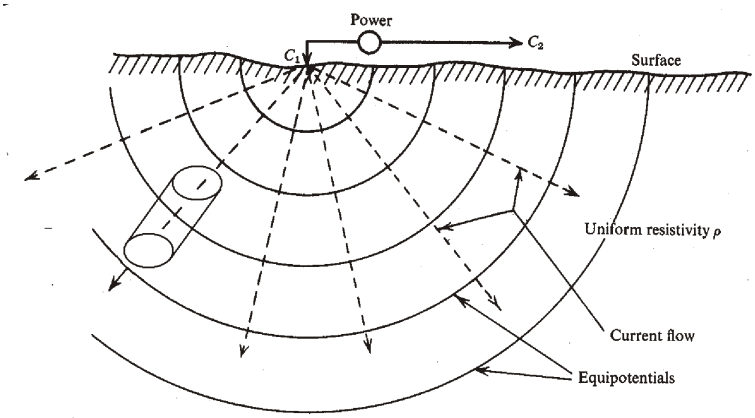

FIGURE 1: Current distribution around a single current electrode in the earth (Keary and Brooks, 1992)

Most configurations rely on **two pairs of electrodes** – one pair for current transmission and the other for measuring the potential difference. The most common DC methods are:

- **Schlumberger sounding,** which has been widely used and is the most popular one (Figure 2). The electrodes are on a line, and the set up is mirrored around the centre. The pair of potential electrodes is kept close to the centre, while the pair of current electrodes is gradually moved away from the centre, for the current to probe deeper into the earth. The distance between the current electrodes is increased in near-logarithmic steps until the scheduled maximum length of the current arm has been reached. Conventional soundings may have a maximum current arm AB/2 of approximately 1.5 km;
- **Dipole sounding or profiling**; here various arrays exis; many used quite much in the 1970s into the 1980s;
- **Wenner sounding**, not much used today, but quite similar to Schlumberger. The electrodes are on a line but the same distance is always kept between all of them.
- **Head-on profiling,** a successful method for locating near-surface vertical fractures or faults. It is really a variety of the Schlumberger method with a third current electrode located far away at a right angle to the profile line.

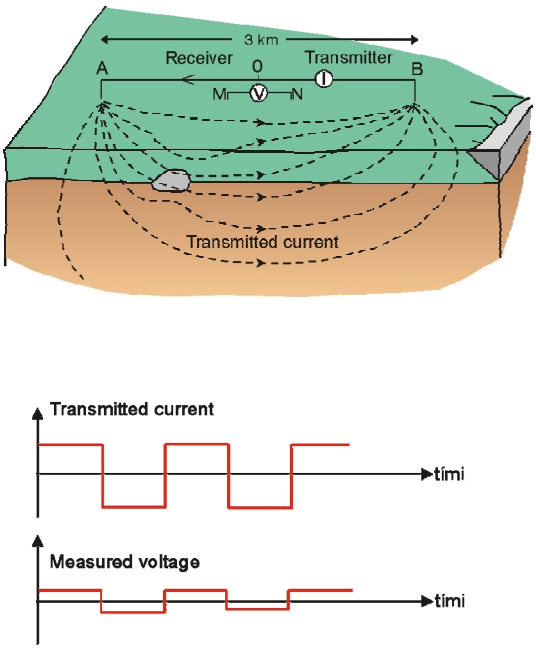

FIGURE 2: The principles behind the Schlumberger configuration and the associated current distribution in the earth

Necessary **equipment** for DC soundings is a good current transmitter able to transmit at least 0.5-1 A, a sensitive voltage receiver, wires on reels, electrodes, and a power source. Using (car) batteries as a source for the current transmitter, the equipment is not very bulky, and usually possible to carry on foot for measurements in areas where access by car is not possible. Good DC equipment is marketed by many companies selling geophysical instruments.

The earth is not homogeneous so what we are looking at is a sort of average resistivity of the earth below the measuring site within a certain depth range. This "average" resistivity is usually referred to as **apparent resistivity, Δ_a.** In the case of Schlumberger soundings, the relationship for apparent resistivity can easily be derived from the equation above and is given as:

$$\Delta_a = \Delta V/I \times (S^2 - P^2)\pi/2P$$

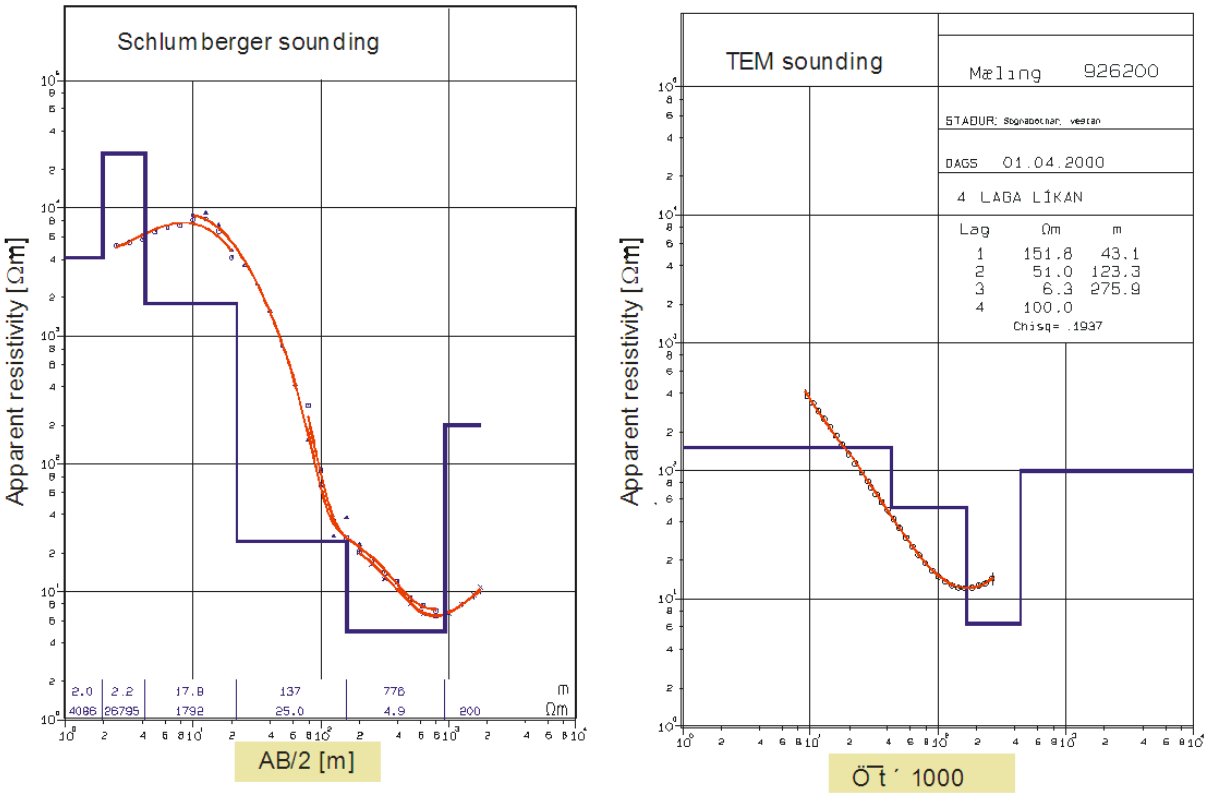

FIGURE 3: Curves showing a typical Schlumberger sounding (left) and a TEM sounding (right) and 1D models for their interpretation

where S = AB/2 and P = MN/2.

Apparent resistivity is plotted as a function of AB/2 on a bilogarithmic scale with increasing electrode separation (Figure 3). The curve does reflect the true image of the resistivity distribution in the earth below, as can be inferred from the 1D interpretation shown with it.

Schlumberger soundings are usually extended to a maximum current arm, AB/2, of 1-2 km, but much longer current arms have been used. But in practice, much longer wire distances can be difficult to control. For the depth penetration of the sounding, a rule of thumb says that it reaches down to about 1/3 of the distance AB, the actual resistivity structure may, however, influence this significantly, usually to a lower value. In principle, the distance between the potential electrodes MN, should be small and fixed, but in practice it needs to be enlarged a few times to increase the measured signal. It is, however, important for it to be kept at all times within 20% of that of the distance between the current electrodes. Due to this increase in MN, the sounding curve consists of a few segments that usually, if local anomalies can be avoided, are well tied together (Figure 3).

For effective measurements, a minimum number of persons in a **field crew** is four, one for extending each current arm, and two for the potential electrodes and measuring equipment. Under good conditions they might be expected to make about 2 soundings per day, and even 3 may be reached under optimal conditions. To this number, extra crew members can be added according to the necessities of the actual project, conditions or routine, such as for cutting down vegetation along the profile, carrying equipment, security etc.

4. THE TEM METHOD

The TEM method uses a magnetic field to induce currents in the earth. In the central loop TEM sounding method (referred to as TEM only from now on), constant magnetic field is built up by transmitting current through a big loop. The current is abruptly turned off. The decaying magnetic field induces secondary currents and a secondary magnetic field, decaying with time. This decay rate of the secondary field is monitored by measuring the voltage induced in a receiver coil (or a small loop) in the centre of the transmitting loop. Current distribution and the decay rate, recorded as a function of time, depend on the resistivity distribution of the earth, and can be interpreted in terms of the subsurface resistivity structures. Other methods may be based on a grounded dipole to create the primary magnetic field. The TEM method is a fairly recent addition to the resistivity methods used in geothermal exploration, developed in the late 1980s.

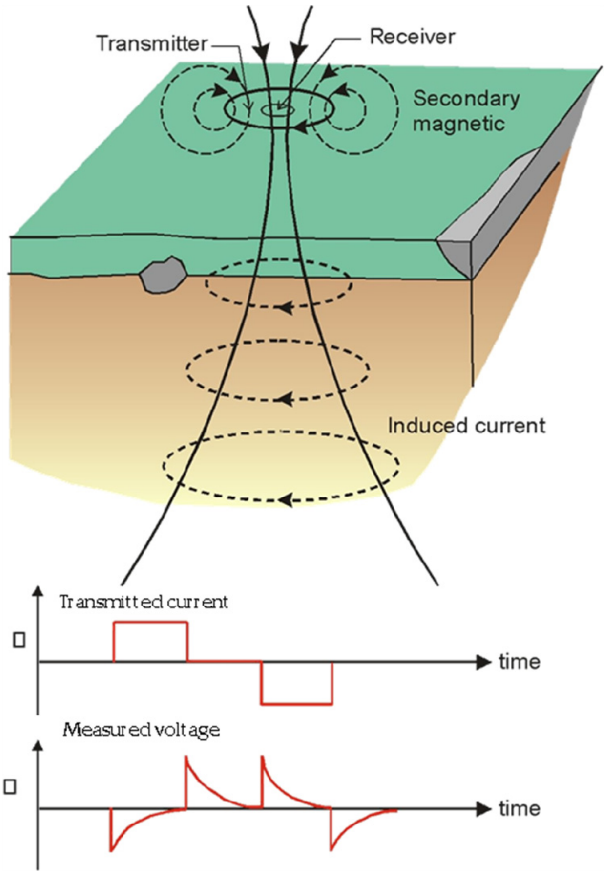

FIGURE 4: The principles behind TEM soundings and the expected magnetic and current distribution in the earth

Figure 4 shows the actual lay-out for a TEM sounding. When the current in the big loop is turned off and the primary magnetic field decays, secondary currents are induced that gradually migrate to deeper levels. The secondary induced magnetic field is monitored by the receiver loop and a receiver in the centre of the survey. Readings are done from the turn-off at fixed intervals during the decay of the secondary magnetic field as it approaches zero, the last ones reaching the deepest structures.

The measured resistivity in the subsurface is, similarly to the Schlumberger soundings, expressed as **apparent resistivity ρ_a,** and is an expression for the „average resistivity" of the structures below the centre of the sounding. It is a function of several variables, including: Measured voltage; time elapsed from turn off; area of loops/coils; number of windings in loops/coils and magnetic permeability. For a homogeneous half-space, apparent resistivity, ρ_a, expressed in terms of induced voltage $V(t, r)$ at late times after the source current is turned off, is given by:

$$\rho_a = \frac{\mu_0}{4\pi}\left[\frac{2\mu_0 A_r n_r A_s n_s I_0}{5t^{5/2}V(t,r)}\right]^{2/3}$$

where A_r, A_s = The area of the receiver loop and the transmitter loop, respectively (m^2);
n_r, n_s = The number of windings in the receiver loop and the transmitter loop, respectively;
I_o = The current sent through the transmitter loop (A);
t = Time elapsed from the turn off (s);
μ_o = Magnetic permeability (H/m).

For a layered earth the expression is much more complicated. See Árnason (1989) for further information and details.

Apparent resistivity is plotted as a function of time after the current was turned off (Figure 3). The graph resembles the Schlumberger sounding graphically. However, it does not reflect the image of the true resistivity as the Schlumberger sounding.

TEM **equipment** is sophisticated and relatively expensive, at least compared to DC equipment. Besides the receiver including a datalogger, a transmitter is required connected to a good electric generator able to generate high currents (the order of 10 A) and thus a strong magnetic field through the transmitting loop. The heavy generator makes it difficult to do measurements by carrying the equipment on foot. In addition, a measuring coil and wires for the loops are needed, the current wires need to be able to carry heavy current. Finally, a field computer is necessary to make preliminary interpretations at the end of a day's work for data quality assessment.

A minimum of three **field crew** members is needed for making TEM soundings and only two if the soundings are carried out on snow-covered earth by the help of snow scooters. They may be able to carry out 4-5 soundings in a day if they are well trained and the conditions are good.

In practice, the big transmitting loop is usually a square with a side of 150-300 m. With good conventional TEM equipment and a transmitter loop 300×300 m, with TEM it is possible to study resistivity structures down to depth levels of approx. 1 km.

5. INTERPRETATION

Apparent resistivity does not show the true resistivity structure of the earth and needs to be interpreted in terms of the actual resistivity distribution. The procedures are similar whether we are considering Schlumberger soundings or TEM soundings. In the interpretation, reference is usually made to the restrictions in the geometry of the resistivity structures:

- **1D** interpretation means that the resistivity distribution is assumed to resemble a horizontally layered earth, where the horizontal layers are assumed to stretch at least well outside the boundaries of the sounding.
- **2D** interpretation means that the resistivity distribution is assumed to be constant in one direction, which usually agrees with the direction of the main structures or the geological strike in the area. Soundings are made along a profile line which should be perpendicular to the strike line. Good data density is required along the profile line, with not more than 1-2 km between soundings. 2D interpretation also allows building into the interpretation variations in the terrain and thus necessary terrain corrections.
- **3D** interpretation allows the resistivity to vary in all directions. For a meaningful 3D interpretation a high data density is requested with a good spread of the different soundings, preferably in a net or close to that.

In the beginning, manual 1D interpretation of Schlumberger soundings was the state of the art, done with the help of master curves that were published in large volumes, but here computers took over in the late 1970s. We distinguish between forward and inverse modelling.

Forward modelling is really the first step in the inversion process. When the data has been plotted on a graph, a model is suggested to fit the resistivity distribution presented in the sounding. The forward algorithm simulates the response of the earth to the measuring equipment by calculating the response of the model to be compared to the actual data. The data and the response are compared and improvements suggested to the model to improve the interpretation. Thus, the interpreter can continue to improve his model until a satisfactory agreement is reached.

Inversion algorithms take care of the improvement of the model, and produce a "best" solution. This they do by improving the model, first by calculating the difference between the measured data and the

response of the model, then suggesting improvements, recalculating the response based on the improved model and thus continuing until a satisfactory agreement has been reached. These calculations (Figure 5) are based on iterative procedures and some conditions built into the actual program, such as how many layers a sounding may have, how good the agreement needs to be, etc.

Usually good 1D interpretation of soundings is the starting model for a more complicated interpretation. The programs for interpretation can both be complicated and computer demanding. Programs for 3D interpretation require both very sophisticated software and high capacity computers, and a good and evenly distributed data coverage.

Inversion programs have been available for 1D interpretation of Schlumberger and TEM soundings for decades. Interpretation using Occam inversion improves the resolution even further by assuming „continuously" changing resistivity instead of a few specific layers. 2D forward interpretation programs have also been available for Schlumberger soundings for a long time, while inversion algorithms have also been available for some time. With a 3D signal source 2D has no real meaning for TEM. For 3D interpretation, forward modelling has been available for both Schlumberger and TEM soundings. Inversion has also been available for DC soundings for some years, and, recently, programs for 3D inversion of TEM and a combined interpretation of TEM and MT data have become commercially available, but these put heavy demand on the computer capacity (K. Árnason, personal comm.).

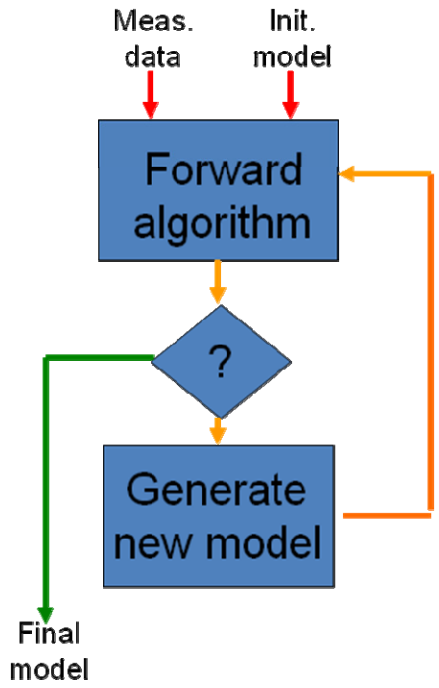

FIGURE 5: Flow diagram showing how a forward model is used as a starting model for the inversion (Árnason, pers. comm.)

The interpreted resistivity data is usually presented in resistivity contour maps and cross-sections. The contour maps show the resistivity distribution at specific depth levels, usually compared to sea level, while the cross-sections show the resistivity changes with depth along a profile line.

6. COMPARISON OF SCHLUMBERGER AND TEM SOUNDINGS

6.1 Advantages and disadvantages

The TEM method has many advantages over the Schlumberger DC sounding method. They relate to several facts, such as the method of transmitting the signal, and the simplicity of the field work. The main advantages are:

- In TEM, no current has to be injected into the earth and shorter wires (though heavier) are used. This is important in areas where the contact resistivity in the surface is very high and thus current transmission difficult, such as in deserts, lava fields and cold areas, making data collection even possible on snow and ice, or bare rock.
- In TEM, distortions due to local inhomogeneities are small, due to the signal (the downward migrating currents) being more downward focussed
- Similarly, TEM is much less sensitive to lateral resistivity variations than DC methods. Thus, 1-D interpretation is much better justified.
- In DC-soundings the monitored signal is low when surveying over low-resistivity structures like in geothermal areas, but strong in TEM-soundings, increasing depth penetration in target areas.

- Finally, TEM needs less manpower, both in the field and for interpretation; and measurements are considerably faster to carry out. Thus it is more cost effective, or allows collection of data in higher density, and consequently giving a more detailed model of the geothermal system.

In the following two subsections examples are taken from two geothermal fields in Iceland and the results of Schlumberger and TEM soundings compared. There are not many geothermal fields where "state of the art" surveys (for its time) have been carried out with both Schlumberger soundings and TEM soundings, and drilling been done to test the results, but this has been done on the outer Reykjanes Peninsula, SW-Iceland and in the Öxarfjördur area, NE-Iceland.

6.2 Results from the outer Reykjanes Peninsula, SW-Iceland

Figure 6 shows the Reykjanes Peninsula in SW-Iceland, the active volcanic fissure swarms and the high-temperature geothermal systems found on the outer part of the Peninsula. They are (from west) the Reykjanes field, where a new 100 MWe power plant went on-line in late 2006, Eldvörp and Svartsengi where the Svartsengi power plant is located producing now 76 MWe (December 2007) and 150 MWth. A by-product of the latter is the famous Blue Lagoon. The area is flat and mainly covered with Holocene lavas with occasional low hyaloclastite mountains dating from the glacial period breaking through the flatness. The elevation is mainly at 10-40 m a.s.l.

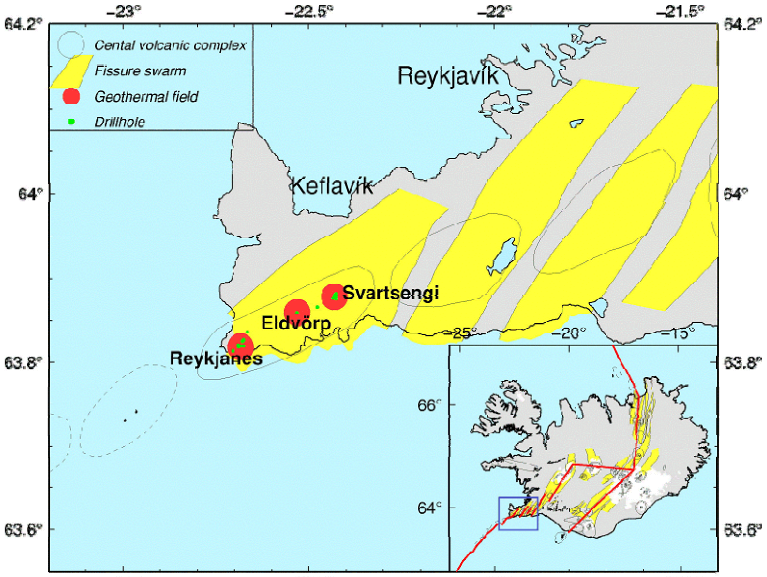

FIGURE 6: The volcanic systems and high-temperature areas on the outer Reykjanes Peninsula, SW-Iceland (H. Eysteinsson, pers. comm.)

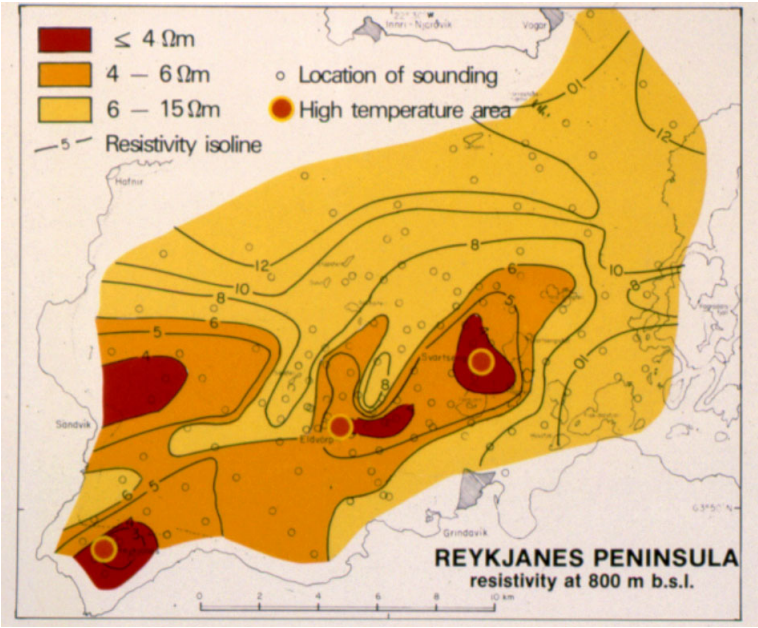

FIGURE 7: DC resistivity map of the outer Reykjanes Peninsula at 800 m b.s.l. (Georgsson, 1984)

The DC survey on the outer Reykjanes Peninsula (Figure 7) was done in the mid 1970s and early 1980s (Georgsson, 1984). The target area was covered with around 150 Schlumberger soundings with maximum current arms around 1500 m. It could prove quite difficult to get satisfactory data for the last few data points in some of the soundings, so the actual maximum current arm was in the range 800-1560 m. With very rough lava fields covering parts of the area, the terrain can be difficult to traverse, so carrying the equipment on foot was the only option in some locations.

The geohydrological situation is also quite unusual. The whole of

the outer part of the peninsula has saline groundwater, with seawater having penetrated through it. Floating on the seawater, like ice on water, is a lens of freshwater, usually with a thickness of 40-50 m. With the actual density contrasts (approx. 1:35) it gives an elevation of the ground water table at 1-1.5 m. Above that the rocks consist of dry lavas. The salinity of the groundwater means that the regional resistivity in the area is quite low, about 10 Ωm.

Figure 7 shows a resistivity map of the area at 800 m b.s.l. based on the Schlumberger soundings. It shows a low-resistivity zone along the target area with a resistivity below 8 Ωm, and anomalies of extra low resistivity, 2-4 Ωm, outlining the active high-temperature fields. Of interest is an additional low-resistivity anomaly 2-3 km to the north of the Reykjanes field, indicating existence of possible new field there.

Figure 8 shows a NW-SE trending resistivity cross-section through the Svartsengi field, and illuminates very well both the special resistivity distribution in the area with its horizontal layers that relate to the geohydrological situation, and the low-resistivity anomaly associated with the Svartsengi high-temperature field. It also explains why 1D interpretation is believed to be adequate for the Schlumberger soundings.

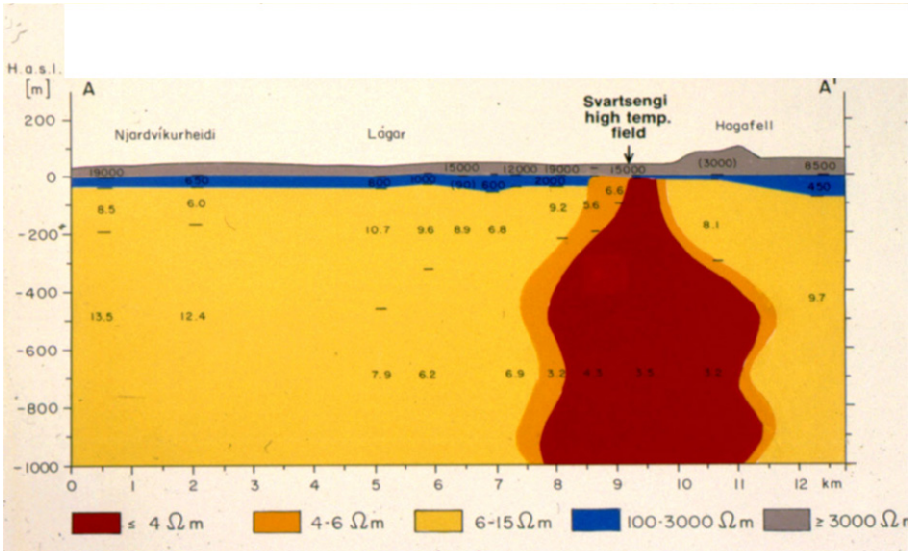

FIGURE 8: DC resistivity cross-section trending NW-SE through the Svartsengi geothermal field, Reykjanes Peninsula (Georgsson, 1984)

The TEM survey dates from the mid 1990s (Karlsdóttir, 1997). Figure 9 shows the elevation of the top of the high-resistivity layer seen in TEM measurements in the area. Even though this is a very different way of presenting the data, the same anomalies are seen associated with the high-temperature activity and even the fourth anomalous area is seen. The difference is that here high resistivity below low resistivity is being shown, which could not be established with certainty in the Schlumberger soundings even though its presence was suspected. A high-resistivity core is something that characterizes high-temperature fields in Iceland, and is associated with changes in alteration mineralogy with depth and temperatures, from smectites and mixed-layer clays to chlorite and epidote, which happens above 240-250°C (Árnason et al., 2000).

In Figure 10 there is a WSW-ENE trending resistivity cross-section along the active high-temperature fields based on TEM data. It shows the existence of the high-resistivity core overlain by a low-resistivity cap. Furthermore, it shows well the close connection between the Eldvörp and Svartsengi fields.

Comparing the results of the two surveys, we can conclude the following:

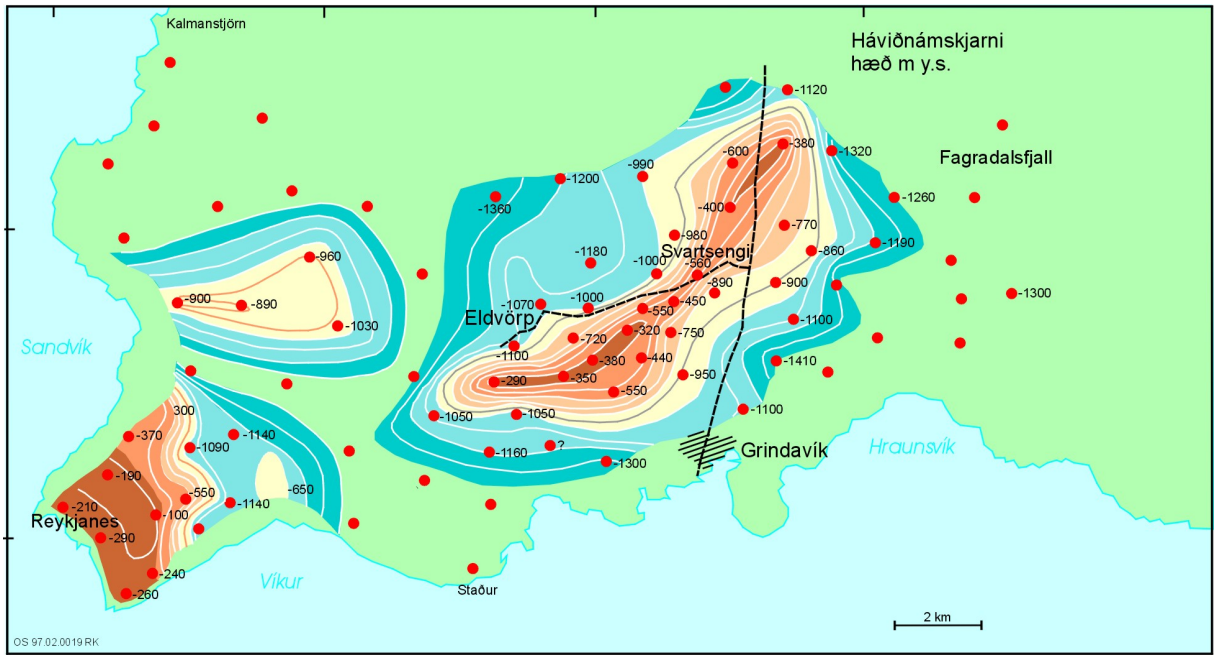

FIGURE 9: TEM resistivity map of the outer Reykjanes Peninsula showing the elevation of the high-resistivity anomaly in m a.s.l. (Karlsdóttir, 1997)

- There is considerably better depth penetration in the TEM soundings;
- The large picture is similar in outlining the active geothermal systems and a possible new system;
- At deeper levels there is much better resolution in TEM with new details in the resistivity structures not seen with certainty in the Schlumberger soundings;
- TEM shows clearly high resistivity inside the geothermal systems, despite the very saline groundwater, something that was suspected but not confirmed from the Schlumberger soundings;
- TEM also shows different layers in the low-resistivity layer;
- The Schlumberger soundings give a better resolution of the uppermost 100-200 m, especially the water table or the fresh water lens floating on the seawater.

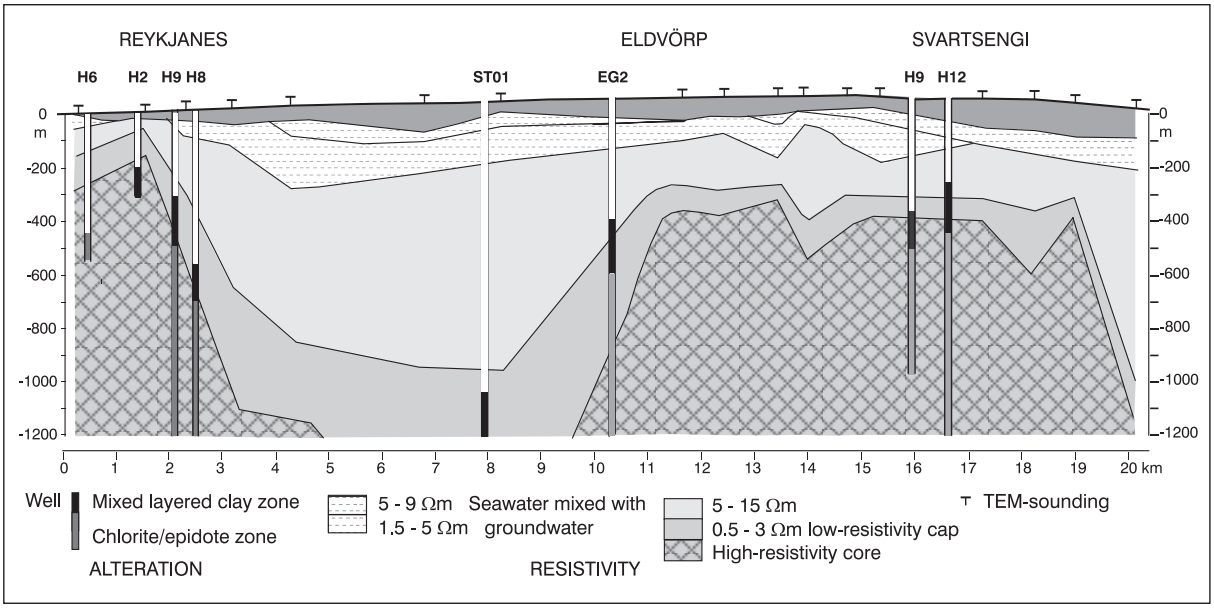

FIGURE 10: TEM resistivity cross-section trending ESE-WNW, along the outer Reykjanes Peninsula through the geothermal fields (Karlsdóttir, 1997)

6.3 Results from the Öxarfjördur area, NE-Iceland

The Öxarfjördur bay and associated lowlands in NE-Iceland is chiefly a N-S trending, 25 km wide, downfaulted trough filled with sediments. The region is dominated by the delta of the Jökulsá-river, one of the major glacial rivers of Iceland which carries a lot of sediments with it, and three active N-S trending fissure swarms which are parts of active volcanic systems further inland. The thickness of the sediments reaches 500-1000 m at the coast in the central part of the area. The geothermal activity is mainly confined within the active fissure swarms with the main manifestations associated with the Krafla fissure swarm (Figure 11). Geothermal activity and active volcanic systems in sedimentary stratigraphy is unique for Iceland.

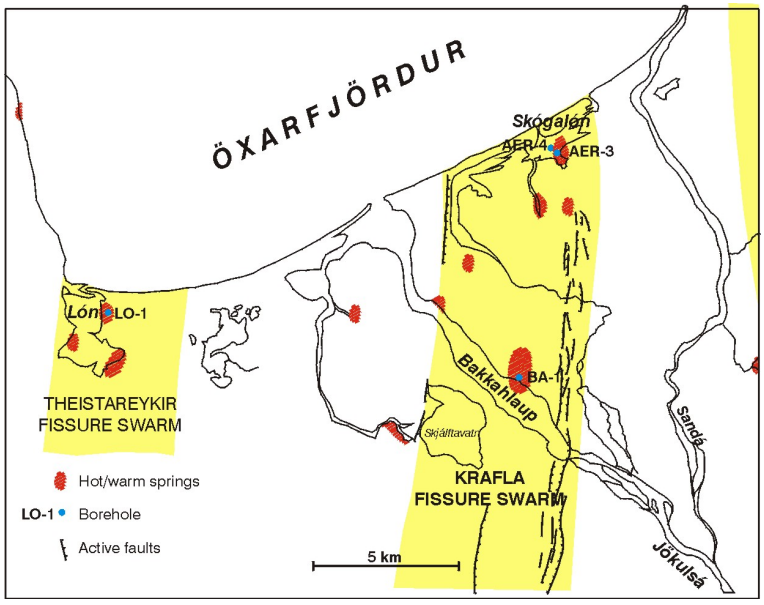

FIGURE 11: Geothermal and tectonic map of the Öxarfjördur area, NE-Iceland (Georgsson et al., 2000)

The **Krafla central volcano** is located about 50 km from the coast, but its fissure swarm stretches well into the Öxarfjördur bay. During 1975-1984 there was intense volcanic activity and rifting associated with the Krafla volcano and its fissure swarm, usually referred to as the Krafla fires. This included several distinct rifting episodes associated with magmatic intrusions (and/or surface eruptions), 3-4 of which were recorded in the Öxarfjördur area, without the lava reaching the surface there, but associated with large surface deformation and faulting along the fissure swarm (Björnsson, 1985).

The surface geothermal activity in the Öxarfjördur area must be considered rather meagre. With the temperatures around 40-80°C, consisting of unimpressive pools or warm ground in the sandy lowlands. The largest areas are in the central part of the Krafla fissure swarm at the banks of Bakkahlaup (the main outlet of Jökulsá), about 8 km from the coastline; and at the coast at Skógalón. During the Krafla fires surface geothermal activity increased considerably in the area, e.g. both Skógalón and Bakkahlaup reaching close to boiling temperatures. The surface activity is now declining again.

The DC resistivity survey in the Öxarfjördur area (Georgsson et al., 2000) included about 60 Schlumberger soundings dating mainly from the mid 1980s, when three main profile lines were measured intended for 2D forward

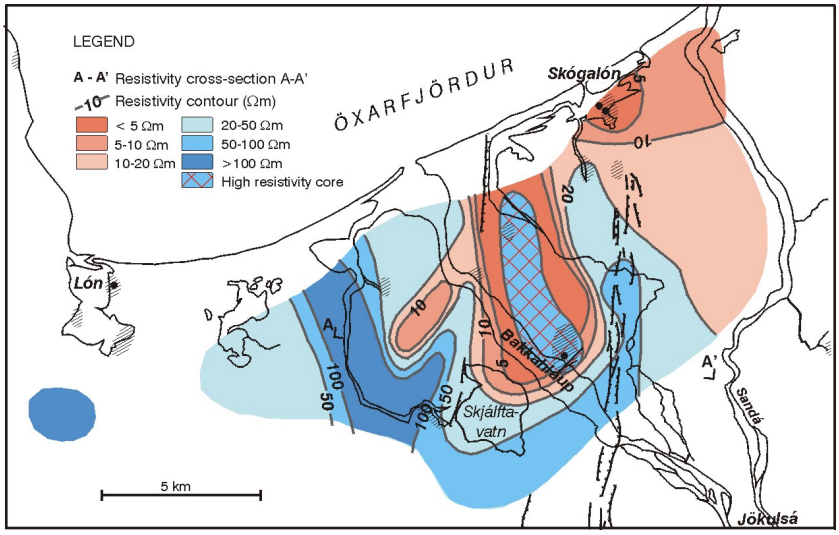

FIGURE 12: DC resistivity map of the Öxarfjördur area at 500 m b.s.l. (Georgsson et al., 2000)

interpretation. Figure 12 shows a DC resistivity map of the Öxarfjördur area at 500 m b.s.l. It shows two main resistivity anomalies, the most important one in the central part of the Krafla fissure swarm associated with the Bakkahlaup geothermal field with resistivity of 1-5 Ωm, and a high-resistivity core below. Another low-resistivity area is associated with the Skógalón field. The Bakkahlaup resistivity anomaly shows typical characteristics of an anomaly associated with high-temperature geothermal activity in Iceland. This is even more evident in the DC resistivity cross-section trending W-E seen in the upper part of Figure 13.

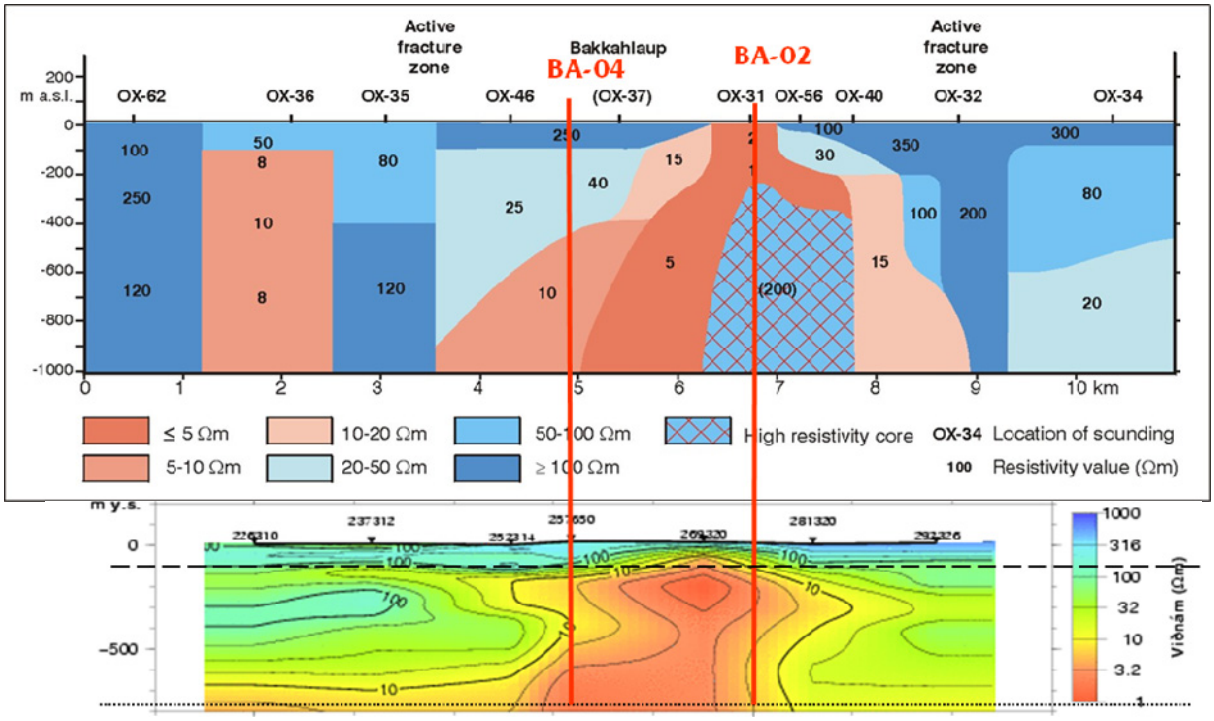

FIGURE 13: DC (above) and TEM (below) resistivity cross-section trending W-E through the Bakkahlaup geothermal field, Öxarfjördur, NE-Iceland (Georgsson et al., 2000; Karlsdóttir and Flóvenz, 2005)

Based on the results of the resistivity survey a deep exploration well, BA-02, was drilled in 1999. It is located centrally in the southern part of the anomaly seen in Figure 12, just north of the geothermal upflow and was drilled down to 1962 m in 1999. The result of the well was quite disappointing with the temperature reaching only 170-180°C at about 500 m, but cooling down below that. Another deep exploration well, BA-03, was drilled late in the year 2000 down to 700 m. It was located about 2 km north of BA-02. The results were even more disappointing. The well had many good aquifers, but none of them seemed to have temperatures above 100°C. It was a good low-temperature well with no indications of the high-temperature activity that was the target for the drilling actvity. The wells confirmed the existence of the thick sediments, being more than 500 m in the Bakkahlaup area, growing thicker towards the coast.

A revision of the conceptual model of the geothermal activity in the area was needed. For that purpose a TEM survey was carried out in 2003 and 2004 (Karlsdóttir and Flóvenz, 2005). Figure 14 shows TEM resistivity maps at 500 and 800 m depth b.s.l. The maps are somewhat similar, showing two main low-resistivity anomalies associated with the Bakkahlaup and Skógalón geothermal fields, and other smaller anomalies. The Bakkahlaup anomaly is comparatively small and higher resistivity beneath the low resistivity is not caused by high temperature alteration as anticipated earlier. The low resistivity in the uppermost 300-500 m is associated with warm saline water in sedimentary surroundings, not a typical low-resistivity cap of a high-temperature field.

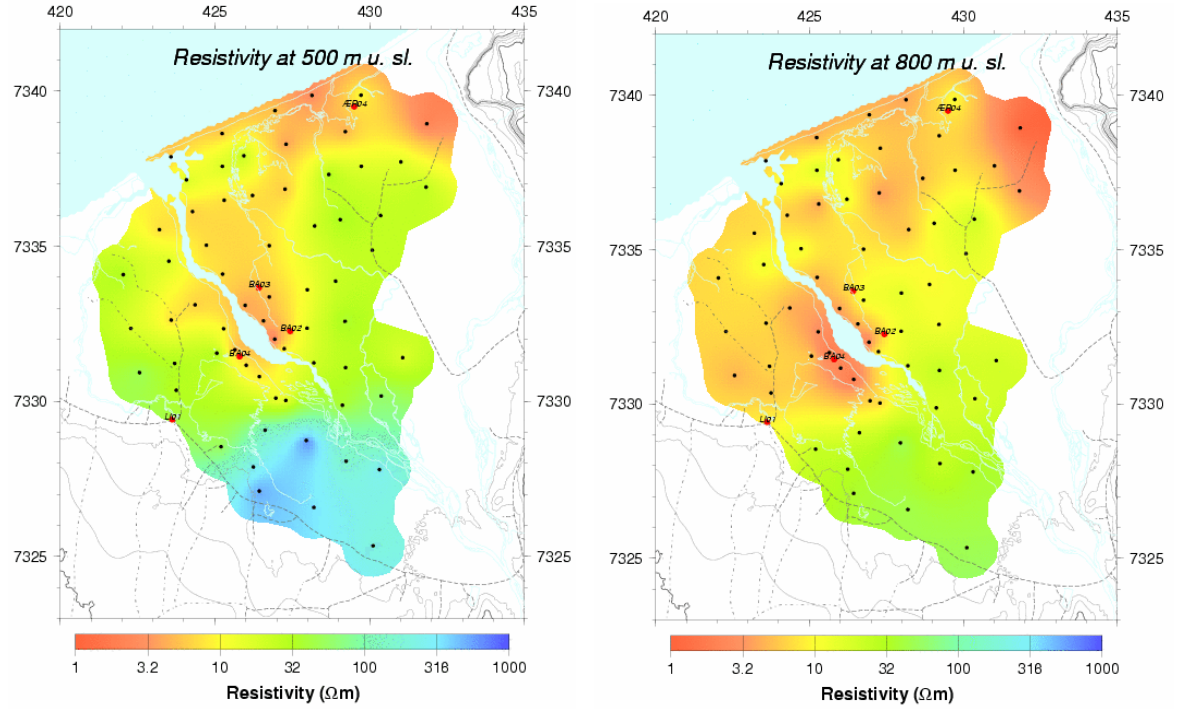

FIGURE 14: TEM resistivity maps of the Öxarfjördur area at 500 and 800 m b.s.l. (Karlsdóttir and Flóvenz, 2005)

This is well illustrated in the TEM cross-section in the lower part of Figure 13, which is along a similar profile line as that shown above it based on the Schlumberger soundings. It shows a narrow upflow zone at depth and a low-resistivity layer interpreted as a discharge of geothermal water along a sedimentary layer at 100-200 m depth to the west but at 200-300 m depth towards east. Both wells cut through this sedimentary layer and show cooling beneath it. Well BA-02 is closer to the upflow and has less saline water, than well BA-03. From the upflow towards the shore in the north, the sedimentary layer is seen as a low-resistivity layer both because of the warm geothermal water as well as the seawater blending with it closer to the coast.

The TEM survey reveals fracture dominated geothermal fields with outflow along shallow sedimentary layers (Figure 14). The most prominent upflow zones are at Bakkahlaup and Skógalón. Contrary to the older model, the upflow zone of the Bakkahlaup geothermal field appears to be quite limited with its centre below Bakkahlaup river, and no confirmed high-resistivity body can be seen at deeper levels. This is in agreement with the results of the drilling of the exploration wells, and well BA-04 drilled in 2004 at the west bank of Bakkahlaup, further confirms this. The geothermal fields in the Öxarfjördur area are not characterized by high-temperature activity but their temperature may reach as high as 200°C. The lowering of the resistivity towards the coast is mainly due to seawater salinity.

The main reason for the difference in the two surveys with regards to the high resistivity may be influenced by several factors, such as the sedimentary surroundings and varying salinity of the ground water, combined with ambiguities in the data caused by compromises in the layout of DC soundings (location and directions of current arms) necessary due to the large glacial river cutting through the area of interest. The interpretation of the DC survey was relevant at the time, but the comparison of the two methods reveals that the DC method gives detailed picture of the uppermost 100-300 m, whereas the TEM method gives better resolution at depths down to 1000 m.

7. CONCLUSIONS

TEM soundings have many advantages over DC soundings, such as:

- in no current transmission into the ground;
- in its low sensitivity to local inhomogeneities;
- in a strong signal being associated with low resistivity (geothermal activity);
- in easy computer interpretation, usually 1D is enough;
- in faster data acquisition and requiring less manpower and thus in cost effectiveness;
- in improved resolution of the resistivity distribution thus giving improved information on the geothermal system.

DC soundings do also have some advantages:

- in their simpler and more robust equipment;
- in the transparency of the data giving confidence in results;
- in showing near surface features better.

Both methods are suited for exploration of geothermal systems. DC measurements are more suitable in low-temperature fields in revealing near surface features such as water bearing fractures in the uppermost 300 m. In high-temperature fields, with very low resistivity at the surface, the DC method will not "see" through the surface layers. The TEM method has the downward resolution in these surroundings and can be applied down to about 1000 m. For deeper exploration MT measurements are advised.

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RESISTIVITY METHODS – MT

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ABSTRACT

Magnetotellurics (MT) is a passive electrical resistivity method that probes the subsurface resistivity structure from a depth of a few tens of meters down to a depth of several tens or even hundreds of km. It is the only method that is capable of revealing the resistivitity at such a great depth. It is a passive method, using the magnetic variations of the geomagnetic field as its source. Contrary to active resistivity methods like, the geoelectrical methods where an injected current into the earth is the source and the TEM method where the source is a current loop.

The basic knowledge of the MT method includes acquisition, processing and interpretation. There exits a variety of books and articles on the method which has developed greatly the last decades as the dynamical range in data recording has inceased and computer capacities as well. A book that covers the practical aspects of applying the magntotelluric technique should recommeded: Practical Magnetotellurics by Simpson and Bahr (2005). Making use of the internet is always a good idea. Take a look at the webside, MTnet which is an internet forum for the free exchange of programs, data and ideas, especially for scientist in non-commercial studies. The address for the web page is: www.mtnet.info.

1. INTRODUCTION

The magnetotelluric (MT) method is a passive surface measurement of the earth‘s natural electrical (**E**) field and magnetic (**H**) field in orthogonal directions. It can be shown that the relationship between the horizontal orthogonal magnetic and electric fields depend on the subsurface resistivity structure. It is therefore used to determine the conductivity of the earth, ranging from a few tens of meters to several hundreds of kilometers. The fundamental theory was first developed by Cagniard (1950) and Tikhonov (1950, reprinted 1986). MT generally refers to recording of 10 kHz to 1000 s (0.001 Hz) or as low as 10.000 s (0.0001 Hz). AMT (audio MT) refers to „audio„ frequencies, generally recording > 100 Hz to 10 kHz. LMT-Long period MT generally refers to recording from 1.000 s to 10.000 s or much higher (to 100.000). The depth of penetration of MT soundings depends on the frequency, the lower the frequency the greater the depth of penetration and vice versa.

The earth‘s electromagnetic field contains a wide spectrum (Figure 1). The low frequencies are generated by ionospheric and magnetospheric currents caused by solar wind (plasma) interfering with the earth‘s magnetic field. Higher frequencies (< 1 Hz) are due to thunderstorms near equator distributed as guided waves between the earth and the ionosphere. The time varying magnetic field

induces electric field and hence currents in the ground. By measuring variations in the magnetic and electric fields in the surface of the ground, information on the subsurface resistivity can be obtained.

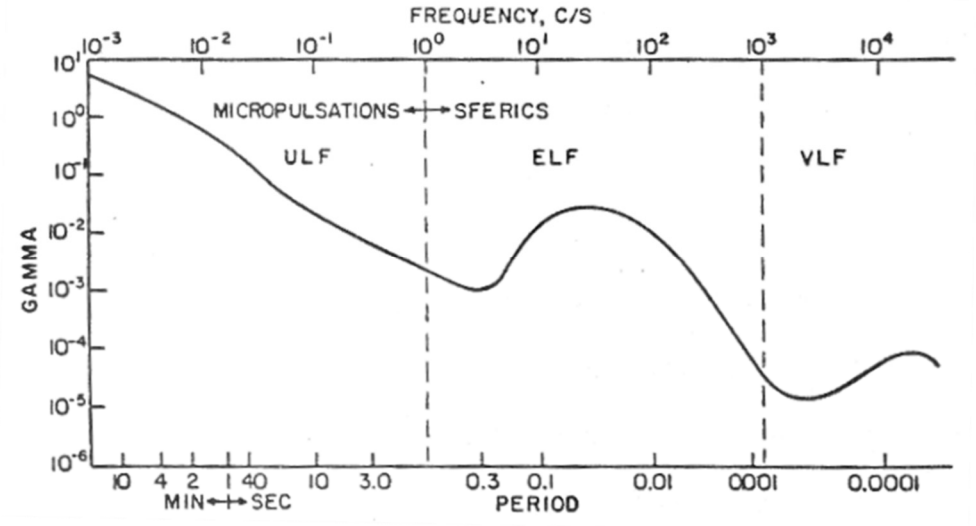

FIGURE 1: The natural magnetic field spectrum

The sunspot cycle has been measured since the mid 17th century. There is a regular cycle of little over 10 years. Presently there is a minimum of activity (see Figure 2), making MT soundings difficult in present years.

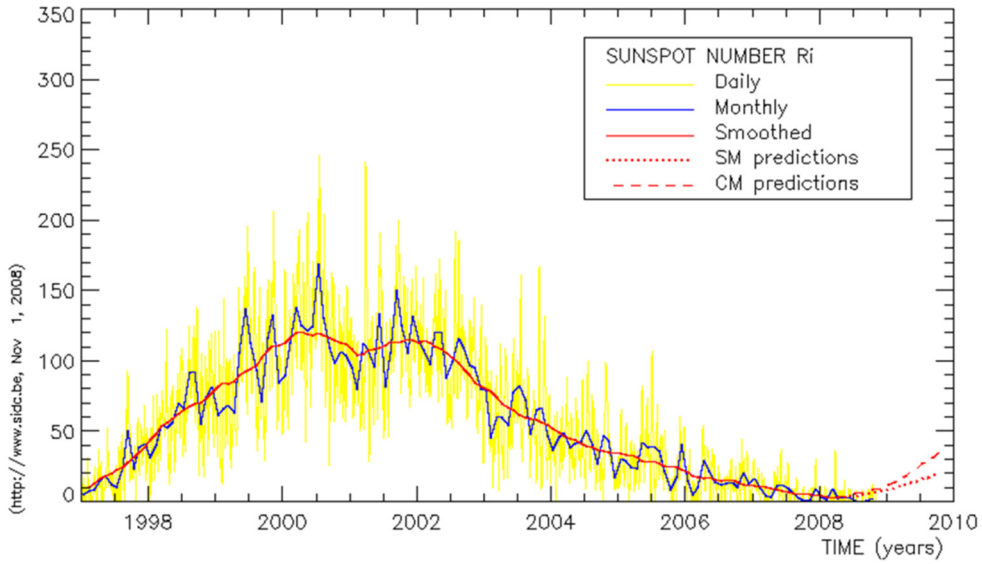

FIGURE 2: Current sunspot cycle

A typical setup for an MT sounding is shown in Figure 3. The horizontal orthogonal magnetic field, H_x (usually alligned in the magnetic north-south direction) and H_y (perpendicular to H_x) and the vertical magnetic field H_z are measured by magnetic coils. The horizontal orthogonal electric field, E_x and E_y are measured by a pair of electrodes (the potentional difference devided by the distance, 50-100 m). A GPS unit is used for syncronizing the data. The digital recording of the electromagnetic fields as a function of time is done through an aquisition unit and the time series saved on a memory card. The time series are Fourier transformed from the time domain to the frequency domain and processed. The tensors and the consequent apparent resistivity and phase are calculated as a funcion of the frequencies for later to be interpreted into a resistivity model of the subsurface (see Figure 5).

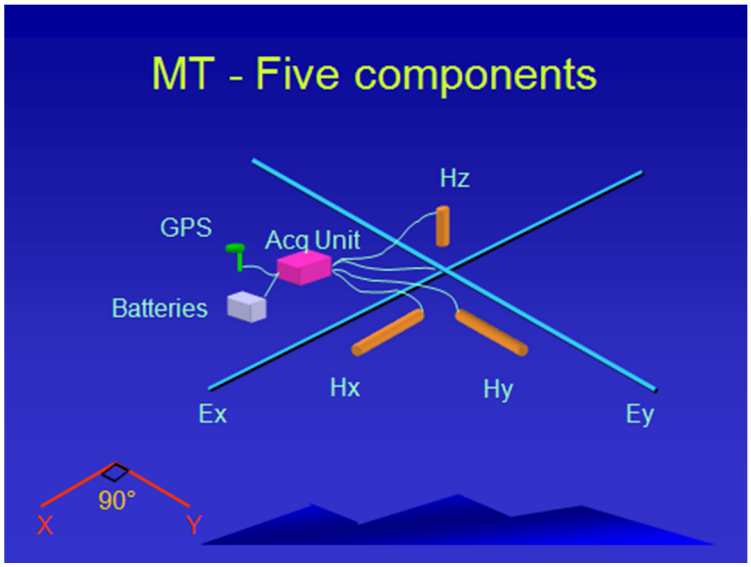

FIGURE 3: The setup of a magnetotelluric sounding

2. GENERAL THEORY OF ELECTROMAGNETISM

The four Maxwells's equations describe the electromagnetic field. They are Gauss's law for the magnetic field (div**B**=0) and Gauss's law for the electric field (div**D**=q), Faradays's law and Ampère's law with Maxwell's term:

$$\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t} \quad \text{Faraday's law}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \varepsilon \frac{\partial \mathbf{E}}{\partial t} \quad \text{Ampere's law}$$

E: Electrical field intensity (V/m)
H: Magnetic field intensity (A/m)
J: Electrical current density; **J=σE**
σ: conductivity (Simens/m); ρ=1/ σ (Ωm)
ε : electrical permittivity
μ: magnetic permeability

Assuming:

- Harmonic dependence of the oscillating electromagnetic fields; **H**,**E** ~ $e^{i\omega t}$;
  $\omega=2\pi\nu$ (angular frequency), $i=\sqrt{-1}$
  ν is frequency; $\nu=1/T$; T is period;
  gives : $\frac{\partial \mathbf{H}}{\partial t} = i\omega\mathbf{H}$; $\frac{\partial \mathbf{E}}{\partial t} = i\omega\mathbf{E}$
- Vertically incident plane wave
  i.e. $\frac{\partial}{\partial x} = \frac{\partial}{\partial y} = 0$

Using Faraday's law above, gives:

$$\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} = -\mu\frac{\partial H_x}{\partial t} \quad \Rightarrow -\frac{\partial E_y}{\partial z} = -\mu i\omega H_x$$

$$\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} = -\mu\frac{\partial H_y}{\partial t} \quad \Rightarrow \quad \frac{\partial E_x}{\partial z} = -\mu i\omega H_y$$

$$\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} = -\mu\frac{\partial H_z}{\partial t} = 0$$

Similarily applying Ampère's law above, gives:

$$\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} = \sigma E_x + \varepsilon\frac{\partial E_x}{\partial t} \quad \Rightarrow -\frac{\partial H_y}{\partial z} = (\sigma + i\omega\varepsilon)E_x$$

$$\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} = \sigma E_y + \varepsilon\frac{\partial E_y}{\partial t} \quad \Rightarrow \quad \frac{\partial H_x}{\partial z} = (\sigma + i\omega\varepsilon)E_y$$

$$\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} = \sigma E_z + \varepsilon\frac{\partial E_z}{\partial t} = 0$$

Combining Faraday's and Ampère's law gives:

$$k^2 = i\omega\mu(\sigma + i\omega\varepsilon)$$

$\sigma = 1/\rho$; and $\rho \approx 1-10^4$ Ωm, or $\sigma \approx 1-10^{-4}$ S/m

$\omega = 2\pi/T$ and $T \approx 10^{-4} - 10^4$ seconds

$\varepsilon = \varepsilon_0\chi_e$; $\varepsilon_0 = 8.85\cdot 10^{-12}$; and $\chi_e \approx 1-100$

$\Rightarrow \quad (\omega\varepsilon)_{max} = 2\pi\cdot 10^4 \cdot 8.85\cdot 10^{-12}\cdot 100 \approx 5\cdot 10^{-5}$

$\Rightarrow \quad \sigma >> \omega\varepsilon$

$\Rightarrow \quad k^2 \approx i\omega\mu\sigma$

For the quasi-stationary approximation:

$$\frac{\partial^2 E_y}{\partial^2 z} = i\omega\mu\frac{\partial H_x}{\partial z} = i\omega\mu(\sigma + i\omega\varepsilon)E_y$$

and:

$$\frac{\partial^2 E_x}{\partial^2 z} = -i\omega\mu\frac{\partial H_y}{\partial z} = i\omega\mu(\sigma + i\omega\varepsilon)E_x$$

Which can be written:

$$\frac{\partial^2 E_x}{\partial^2 z} = k^2 E_x \; ; \quad k^2 = i\omega\mu(\sigma + i\omega\varepsilon)$$

$$\frac{\partial^2 E_y}{\partial^2 z} = k^2 E_y$$

The general solutions for a homogeneous earth (σ constant) can be written as:

$$E_{x,y} = (A_{x,y}e^{ikz} + B_{x,y}e^{-ikz})e^{i\omega t}$$

$$H_x = \frac{1}{i\omega\mu}\frac{\partial E_y}{\partial z} = \frac{k}{i\omega\mu}(A_y e^{ikz} - B_y e^{-ikz})\, e^{i\omega t}$$

$$H_y = \frac{-1}{i\omega\mu}\frac{\partial E_x}{\partial z} = \frac{-k}{i\omega\mu}(A_x e^{ikz} - B_x e^{-ikz})\, e^{i\omega t}$$

$A_{x,y}$ and $B_{x,y}$ are constants to be determined

As $z\to\infty \Rightarrow H\to 0$ and $E\to 0 \Rightarrow A_{x,y}=0$; and we get:

$$E_x = B_x e^{-ikz}e^{i\omega t} \quad ; \quad E_y = B_y e^{-ikz}e^{i\omega t}$$

$$H_x = \frac{-k}{i\omega\mu}B_y e^{-ikz}e^{i\omega t} = \frac{-k}{i\omega\mu}E_y$$

$$H_y = \frac{k}{i\omega\mu}B_x e^{-ikz}e^{i\omega t} = \frac{-k}{i\omega\mu}E_x$$

The impedance tensor elements Z_{ij} are defined as:

$$Z_{xy} = \frac{E_x}{H_y} = \frac{i\omega\mu}{k} \approx \frac{i\omega\mu}{\sqrt{i\omega\sigma}} = \sqrt{\omega\mu\rho}\cdot e^{i\pi/4}$$

$$Z_{yx} = \frac{E_y}{H_x} = \frac{-i\omega\mu}{k} = -Z_{xy}$$

and we can calculate the resistivity of the half -space

$$\rho = \frac{1}{\omega\mu}|Z_{xy}|^2 = \frac{1}{\omega\mu}|Z_{yx}|^2$$

The resistivity may also we written as:

$$\rho = \frac{1}{\omega\mu}\left|\frac{E}{H}\right|^2 = \frac{T}{2\pi\mu}\left|\frac{E\cdot 10^{-6}\cdot\mu}{B\cdot 10^{-9}}\right|^2 = \frac{T\mu}{2\pi}\left|\frac{E'}{H'}\right|^2\cdot 10^6 = 0.2T\left|\frac{E'}{H'}\right|^2$$

For a none homogeneous earth the apparent resistivity (ρ_a) and phase (Θ_a) are defined as.

$$\rho_a = \frac{1}{\omega\mu}|Z_0|^2 \quad ; \quad \theta_a = \arg(Z_0) \neq 45°$$

Z_0 is impedence at surface

The general definision of the impedance tensor is:

$$\vec{E} = \begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix}\begin{bmatrix} H_x \\ H_y \end{bmatrix} = \overline{Z}\vec{H}$$

For 1D earth, $Z_{xx} = Z_{yy} = 0$ and $Z_{xy} = -Z_{yx}$.
For 2D earth is possible to rotate the tensor in the strike direction and $Z_{xx} = Z_{yy} = 0$.
For 3D earth it is not possible to rotate the tensor and get $Z_{xx} = Z_{yy} = 0$.

Figure 4 shows the apparent resistivity and phase as a function of the period for an MT station. The two resistivities ρ_{xy} and ρ_{yx} are not equal. The resistivity structure is therefore not 1D. The strike direction (Zstrike) is around 20°, giving an indication of a 2D structure, since Zstrike is more or less the same value for all frequencies and the skew is low. The coherency is close to one, which means that there is a good correlation between the electric and magnetic fields.

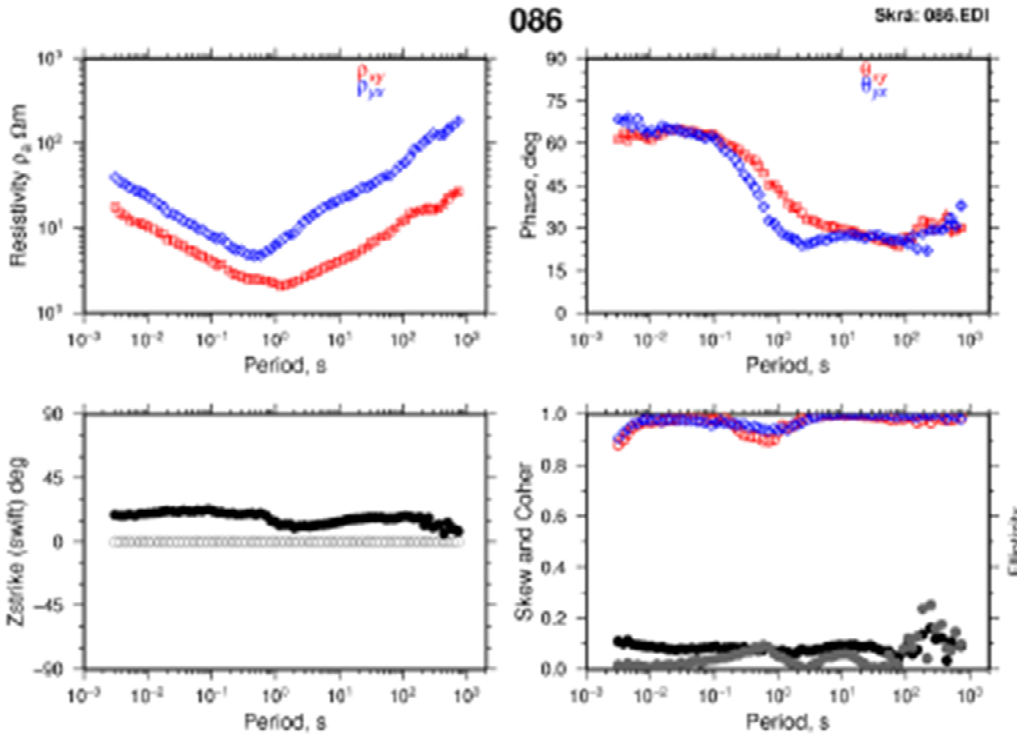

FIGURE 4: Apparent resistivity and phase, Zstrike, Skew and coherency for an MT sounding (taken from Hersir et al., 2009)

Figure 5 shows the joint inversion of the MT sounding and a TEM sounding measured at the same location.

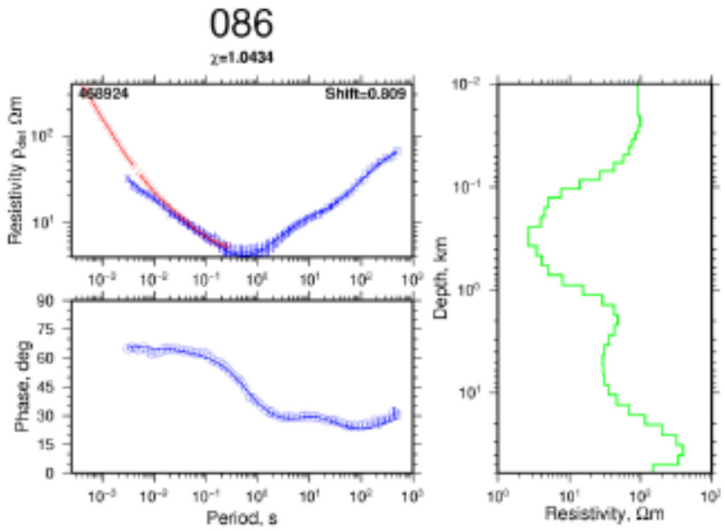

FIGURE 5: Joint inversion of TEM MT data. Red dots denote TEM data and the blue ones MT data. The resistivity model is shown in green to the left (taken from Hersir et al., 2009)

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MAGNETO-TELLURIC (MT) DATA PROCESSING

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ABSTRACT

One of the most successful ways to improve the quality of MT transfer functions estimations is to follow the principles of robust statistics. Adaptation of robust statistics to the MT data processing problem has been discussed by Egbert and Booker (1986), Chave et al. (1987) and Chave and Thomson (2003). This paper is intended to guide on the Magneto-telluric data processing. It introduces softwares applied in data processing. It details procedures used in the MT data processing with emphasis on actual steps that are followed to realise good results.

1. INTRODUCTION

The MT method is a passive-surface electromagnetic geophysical technique that measures variations in the Earth's natural electromagnetic fields to investigate the electrical resistivity structure of the subsurface from depths of tens of meters to tens of kilometers (Vozoff, 1991). Worldwide lightning activity at frequencies of 10,000 to 1 Hertz (Hz) and geomagnetic micro-pulsations at frequencies of 1 to 0.001 Hz provide the majority of natural signal used by the MT method. A small amount of electromagnetic energy reflects and propagates vertically into the earth due to the resistivity contrast at the air-earth interface (Vozoff, 1972).

The natural fields are recorded in the xyz direction for the magnetic field and the xy direction for the electric field at the Earth's surface. The resulting time-series signals are used to derive tensor apparent-resistivities and phases by first converting them to complex cross-spectra using Fourier-transform techniques. Least squares, cross-spectral analysis (Bendat and Piersol, 1971) is used to solve for a tensor transfer function. Prior to conversion to apparent resistivity and phase, the tensor is normally rotated into principal directions that usually correspond to the direction of maximum and minimum apparent resistivity. Checks for coherency, smoothness and correspondence between magnetic and electric channels is critically evaluated so as to ensure good resistivity results.

An introduction to the MT method and references for a more advanced understanding are contained in Dobrin and Savit (1988) and Vozoff (1991).

2. DATA PROCESSING OVERVIEW

The following steps are followed:

1. Transfer the files from the MTU-A's Flash card to your PC hard drive.
2. Verify and edit the parameters saved in the Site Parameters Table (.TBL) file of each site.
3. Archive the raw data and Site Parameters on CD-R, DVD, or other storage medium.
4. Create Fourier coefficients from the raw data.
5. Reprocess the Fourier coefficients using a robust reprocessing program and possibly data from the reference site.
6. Edit the resulting crosspowers one frequency at a time to verify the viability of the sounding and to reduce or eliminate low quality data.
7. Translate the edited crosspowers into industry standard EDI format for use by interpretation software.

SSMT2000 program is used to complete steps 1 through 5 and the MT EDITOR for steps 6 and 7.

3. SOFTWARES USED

3.1 Synchro time series view

This program takes as input raw time series files and displays them in graphical format. It can also compute power spectra densities and coherency between channels and display these characteristics in graphical format as seen in the Figures 1, 2 and 3 below.

The site Parameter (TBL) file is a record of all the parameters associated with a site's time series files. Depending on the firmware of the MTU/MTU-A and the set-up method used, some parameter values may not have been recorded automatically. Therefore actual measurements taken during field setup must be added manually before processing can proceed. Normally, the crew will have written the values on the Layout Sheet for the site.

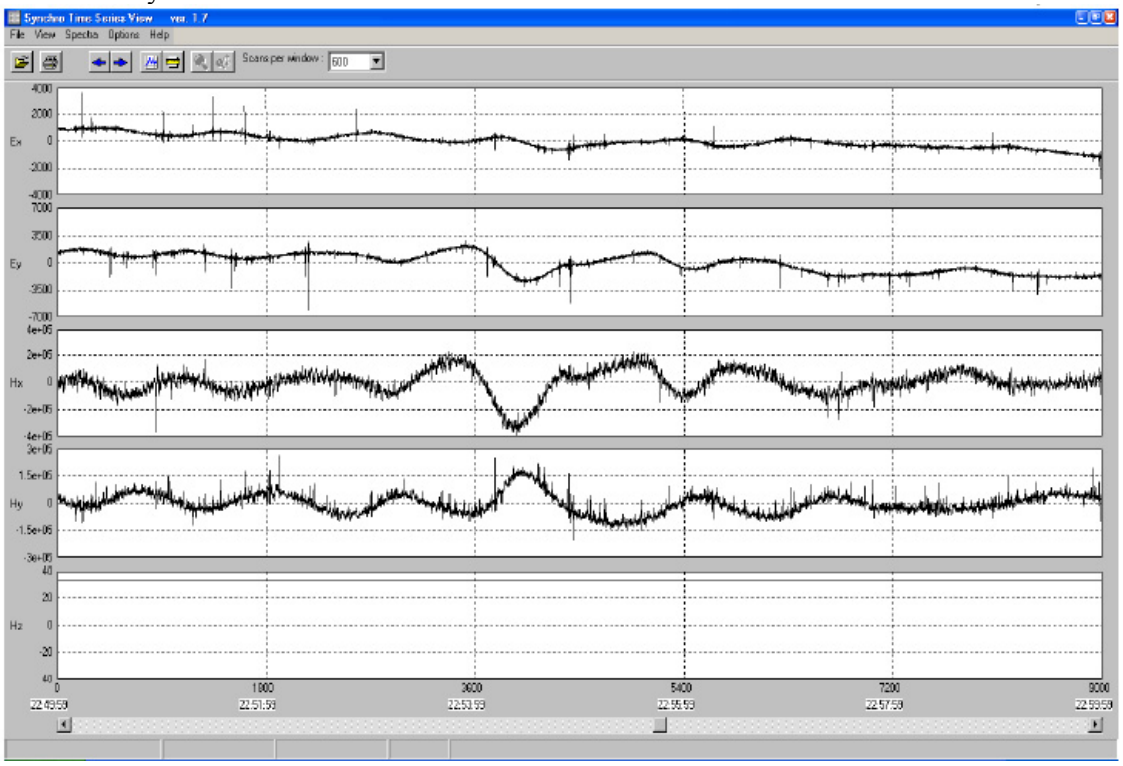

FIGURE 1: Typical time series plot

3.1.1 Power spectra density

Power spectra density plots displays time series as a function of frequency. These plots inform the geophysicist how the MT layout was done in the field. In case the telluric lines were not exactly N-S

and E-W then the curves in the upper plot will be far apart. Similarly if the magnetic coils were not aligned exactly in their respective direction or they are not properly leveled then the lower curves will out of phase by a big margin.

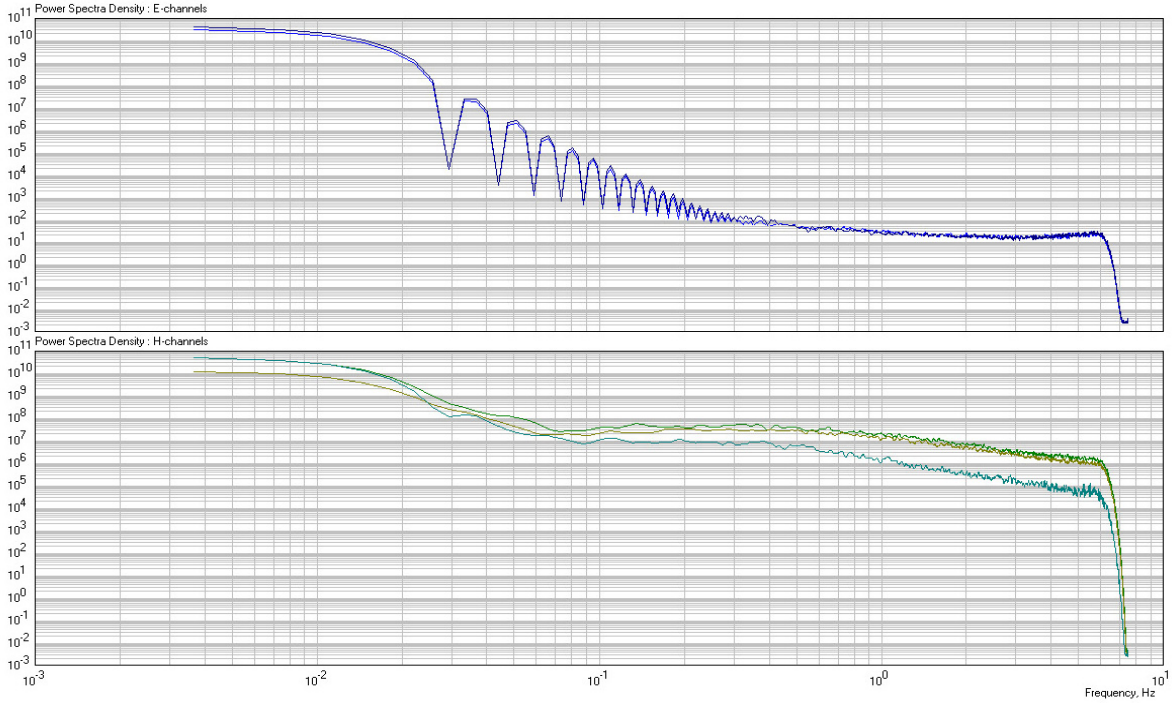

FIGURE 2: Power spectra density plot

3.1.2 Coherency test

Coherence is a factor that relates the magnetic field to its orthorgonal electric field. If the data is coherent then Hx and Ey should be similar so is the Hy and Ex. Ideally the coherence should be 1 but that does not happen, therefore the closer it is to 1 the more coherent the data is.

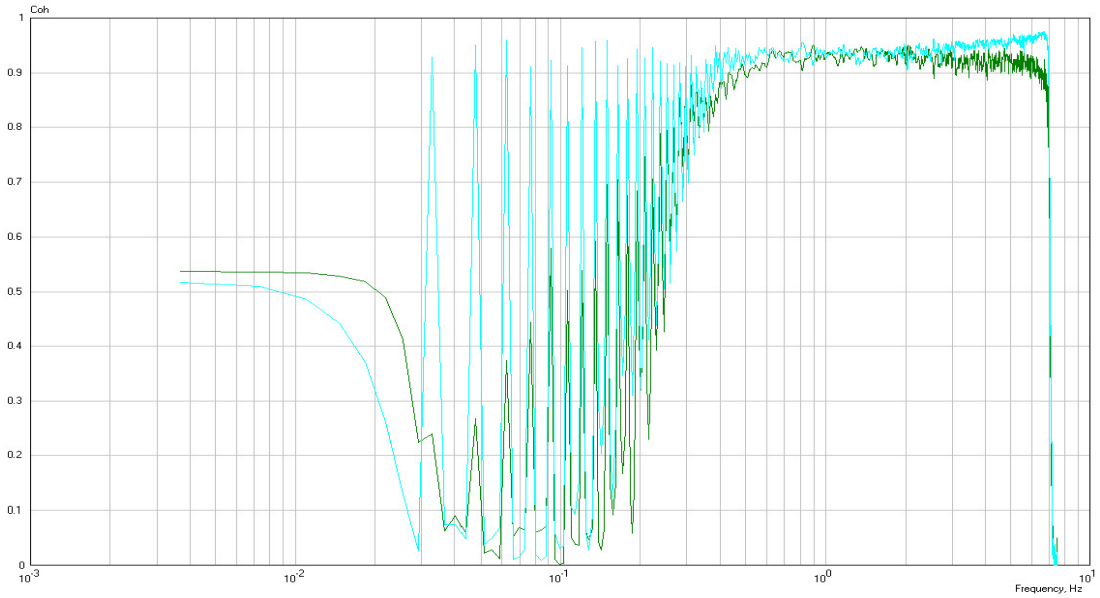

FIGURE 3: Coherence plot, blue shows Hx vs Ey and green shows Hy vs Ex

3.2 SSMT2000

This program takes as input raw time series files, calibration files, and site parameter files to produce Fourier coefficients, which are then reprocessed with data from reference sites, using robust routines. The output is MT Plot files containing multiple crosspowers for each of the frequencies analysed. The processing starts with editing site parameters to reflect the measured readings from the field as shown in Figure 5. The data is then fourier transformed by TStoFT to generate fourier coefficients.

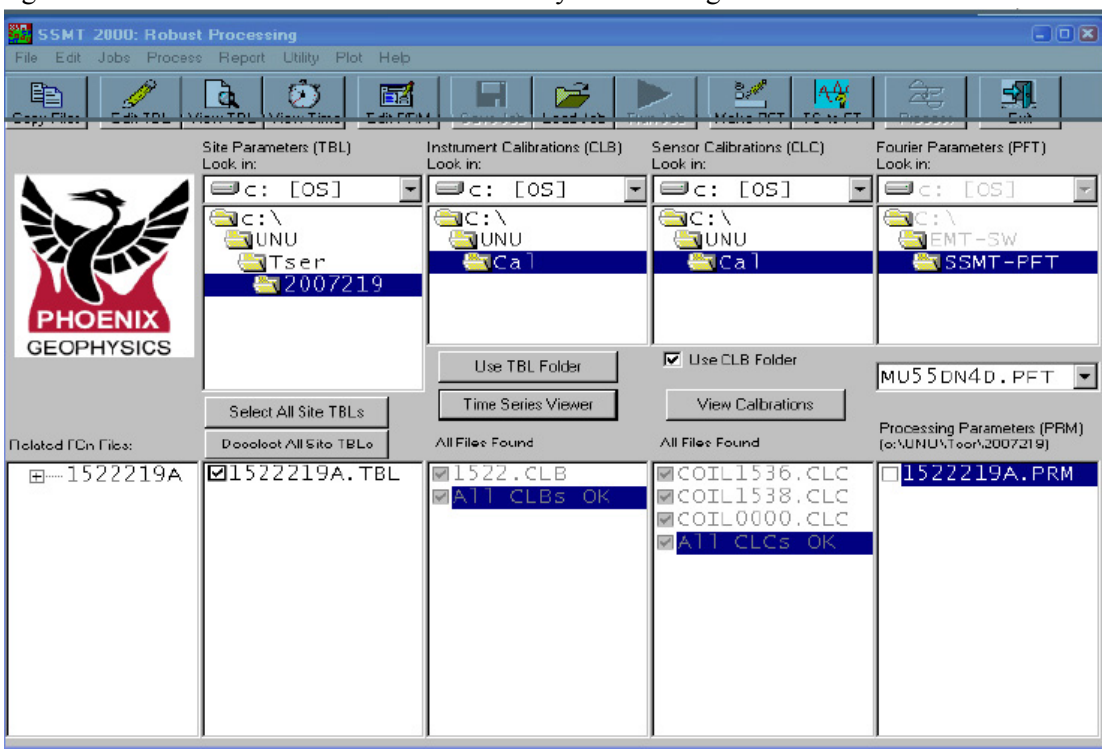

FIGURE 4: SSMT 2000 processing package

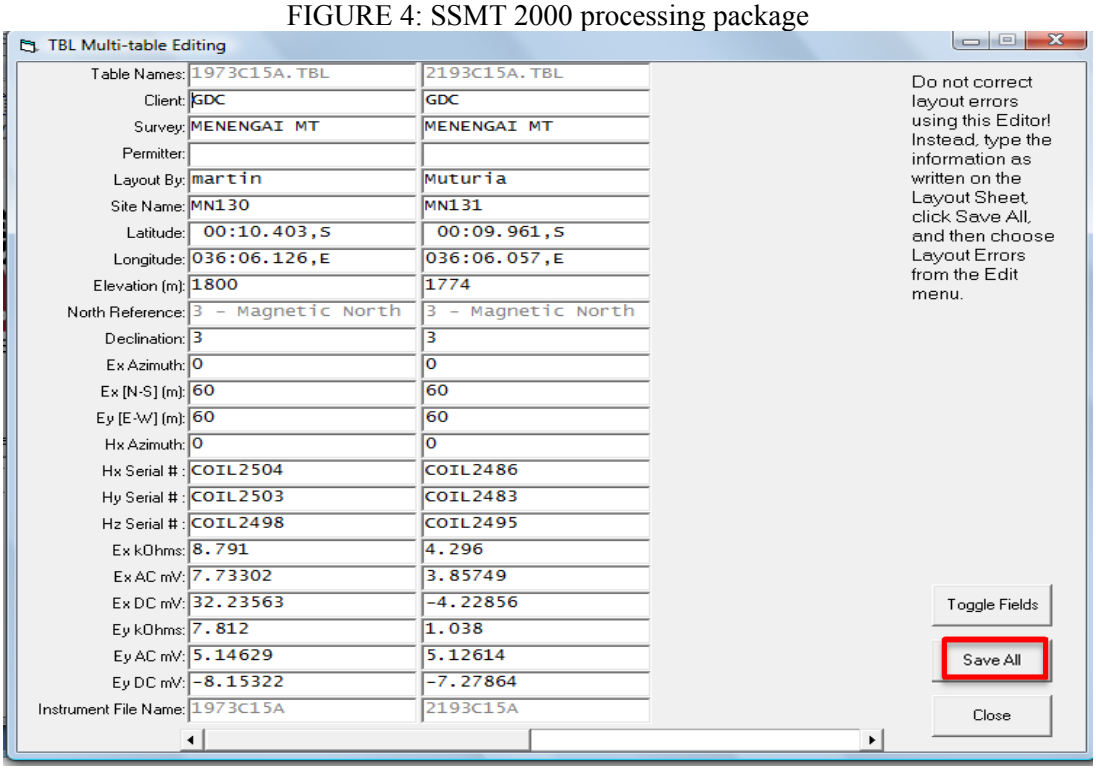

FIGURE 5: Field parameter file

3.2.1 Verifying acquisition times

Typically, data is combined from one or two survey sites with data from a remote reference site in the robust processing stage, in order to reduce the effects of noise. However, only data acquired over the same time span can be combined. SSMT2000 makes it easy to review the time spans over which data were acquired.

To review data acquisition time spans, click on View Time icon from the main menu and the data acquisition period is displayed as seen below.

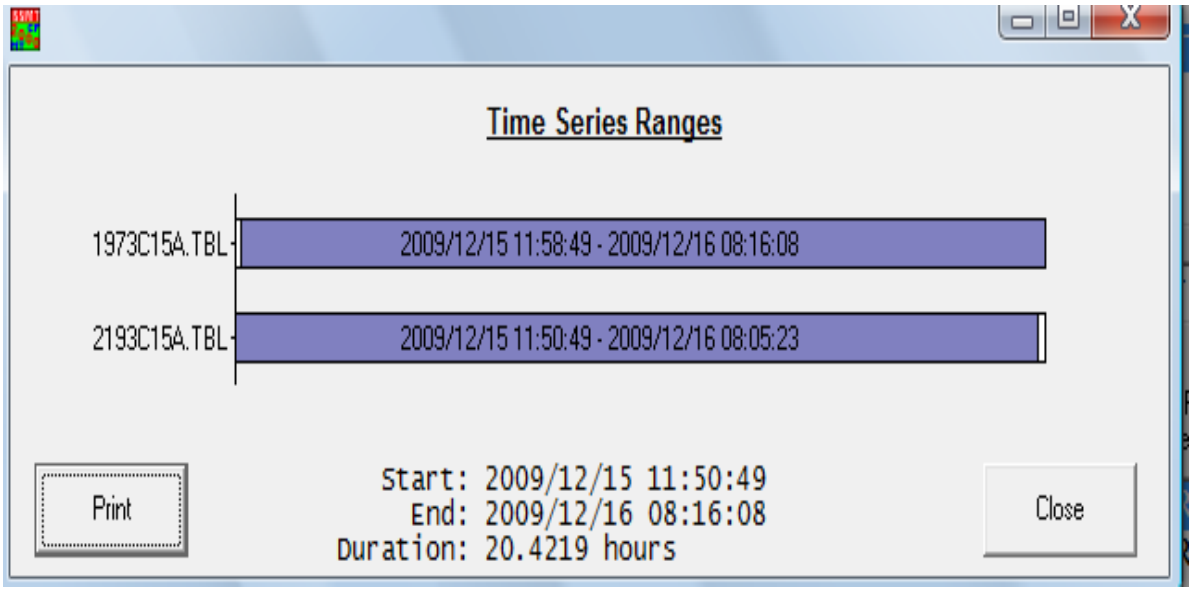

FIGURE 6: Acquisition time display

3.2.2 Robust processing parameters

Two schemes of initial processing that attempt to filter out noise-affected data are controlled by the robust processing parameters: Coherency and Rho variance. This process reduces the size of the error bars and smooth the curves in plots of apparent resistivity. “Coherency” refers to eight processing schemes that compare survey site data with reference site data, and process only data that are coherent. Cultural noise that is present at the survey site but not at the reference site is therefore reduced.

Before running robust processing it is first necessary to set up the parameters for this stage of processing. Robust Parameter (PRM) files are unique to each site and cannot be copied to other folders and used to process other data. This parameter file is available from the SSMT program by clicking on Edit PRM. At this stage you have a choice of whether to process data using local or remote magnetic reference.

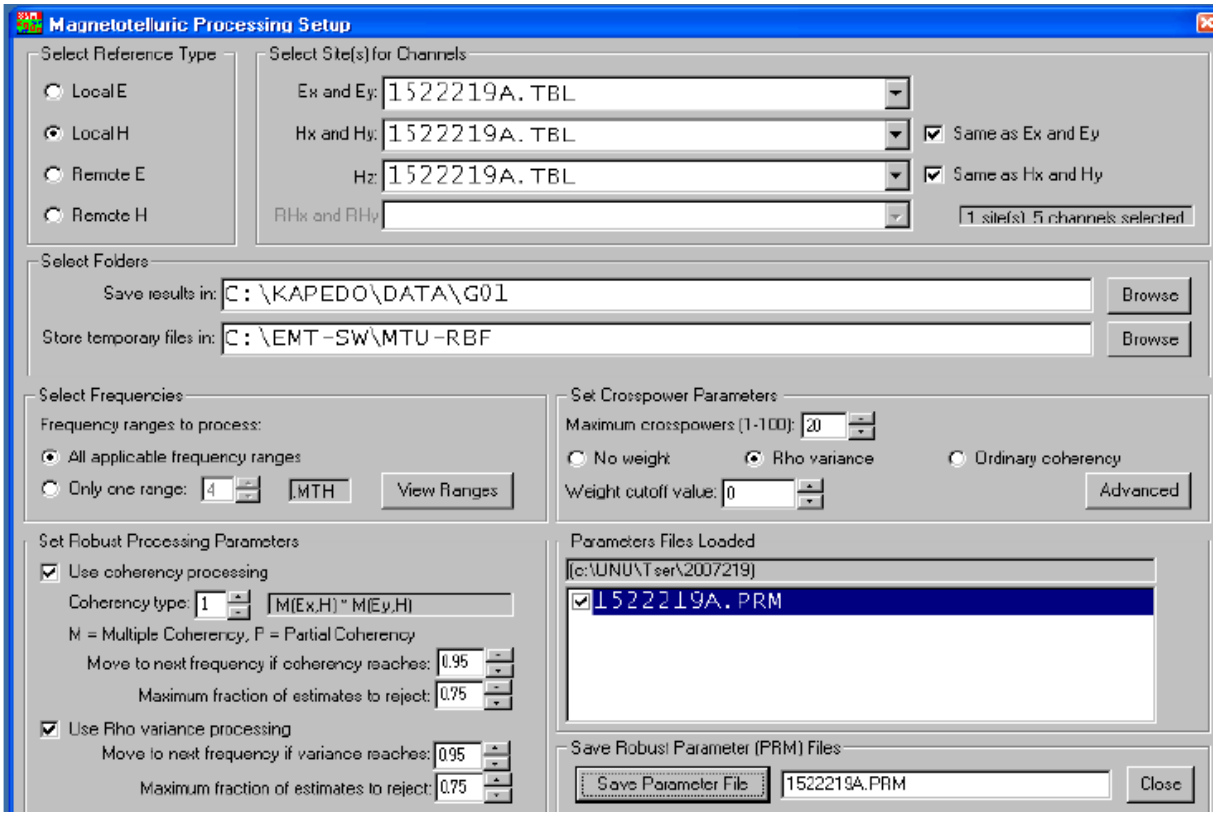

FIGURE 7: Robust processing parameter file

3.3 MT-Editor

This program takes as input the MT Plot files created by SSMT2000 and displays the resistivity and phase curves as well as the individual crosspowers that are used to calculate each point on the curves. Crosspowers that were affected by noise can automatically or manually be excluded from the calculations. The program also allows you to display a variety of parameters of the plot files such as tipper magnitude, coherency between channels, and strike direction. The output is industry-standard EDI files suitable for use with geophysical interpretation software such as WinGLink or LINUX based TEMTD. The primary objective of editing is to create a smooth apparent resistivity curve, by eliminating from the calculation of each data point any crosspowers that were affected by noise. The editing is done by deleting or restoring individual crosspowers in the two graphs on the right of the window. The effect can be seen in the two graphs on the left of the window. There are two methods of editing, auto and manual, though it's best to start with autoediting and then refine the result with manual editing.

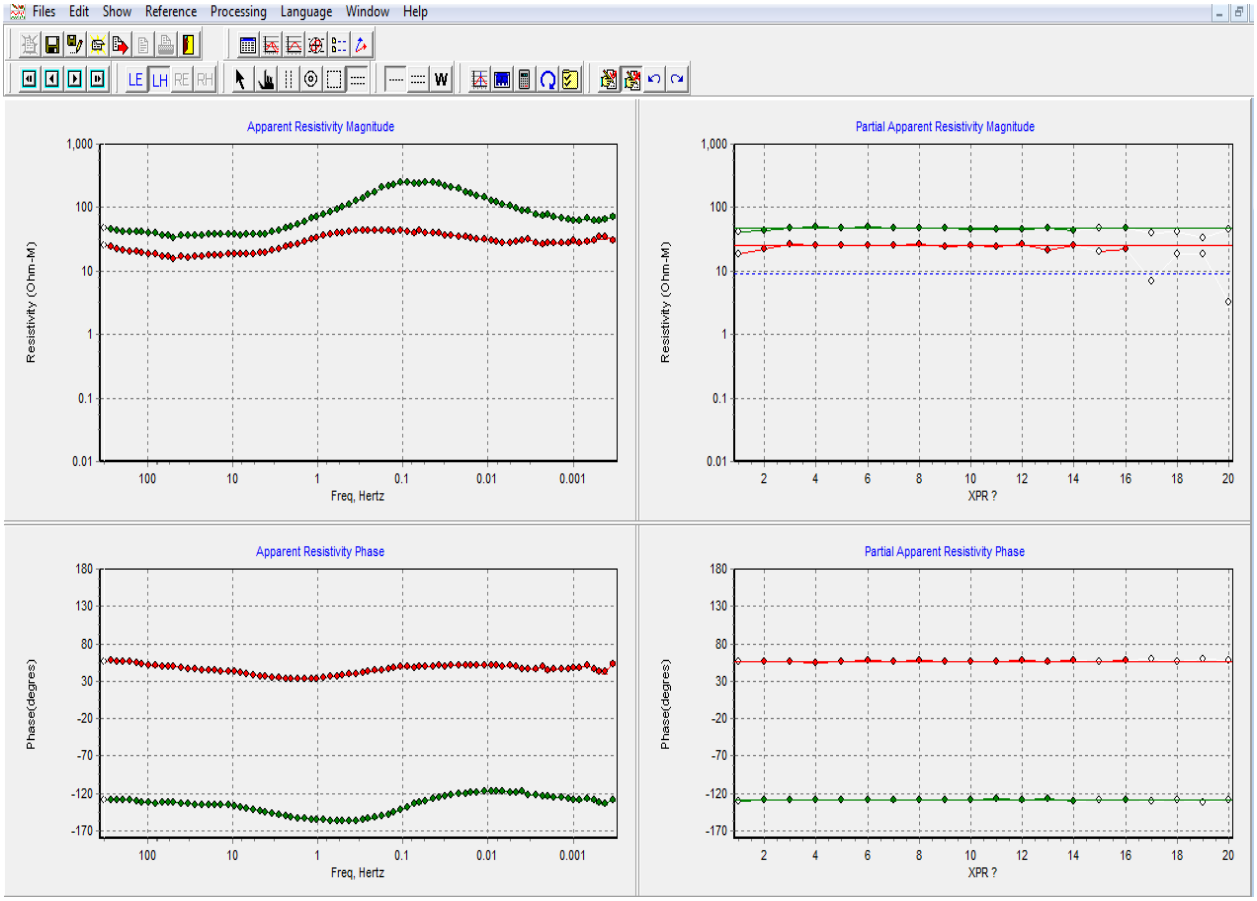

FIGURE 8: MT-editor frame

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organized by UNU-GTP, GDC and KenGen, at Lake Bogoria and Lake Naivasha, Kenya, Oct. 31 – Nov. 22, 2013.

STRENGTHS AND WEAKNESSES OF GRAVITY AND MAGNETICS AS EXPLORATION TOOLS FOR GEOTHERMAL ENERGY

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ABSTRACT

There are many different geophysical techniques available to the earth scientist, each with its own strengths and weaknesses. Some aspects of geophysical surveys still prohibit wide application of these techniques. Some problems encountered are shallow depth penetration ability of the instruments, interpretation of data can be difficult and results ambiguous, and instrumentation can be expensive. The techniques can be divided into the two broad categories: passive and active methods. Passive methods detect anomalies or changes in the Earth without introducing any energy. These include magnetometry, gravity and magnetotellurics. Active methods introduce some sort of energy into the ground and then detect subsurface responses. Active techniques include resistivity and electromagnetics.

This paper describes procedures for planning and executing specialized geophysical work in geothermal-resources investigations. It covers the potential field's methods of gravity and magnetics. The general physical principles underlying each method and its capabilities and limitations are described. Possibilities for non-uniqueness of interpretation of geophysical results are also noted. Examples of actual use of the methods are given to illustrate applications and interpretations in selected case examples of geothermal areas in Kenya. The objective of the paper is to provide the potential or young geophysicist with a sufficient understanding of the capabilities, limitations, and relative cost of gravity and magnetic geophysical methods to make sound decisions as to when use of these methods is desirable.

1. INTRODUCTION

Geophysical techniques are often useful for discovering unknown subsurface conditions. Most of these techniques are classified as non-invasive, requiring only minimal disturbance of surface cover. Projects involving successful application of exploration, monitoring or geophysics in geothermal industry include:

Micro-seismic event mapping for an irregular concealed erosional contact such as a fault. Results are used to reduce the number of drilled holes needed to design for a geothermal power plant or other direct uses. Magnetic survey supplements gravity studies to locate heat sources. Electromagnetic

conductivity and DC resistivity profiles maps can be used to infer the presence of a heat source and geothermal reservoir. Results are usually confirmed by drilling.

Gravity, seismic refraction & reflection, and electrical resistivity delineate bedrock valleys concealed by sediments or volcanic materials. The integrated interpretation of geophysical and hydrogeological information suggests that geothermal wells drilled into the centre of such anomalies are more likely to encounter substantial steam or hot water than wells drilled at random or wells drilled based on an incomplete knowledge of the anomaly location.

Techniques for geophysical detection and mapping of permeable fractures have been developed, tested and applied. In addition to the surface techniques briefly outlined here, some subsurface conditions can be resolved by geophysical measurements involving boreholes. Geophysical techniques do not eliminate the need to drill and sample. However, geophysical prospecting can reduce the overall costs and improve the overall quality of a site investigation by:

(1) Targeting anomalous areas where sampling is most likely to encounter extreme values;
(2) Providing physical evidence needed to justify interpolation of subsurface conditions between sample locations;
(3) Providing physical evidence that areas not directly sampled are unlikely to conceal unexpected conditions.

Proper application of geophysical measurements can significantly reduce the number of wells needed to characterize a prospect while improving the confidence of interpretations based on direct borehole measurements. Geophysical techniques become increasingly cost-effective as the area and depth to be investigated increase. One limitation, however; certain routine geophysical methods sometimes cannot be used due to cultural noise (electrical power lines or transformers, heavy vehicular traffic, buried pipes, pavement) or natural conditions. The experienced geophysicist knows how to recognize and minimize any influence due to such noise. Site visits (see Figure 1) preferably by a combined team of earth scientists and engineers are often required prior to finalizing plans for a geophysical prospecting project.

FIGURE 1: A team of earth scientists making site visits to a potential geothermal prospect

2. SELECTION OF GEOPHYSICAL METHODOLOGIES FOR GEOTHERMAL ENERGY PROSPECTING

Geophysical prospecting of high temperature geothermal reservoirs aims at identifying either fluid trapping structures or anomalies related to the properties of the hydrothermal fluid and rock to fluid

interactions. Two types of reservoir environments can be characterized: (i) sedimentary reservoirs, where a carbonate reservoir is generally capped by a dominantly argillaceous, hydraulically impervious and thermally insulating cover, and (ii) volcanic and volcano-sedimentary reservoirs associated with hydrothermally altered areas.

Based on the aforementioned exploration goals and reservoir settings, a wide spectrum of geophysical methods can be applied whose selection is largely commanded by local geological conditions and expected reservoir morphology. For example, detection of a geothermal heat source is best carried out by using a combination of gravity and magnetic measurements, while reservoir characteristics are best imaged by use of electric or electromagnetic techniques.

Geophysical investigations can be a timesaving and cost-effective method for providing both qualitative and qualitative subsurface information for a site. They can be used for screening large areas for potential geothermal reservoirs, for focusing resources for intrusive investigation activities on the anomalous areas, and for identifying or confirming the presence and extent of heat sources. Buried hot rocks will (most likely) exhibit different bulk material properties than the surrounding native country rock. This will typically allow geophysical instruments to distinguish geothermal reservoir from relatively cooler surrounding areas.

The interpretation of geophysical contacts is based on geologic assumptions: (1) earthen materials have distinct subsurface boundaries, (2) a material is homogeneous (material properties are the same throughout) and (3) the unit is isotropic (material properties are the same in all directions). Since these conditions rarely occur in nature, and almost never occur in volcanic environments, geophysical methods are most often used in conjunction with other intrusive methods in order to more correctly assess the site. Non-intrusive geophysical methods can be utilized as preliminary screening before performing intrusive investigations, they may be implemented as the primary investigative technique, they may be used in combination with intrusive investigation methods such as bore holes or test pits, or they can be used in combination with other non-intrusive geophysical methods. Understanding the specific strengths and weaknesses of each method will allow the investigator to decide how to best utilize geophysical investigation.

The results obtained from a geophysical investigation are subjective and rely on geologic interpretation. Geophysical techniques do not directly measure the parameter needed to solve the problem but instead measure contrasts in material properties. For example, seismic methods measure velocities of seismic waves through the subsurface material recorded by the receivers, called geophones, and correlated to the material properties of the subsurface. Careful analysis can tell us whether it is a direct surface wave, one reflected from a subsurface geologic interface, or a wave refracted along the top of a geologic interface. Although geophysical interpretations are not always perfectly accurate, geophysical equipment is very precise. That is to say that the measurements obtained from non-intrusive geophysical techniques are very exact. The raw data is good data. The problem resides in the geophysical interpretation of the data, which are often educated estimations and/or calculated correlations and can lead to inaccuracies. However, when the appropriate geophysical technique is coupled with an intrusive investigation, large volumes of material can be explored accurately and cost-effectively. In the discussions that follow each of the major geophysical methods will be briefly described with emphasis on the applications and limitations in geothermal energy investigations.

2.1 Overview of the magnetic method

Several minerals containing iron and nickel display the property of ferromagnetism. Rocks or soils containing these minerals can have strong magnetization and as a result can produce significant local magnetic fields. The magnetization can be either remanent (a permanent magnetization created by the earth's magnetic field during some process in the history of formation of the mineral) or induced magnetization created by the presence of the earth's magnetic field. In most rocks both are present.

The goal of the magnetic method is to map changes in the magnetization which are in turn related to the distribution of magnetic minerals.

Instruments used to measure the magnetic field are called magnetometers. An important distinction between the magnetic and gravity methods is that magnetization depends on the inducing field so that the resulting field from an object depends, in a rather complex way, on how the induced field interacts with the inducing field to alter it and hence to change the magnetization. These are the so called demagnetization effects. For gravity the effect of a body is simply the Newtonian gravitational attraction of the point masses which make it up - the force of attraction has no effect on the density. Fortunately, for most practical situations the magnetization of rocks is weak and a simple approximation does allow magnetic anomalies to be calculated in a manner equivalent to the linear summation used in gravity.

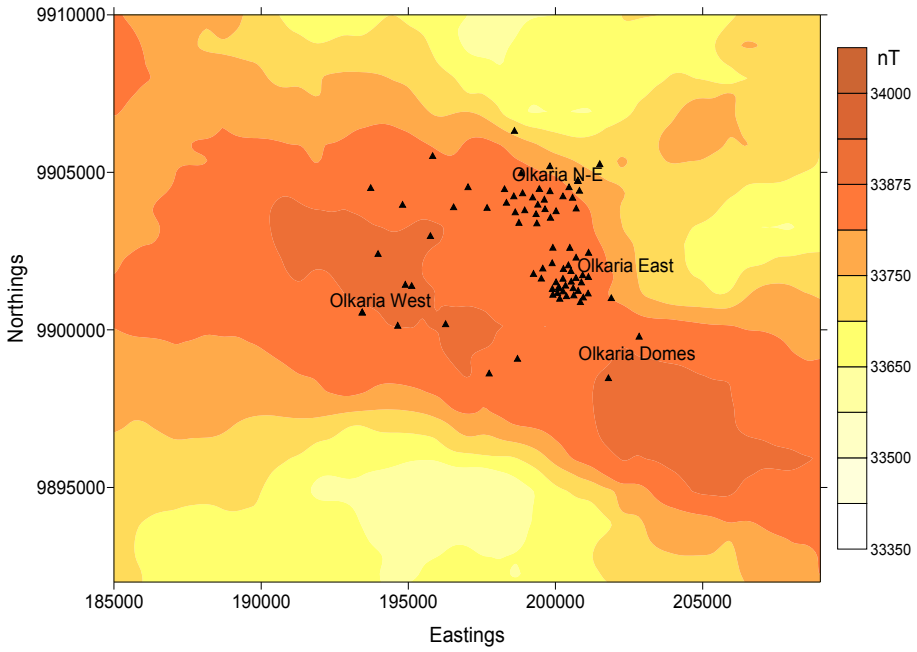

FIGURE 2: Magnetic anomaly over Olkaria geothermal field, Kenya. It is obvious that the anomaly trends in a NW-SE direction

The aim of a magnetic survey is to investigate subsurface geology on the basis of the anomalies in the earth's magnetic field resulting from the magnetic properties of the underlying rocks. In general, the magnetic content (susceptibility) of rocks is extremely variable depending on the type of rock and the environment it is in. Common causes of magnetic anomalies include dykes, faults and lava flows. In a geothermal environment, due to high temperatures, the susceptibility decreases. Used with gravity, this method can be used to infer heat. Positive anomalies are generally interpreted to occur in demagnetized zones corresponding to heat sources with a temperature above the curie point of magnetite (575^{o}C). Ground magnetic measurements do provide more detailed information on sub-surface structures that could act as heat sources in comparison to aeromagnetic data. Figure 2 is an example of aerial magnetic measurements of Olkaria geothermal field, Kenya.

2.2 Overview of the gravity method

Gravity meters measure the *difference* in gravity between a base station (where the absolute value of gravity is known) and a series of field stations. Most base stations are established by measuring the difference in gravity between the new base and an already established base station. Many base stations trace their origin back (through a line of base stations) to Potsdam, Germany, where physicists attempt to measure "g" to a precision of one part in a million.

Many workers prefer the LaCoste and Romberg meter over others that have been used. Once the gravity at a new field site is known, theoretical gravity is calculated. Theoretical gravity depends on latitude, elevation, and on the surrounding topography. Many of the commonly applied equations can be found good geophysics textbooks or by taking a class in gravity field methods. The difference

between the observed and theoretical gravity is called the Bouguer anomaly. If the Bouguer anomaly is negative, it means the observed gravity is less than the theoretical.

Because the force of gravity is proportional to the mass responsible for the gravitational field and inversely proportional to the square of the distance between any part of that mass and the observation point, a local lack of normal mass (say, a thick layer of low-density sediments instead of heavy igneous rocks of negligible porosity) will result in a local gravity low. A mass of unusually dense rock (gabbro intruding sedimentary rock or acidic volcanics) will generate a gravity high.

Volcanic centres, where geothermal activity is found, are indicators of cooling magma or hot rock beneath these areas as shown by volcanic flows, ashes, volcanic domes and abundant hydrothermal activities in the form of fumaroles and hot springs. Gravity studies in volcanic areas have effectively demonstrated that this method provides good evidence of shallow subsurface density variations, associated with the structural and magmatic history of a volcano. There is a correlation between gravity highs with centres of volcanism, intensive faulting and geothermal activity. During interpretation, to reduce ambiguity, use is made of seismic data to constrain the models generated. Figure 2 is an example of a gravity anomaly over Olkaria geothermal field in Kenya.

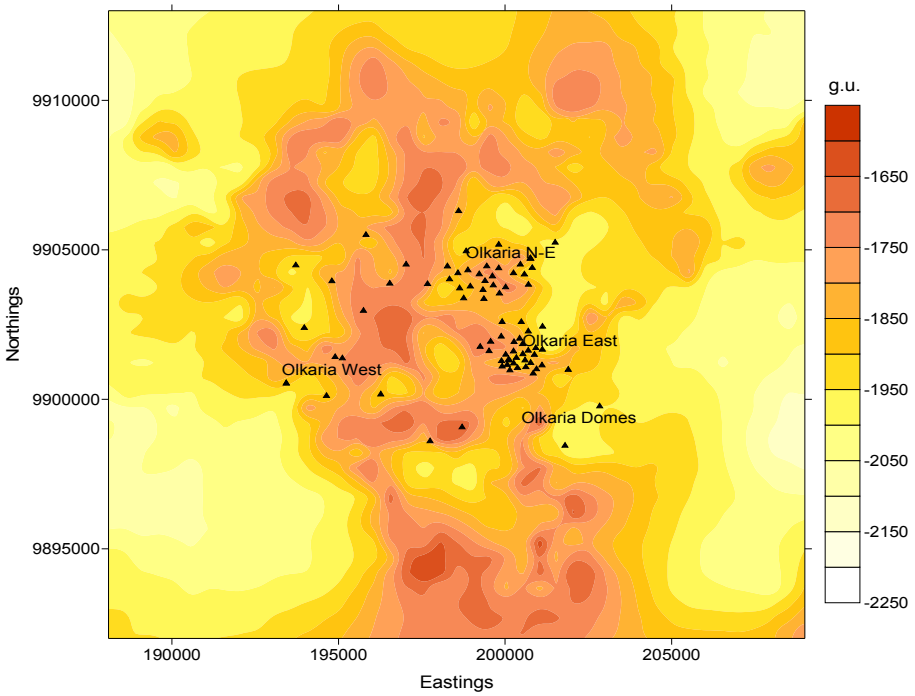

FIGURE 3: Gravity anomaly over Olkaria geothermal field in Kenya

By now it is obvious that many geophysical methodologies are available to the geophysicist. But which ones are applicable to geothermal energy prospecting? Table 1 is a summary of the advantages and disadvantages of the common methods that have been used in exploration for geothermal energy.

TABLE 1: Strengths and Weaknesses of common geophysical methods used in exploration for geothermal energy

Method	Strength	Weakness
Seismic Refraction		
Conventional reversed profiles:	Classical engineering method. Reveals general layering in the subsurface. Relatively short processing time in lab compared to other seismic methods. Excellent complement to DC resistivity and GPR surveys for depth to the water-table or depth to bedrock.	If structure is not dipping planar, then more refined methods should be (have been) used, such as the delay time method (below). Somewhat more time intensive in field than above conventional refraction method, and considerably more time intensive in lab.

Delay time or time term method:	In principle, since each geophone or shot position can lead to an estimate of the local depth to the refractor beneath the respective "station", this procedure can result in a highly detailed configuration of the refracting surface, e.g. bedrock.	General to both refraction methods: While a layer may be detected at depth, its seismic velocity may not be an unambiguous discriminator between bedrock and the groundwater table. Low velocity layers, sandwiched between higher velocities, are masked and total depths are biased. Complementary data may be required.
Seismic Reflection	Often, good resolution of layering from depths of 20 m to more than several hundred meters. For decades, the favoured tool of the oil industry for deep exploration, but has fewer proponents or service providers for shallow (<100 m) investigations.	Labour intensive both in the field and by skilled interpreters in the lab. Cost is usually justified when information from depths of 100 m or so is needed. Extracting precise interval velocities from multilayered media is sometimes difficult.
Gravity	The method "weighs" the earth directly beneath a field site. Because of the density difference between unconsolidated sediments and surrounding bedrock in a sediment-filled valley, for example, the technique is very effective for gross characterization of depth to bedrock beneath 10's to 100's of meters of sediments. Effective in culturally developed areas where buried water mains and utility lines, overhead wires, pavement, etc., may "mask" other geophysical signatures.	Relatively time intensive for a trained interpreter in the field and lab. Needs to be "calibrated" at one or more control points using complementary well data or other geophysics (e.g. seismic refraction/reflection).
DC Resistivity (four electrode "sounding" or "profiling" methods: Wenner, Schlumberger, Dipole-dipole.)	Direct indicator of electrical conductivity, which, in turn, is an indirect indicator of soil moisture or percent saturation. Good for determining depth to the water table. Good indicator of bedrock at depth. Very effective complement to seismic refraction or GPR data.	Vertical resolution in the best of cases is somewhat coarse. Method needs special care when lateral features are encountered, adding greatly to acquisition cost and interpretation. Requires a lateral clearance for a horizontal array that may be 10 times the depth of resolution.
Electromagnetic *"Active" Sources*: Frequency domain (FDEM) Time domain (TDEM)	Very effective for the rapid reconnaissance of an area for mapping depth to bedrock, depth to water-table, detecting clay lenses. Also effective for mapping infrastructure hazardous to drilling or excavation. Several light-weight FDEM and TDEM units are available for use by single operators for rapid reconnaissance. Active source (horizontal loop) methods can be specially deployed to map features at several 100 m's depth. TDEM appears to have good potential for vertically probing in areas of restricted horizontal access. Whereas TDEM has been used by the mineral industry for deep exploration for many years, it has few service providers for shallow (<100 m) investigations.	Topography can be a problem in interpreting FDEM data. TDEM is not widely used for shallow studies (less than 20 m) in resistive terrains, except for shallow (1 or 2 m) metallic infrastructure investigations. In some cases, source effects can be significant.
Electromagnetic "*Distant" or "Passive" Sources*: VLF (Very Low Frequency) Method(s) Controlled Source Audio Frequency Magnetotellurics Magnetotellurics Tellurics Magnetic variations	Particular methods are effective for mapping depth to bedrock, depth to water-table, detecting clay lenses, and for delineating fracture patterns in bedrock, sometimes to may 10's of meters.. Generally, these methods are very cost effective for large scale reconnaissance studies, or in areas of rugged terrain. Also effective for mapping infrastructure hazardous to drilling or excavation. Various methods can be used in "profiling" or in "sounding" modes, and in some cases lead to	Conventional VLF sometimes has difficulty receiving multiple stations. In some cases, interpretations of local structure are distorted by 2D and 3D effects beyond the immediate survey area. While VLF instruments are relatively inexpensive, the technique is not highly developed. Other instrumentation is relatively expensive, and requires some expertise in interpretation.

	direct estimates of the subsurface resistivity. Distant source methods - whether the signal source is controlled, uncontrolled, or natural - have the advantage that the roving field instrumentation is light-weight and portable, and that the interpretation of field data is, in ideal cases, relatively free of source effects.	
Magnetics	Often useful to delineate geologic features related to hydrogeology, e.g. bedrock lineations, intrusives, geologic contacts, heat sources etc. Very effective for identifying infrastructure hazardous to drilling or excavation. One of the most cost-effective techniques for screening an area for steel USTs, buried drums, water mains, etc.	Local traffic and other magnetic disturbances often require gradient (two sensor) techniques. Lower cost proton precession units tend to be more unstable than more expensive alkali-vapour units in the presence of high magnetic field gradients typical of many industrial sites. Depth resolution is poor except for small, shallow targets.

3. OVERVIEW OF DESIGN OF GEOPHYSICAL SURVEYS

Geophysical surveys can be useful in the study of most subsurface geologic problems. Geophysics also can contribute to many investigations that are concerned primarily with surface geology. However, geophysical surveys are not always the most effective method of obtaining the information needed. For example, in some areas auger or drill holes may be a more effective way of obtaining near-surface information than geophysical surveys. In some investigations a combination of drilling and geophysical measurements may provide the optimum cost-benefit ratio. Geophysical surveys are not practical in all ground-water investigations, but this determination usually can be made only by someone with an understanding of the capabilities, limitations, and costs of geophysical surveys.

A clear definition of the geologic or hydro-logic problem and objectives of an investigation is important in determining whether exploration geophysics should be used and also in designing the geophysical survey. The lack of a clear definition of the problem can result in ineffective use of geophysical methods. The proper design of a geophysical survey is important not only in insuring that the needed data will be obtained but also in controlling costs, as the expense of making a geophysical survey is determined primarily by the detail and accuracy required. In this, the geophysicist plays a great role:

- The geophysicist in normally the one who designs the geophysical survey (written and oral presentation) including which instruments to use and why, what are the survey characteristics (providing guidelines for survey time constraints)
- The geophysicist discusses and debate the merits of the various proposed geophysical techniques and survey characteristics
- The geophysicist and technicians carry out the field geophysical survey as teams
- The geophysicist and technicians use computers to process, display, model and interpret the geophysical data they collect
- The geophysicist must create models of expected anomalies for each of the different instruments proposed
- Results are then presented of the investigations both orally and in a written form (e.g., technical report, scientific paper, scientific poster, etc. depending on project requirements).

4. COLLECTION AND REDUCTION OF GEOPHYSICAL DATA

Some simple geophysical surveys can be made by individuals with little previous experience and with an investment in equipment of only a few hundred dollars. Other surveys require highly skilled personnel working with complex and expensive equipment. Good equipment and technical expertise are essential to a high quality survey. Attempts to use obsolete or “cookbook” interpretation methods

in geophysical surveys often increase the total cost of the survey and result in an inferior product. Some geophysical data can be used directly in geologic interpretations. Other geophysical data require considerable processing before the data can be interpreted, and the cost of data reduction is a major part of the total cost of the survey. Many data processing operations in use today require the use of electronic computers.

Interpretation of geophysical data can be completely objective or highly subjective. It can range from a simple inspection of a map or profile to a highly sophisticated operation involving skilled personnel and elaborate supporting equipment. Some interpretations require little understanding of the geology, but the quality of most interpretations is improved if the interpreter has a good understanding of the geology involved. Although some individuals are both skilled geophysicists and geologists, a cooperative effort between geologists and geophysicists is usually the most effective approach to the interpretation of geophysical data.

5. CONCLUSIONS

Given the site conditions and targets of investigation, the choice of a geophysical surveying method for geothermal energy should bear several factors in mind. First, the technique must be suited to detecting the necessary targets at the site imaged as anomalous features. Second, the technique must be appropriate for the conditions of the area, especially the subsurface geology and ground surface. If a particular method is conducted, it would best be used to complement it with another method of geophysical survey, e.g. gravity and magnetometry. Experience from geothermal exploration suggests that both self potential and seismic surveys are probably not the best methods to utilize as first choices. These methods are often difficult to carry out and not generally regarded as the best methods. These methods should only be used when there are special circumstances or targets that these methods are specifically suited for. Besides, seismics are very expensive because field logistics are difficult to implement.

Strong support for the use of a certain method comes from surveys conducted elsewhere for geothermal energy exploration. Resistivity, gravity and magnetic methodologies have been widely applied. Data is often complex and may not be interpretable. It could mean the data is possibly erroneous, but could also be accurate data requiring more sophisticated processing and interpretation. When this distinction is made, other reasons ruled out and no anomaly is seen then it can be concluded that the survey was not successful.

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APPLICATIONS OF POTENTIAL FIELD METHODS FOR GEOTHERMAL EXPLORATION – A CASE FOR OLKARIA AND MENENGAI GEOTHERMAL FIELDS, KENYA

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ABSTRACT

Many different geophysical techniques are available to the earth scientist, each with its own strengths and weaknesses. Some problems encountered are shallow depth penetration ability of the instruments, interpretation of data can be difficult and results ambiguous, and instrumentation can be expensive. The techniques can be divided into the two broad categories: passive and active methods. Passive methods detect anomalies or changes in the Earth without introducing any energy. These include magnetometry, gravity and magnetotellurics. Active methods introduce some sort of energy into the ground and then detect subsurface responses. Active techniques include resistivity and electromagnetics.

Magnetometry and gravity are often referred to as the Structural Methods. In this paper we discuss procedures for executing magnetic and gravity methods in geothermal-resources investigations. The general physical principles underlying each method and their capabilities and limitations are described. Possibilities for non-uniqueness of interpretation of results are also presented. Examples of actual use of the methods are given to illustrate applications and interpretations in selected case examples of the geothermal fields of Olkaria and Menengai in Kenya. The objective of the paper is to provide the reader with a sufficient understanding of the capabilities, limitations, and relative cost of magnetic and gravity methods to make sound decisions as to when use of these methods is desirable.

1. INTRODUCTION

Geophysical techniques are often useful for discovering unknown subsurface conditions. Most of these techniques are classified as non-invasive, requiring only minimal disturbance of surface cover. Projects involving successful application of exploration, monitoring or geophysics in geothermal industry include:

Micro-seismic event mapping for an irregular concealed erosional contact such as a fault. Results are used to reduce the number of drilled holes needed to design for a geothermal power plant or other direct uses. Magnetic survey supplements gravity studies to locate heat sources. Electromagnetic conductivity and DC resistivity profiles maps can be used to infer the presence of a heat source and geothermal reservoir. The integrated interpretation of geophysical and hydrogeological information suggests that

geothermal wells drilled into the centre of such anomalies are more likely to encounter substantial steam or hot water than wells drilled at random or wells drilled based on an incomplete knowledge of the anomaly location.

In geothermal energy exploration the potential fields of Gravity and Magnetics have been used to delineate bedrock valleys concealed by sediments or volcanic materials and mapping of permeable fractures during the early stages of investigations. These measurements can significantly reduce the number of wells needed to characterize a prospect while improving the confidence of interpretations. Gravity and Magnetics techniques are cost. One limitation, however, is that they sometimes cannot be used due to cultural noise (electrical power lines or transformers, heavy vehicular traffic, buried pipes, pavement) or natural conditions. The experienced geophysicist knows how to recognize and minimize any influence due to such noise. Site visits (Figure 1) preferably by a combined team of earth scientists and engineers are often required prior to finalizing plans for a gravity or /and magnetics prospecting project.

FIGURE 1**:** A team of earth scientists making site visits to a potential geothermal prospect

This paper is a brief review of the gravity and ground magnetics methodologies used as part of surface geophysical exploration and their application in geothermal energy investigations with particular reference to Olkaria and Menengai geothermal fields in Kenya. It explains the capabilities of these methods and, in a general way, the processing and interpreting the data. No mathematics is employed, and the scope is limited to an elementary discussion of theory, a description of the methods, and examples of their applications. It is in no way intended to be an exhaustive discourse on applications of these potential fields. Rather its aim is to provide the general geothermist with a rudimentary under-standing of how surface measurements may be of help.

2. SELECTION OF GEOPHYSICAL METHODOLOGIES FOR GEOTHERMAL ENERGY PROSPECTING

Geophysical prospecting of high temperature geothermal reservoirs aims at identifying either fluid trapping structures or anomalies related to the properties of the hydrothermal fluid and rock to fluid interactions. Two types of reservoir environments can be characterized: (i) sedimentary reservoirs when a carbonate reservoir is generally capped by a dominantly argillaceous, hydraulically impervious and thermally insulating cover, and (ii) volcanic and volcano-sedimentary reservoirs associated with hydrothermally altered areas.

Based on the aforementioned exploration goals and reservoir settings, a wide spectrum of geophysical methods can be applied whose selection is largely commanded by local geological conditions and expected reservoir morphology. For example, detection of a geothermal heat source is best carried out by using a combination of gravity and magnetic measurements, while reservoir characteristics are best imaged by use of electric or electromagnetic techniques.

Buried hot rocks will (most likely) exhibit different bulk material properties (such as density and magnetisation) than the surrounding native country rock. This will typically allow gravity meters and magnetometers to distinguish geothermal reservoir from relatively cooler surrounding areas.

The interpretation of geophysical contacts is based on geologic assumptions: (1) earthen materials have distinct subsurface boundaries, (2) a material is homogeneous (material properties are the same throughout) and (3) the unit is isotropic (material properties are the same in all directions). Since these conditions rarely occur in nature, and almost never occur in volcanic environments, geophysical methods are most often used in conjunction with other intrusive methods (where signal are 'injected into the ground) in order to more correctly assess the site. Non-intrusive geophysical methods (such as gravity and magnetics) can be utilized as preliminary screening before performing intrusive investigations; they may be implemented as the primary investigative technique. Understanding the specific strengths and weaknesses of each method will allow the investigator to decide how to best utilize geophysical investigations.

The results obtained from a gravity or magnetic investigation are subjective and rely on geologic interpretation. These techniques do not directly measure the parameter needed to solve the problem but instead measure contrasts in material properties. Although geophysical interpretations are not always perfectly accurate, the geophysical equipment is very precise. That is to say that the measurements obtained from non-intrusive geophysical techniques are very exact. The raw data is good data. The problem resides in the geophysical interpretation of the data, which are often educated estimations and/or calculated correlations and can lead to inaccuracies. However, when the appropriate geophysical technique is applied, large volumes of material can be explored accurately and cost-effectively.

Several minerals containing iron and nickel display the property of ferromagnetism. Rocks or soils containing these minerals can have strong magnetization and as a result can produce significant local magnetic fields. The magnetization can be either remanent (a permanent magnetization created. The aim of a magnetic survey is to investigate subsurface geology on the basis of the anomalies in the earth's magnetic field resulting from the magnetic properties of the underlying rocks. In general, the magnetic content (susceptibility) of rocks is extremely variable depending on the type of rock and the environment it is in. Common causes of magnetic anomalies include dykes, faults and lava flows. In a geothermal environment, due to high temperatures, the susceptibility decreases. Used with gravity, this method can be used to infer heat. Positive anomalies are generally interpreted to occur in demagnetized zones corresponding to heat sources with a temperature above the Curie Point of magnetite (575°C). Ground magnetic measurements do provide more detailed information on sub-surface structures that could act as heat sources in comparison to aeromagnetic data. In the discussions that follow we briefly describe Magnetic and Gravity methods with emphasis on the use and limitations in geothermal energy investigations as experienced at Olkaria and Menengai Geothermal Fields.

2.1 Application of the magnetic method over Olkaria

An aeromagnetic survey was flown in 1987 for the National Oil Corporation of Kenya (NOCK). Maps prepared from these data have been used to corroborate the gravity interpretation for a qualitative assessment of the shapes and trends of the anomalies, in conjunction with the geologic map of Kenya. Results from the larger rift indicate that the axis of the rift is marked by a series of high amplitude magnetic anomalies whose wavelengths are less than 2.5 km, with the positive anomalies coinciding closely with known Quaternary volcanoes. The residual aeromagnetic data shows that the Greater Olkaria Geothermal Area has a positive anomaly that has a NW-SE trend. The positive magnetic anomaly separates two negative anomalies to the south and the north. The negative anomalies correspond to normally magnetized rocks. The positive anomaly occurs in a demagnetized zone corresponding to the heat source that is silicic origin. This provides some evidence for heat source at a temperature above the Curie point of Magnetite (above 575°C) close to the surface. The occurrence of magnetic and gravity anomalies at the intersections of NE and NW rift faults, is an indication of distinct

near surface heat sources controlling the reservoir characteristics of the geothermal systems at Olkaria. Figure 2 is an example of aerial magnetic measurements over Olkaria geothermal field, Kenya.

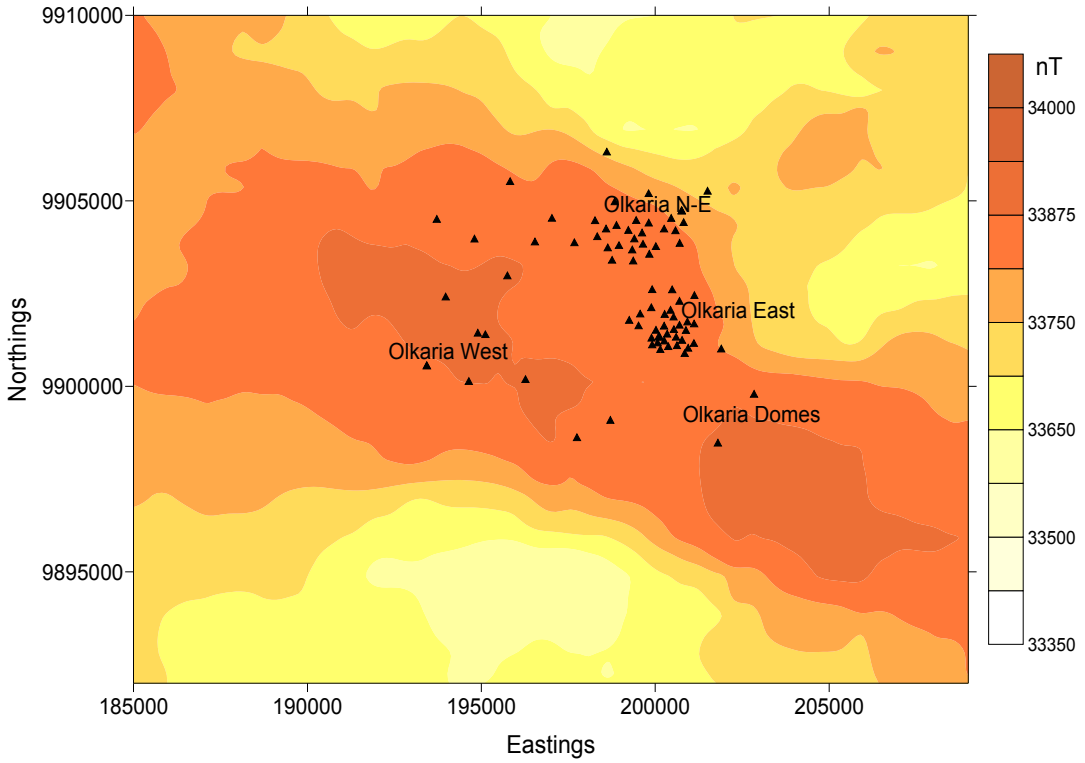

FIGURE 2: Total magnetic intensity over the Greater Olkaria area over Olkaria geothermal field, Kenya. It is obvious that the anomaly trends in a NW-SE direction

Studies of residual magnetic anomalies indicate that different anomaly patterns are associated with subsurface outflows and reservoirs hosted in both normally and reversely magnetised rocks. Several of these anomalies can be clearly correlated with surface expressions of volcanism such as craters, domes or cones, localised basaltic lavas or plugs. Most of the volcanic centres tend to lie in areas with magnetic highs (positives). Sometimes a superimposed magnetic low (negative) exist; but this is generally weak or zero. The central geothermal area has a positive magnetic anomaly trending NW-SE. This anomaly is superimposed on a broad regional negative anomaly that covers the entire southern Lake Naivasha region (Bhogal and Skinner 1971). Finally, a rather subdued and almost featureless pattern occurs over a few areas where rocks lying outside the reservoir have lost their magnetisation by interaction with acidic, steam-heated water.

2.2 Application of the magnetic method over Menengai

Both the aeromagnetic survey flown in 1987 data for the National Oil Corporation of Kenya (NOCK) and results from ground magnetic investigations, that have be carried out by various workers and organisations (Geotermica, 1987; Gislason, 1989), including the Geothermal Development Company (GDC), have been used to study the geothermal potential of Menengai. The work of Kemei et al (2011) suggest that the northern part of Menengai geothermal field is demagnetized indicating a zone of possible high temperature and higher degree of hydrothermal alteration and intruded with high density bodies in the upper crust. This zone is large and extends beyond the area investigated towards the north. Used in conjunction with gravity data the magnetic signatures over Menengai area suggest the presence of a heat source and a geothermal reservoir hosted within the fractured/faulted brittle trachytic lavas of the rift floor to the north and northeast of Menengai caldera.

The aero-magnetic contour map (Figure 3) indicates a circular positive anomaly coincident with the Olrongai area. Positive magnetic anomalies are normally interpreted as being caused by changes in the

magnetisation of rocks. This anomaly is probably caused by demagnetisation due to heating of the rocks above the Curie Point of the magnetite in the rock which is about 575 degrees Celsius at depths of between 3 to 4 km. If this interpretation is correct, then the area with the highest porosity is the Olrongai-Menengai extending to the Solai Axis and to the south-east.

The crater tends to interrupt the NW-SE trending anomaly which suggests structures in this direction which would control any possible geothermal fluids. This positive anomaly also coincides with a resistivity low.

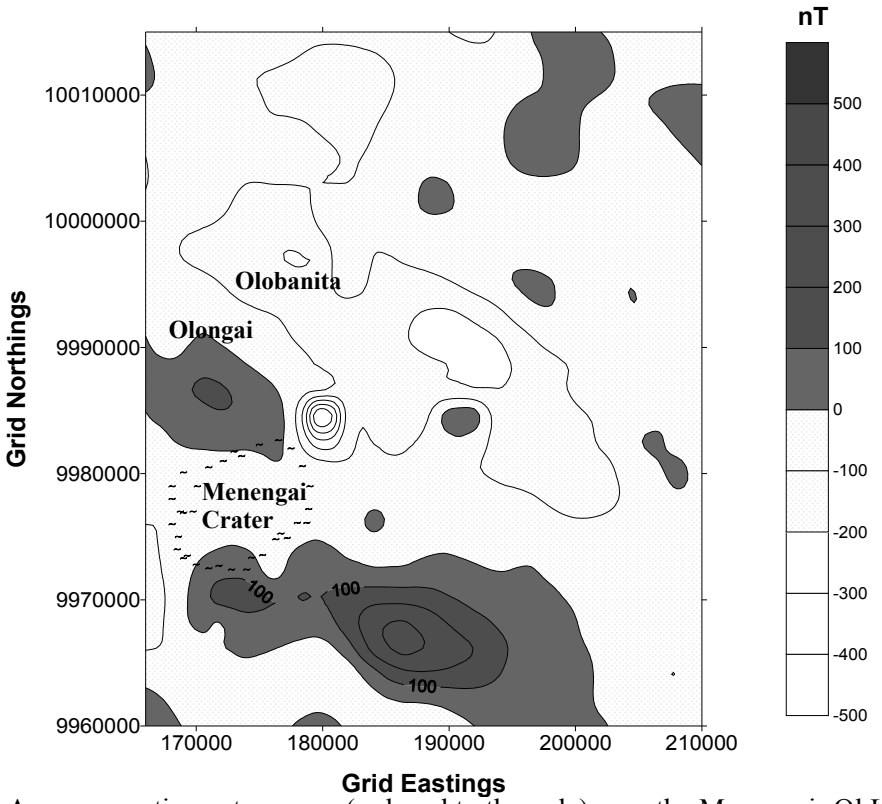

FIGURE 3: Aero-magnetic contour map (reduced to the pole) over the Menengai- Ol Longai - Olbanita geothermal areas, Kenya. Note the NW-SE trending anomalies

Experience of using the magnetic method over both Olkaria and Menengai Geothermal Fields is that it needs to be used in conjunction with gravity. Both fields are slowly getting populated accompanied by increasing human activity which introduces cultural noise (power lines, piping etc) into the data. This necessitates extra computing time to process the data so as to remove the cultural noise and to produce a 'clean' baseline data set against which the products of quicker automatic and semi-automatic intelligent routines of deculturing can be compared. Hence it is important to communicate the scale of the problem encountered and to show that by applying considerable care, it is possible to attain high-quality data.

2.3 Application of the gravity method over Olkaria

Volcanic centres, where geothermal activity is found, are indicators of cooling magma or hot rock beneath these areas as shown by volcanic flows, ashes, volcanic domes and abundant hydrothermal activities in the form of fumaroles and hot springs. Gravity studies in volcanic areas have effectively demonstrated that this method provides good evidence of shallow subsurface density variations, associated with the structural and magmatic history of a volcano. There is a correlation between gravity highs with centres of volcanism, intensive faulting and geothermal activity. During interpretation, to reduce ambiguity, use is made of seismic data to constrain the models generated. Figure 4 is an example of a gravity anomaly over Olkaria geothermal field in Kenya.

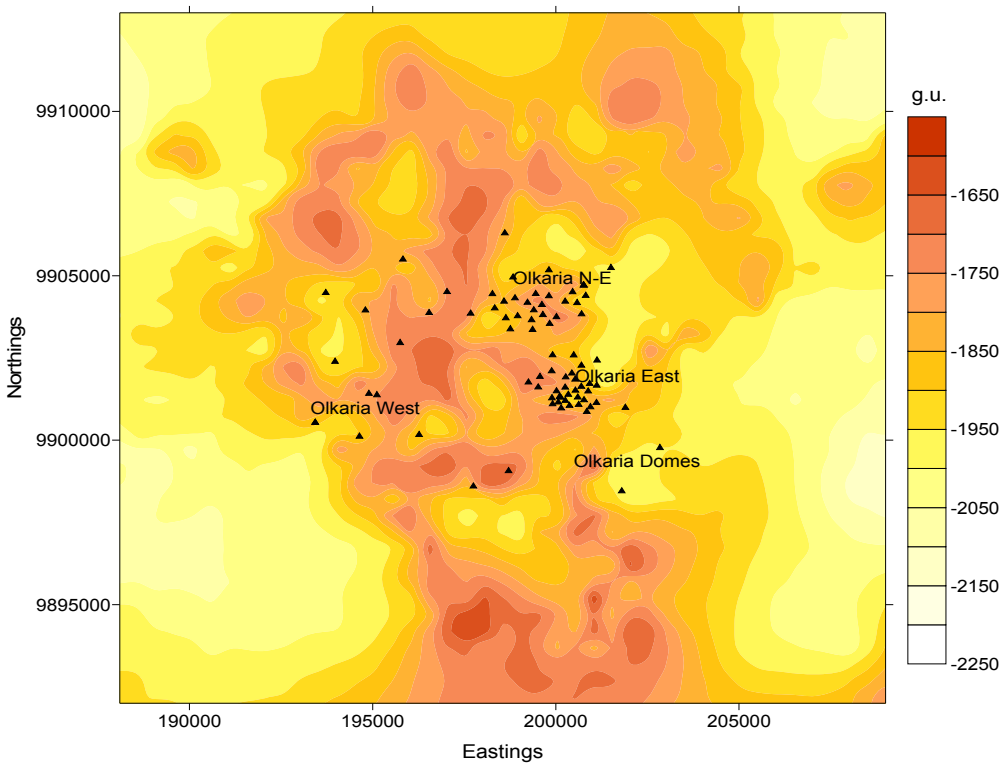

FIGURE 4: Gravity anomaly over Olkaria geothermal field in Kenya

Geological observations indicate that the Olkaria area is underlain by an intrusive mass, part of which still contains residual magma. North-South fracturing in the area has provided loci for eruptions of pleistocene to Recent volcanics, including a number of rhyolitic domes, comenditic flows,pumiceous obsidian flows and dykes. The line of white ash and pumice eruption,phreatic explosion vents, and Ololbutot flow of magma in Olkaria along the north-south Ololbutot fracture. A two-dimensional geologic model of Olkaria is constructed and updated regularly using newer geological and gravity data and the seismic results from current and previous works (Figure 5). Two-dimensional modelling of the gravity data shows that the western part of the Olkaria area is down-faulted relative to the eastern part and the Olkaria area lies partly on a graben structure and partly on a horst structure. Further interpretation of gravity data within the Greater Olkaria Area shows that a dense body occurs at the southern part of Olkaria (Ndombi, 1981). The Olkaria West, EPF and NE fields occur within gravity lows. The major north-South fractures, most of which lie on the horst structure, have been intruded by dyke-like bodies of ryolitic composition. The largest intrusion has occurred along Ol Olbutot fault zone. This intrusion is still in magmatic state and appears to be the main heat source for the present geothermal phenomena at Olkaria. Our interpretation indicates that this system of dikes is a significant hydrogeological barrier between Olkaria West and EPF/NE. The geothermal field has been well delineated by aid of resistivity data. It is contained within a roughly north-south trending zone,up to an average of 2 km on either side of the Ololbutot fracture line , and is bounded by the north-south Olkaria and OI'Njorowa faults.

The Menengai-Olbanita area is located in a region of intracontinental triple junction where the Nyanza rift joins the Kenya rift and is considered to overly a mantle plume (Burke and Dewey, 1973; KRISP Working group 1994). The surface is comprised of several eruptive volcanoes with caldera collapses and concentration of tectonic grid faulting. The Menengai complex is dominated by a central volcano with a large caldera of about 12km in diameter. The Olbanita volcanic complex consists of the remnants of an old caldera 8 km north of Menengai. The surface in both areas is covered by mainly pyroclastics, tuffs and minor occurrence of trachyte and basalt.

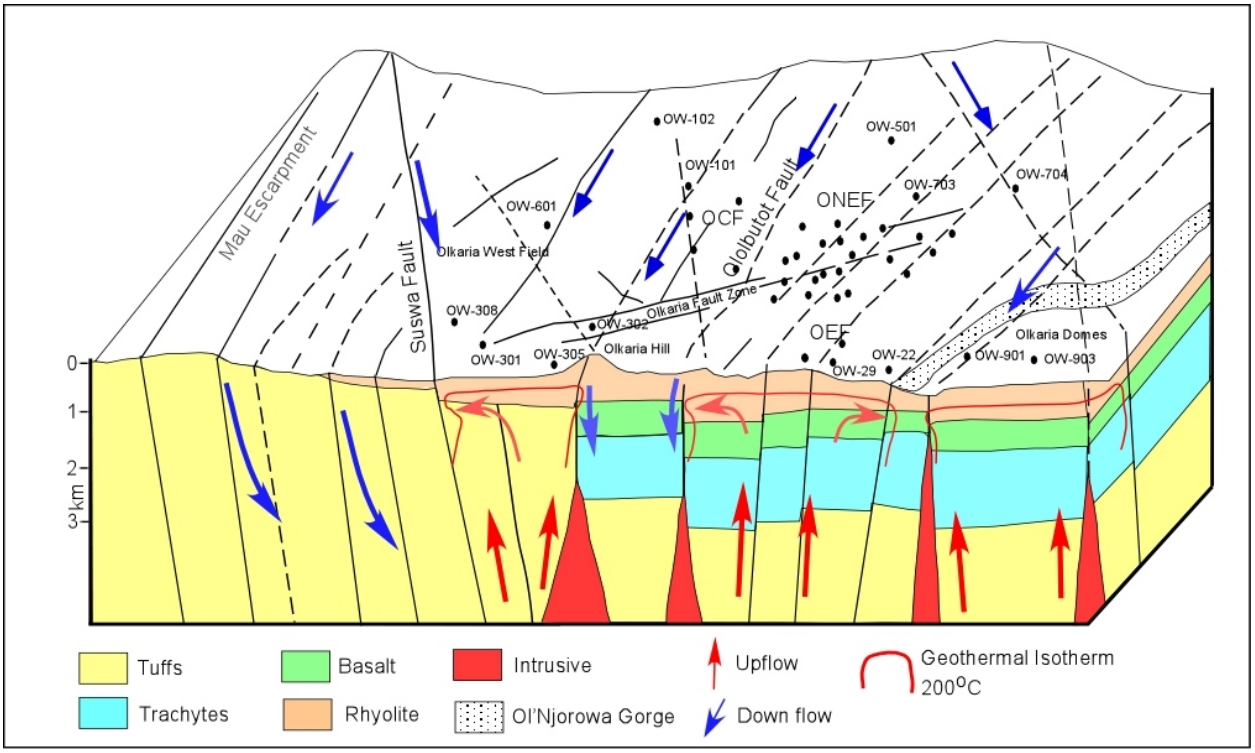

FIGURE 5: An integrated geophysical model of Olkaria geothermal field

Gravity studies by Geotermica Italiana (1987) collected some 1400 data points. Later KenGen and the Geothermal Development Company in-filled more gravity stations in and around the Menengai Caldera. Analysis of this data shows a large positive anomaly, located in the central part of the area. This is interpreted as being related to a dense body located some 3.5-4 km deep and a density of 2.8 gcm-3 that could a heat source for the geothermal system. This anomaly coincides with the Molo Volcanic Axis (Figures 5 and 6).

Data from the Solai area showed that the N-S trending anomaly, which reaches a maximum in the Molo Volcanic Axis, is less prominent within the Solai fault zone. Despite the Solai fault zone having relatively intense tectonic activity, it is less volcanically active than the Molo axis system due to relatively few eruptions of lavas. However, the intense tectonic activity may likely result in high permeability giving rise to some likelihood of cold waters from the eastern escarpment infiltrating any possible geothermal reservoir in the area.

Gravity data interpretation by KenGen (Mariita et al., 2004) by analysis of profiles through the caldera indicate the presence of a high density body with peaks beneath this structure (Figure 8). Since the volcano is relatively young this body could still be hot, the heat being conducted to near surface regions by dykes.

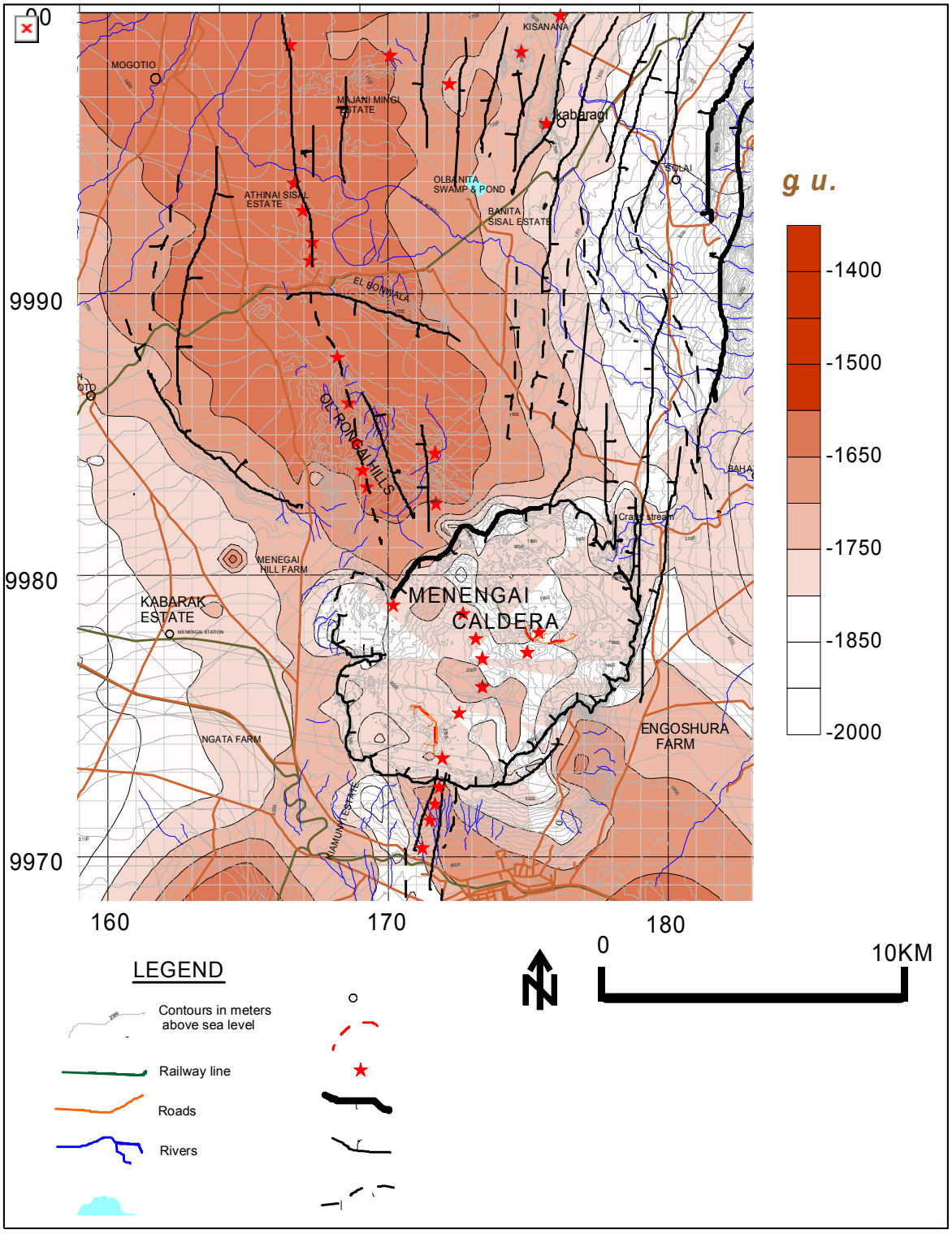

FIGURE 6: Gravity contour map of Menengai - Ol Banita geothermal prospects using Bouguer density of 2.3 gcm^{-3}

As shown in Figure 6, gravity high runs through the central part and trends NNW-SSE. This coincides with the Molo Volcanic Axis. A NE-SW trending low gravity anomaly interrupted by Menengai caldera can be seen (Figure 7). This low corresponds to a NE-SW tectonic structure that seems to define the shape of Menengai caldera. This low gravity might be due to fracturing thus lowering the bulk density, indicating presence of high permeability. Within the caldera (Figure 8), the influence of the surficial lavas is seen corresponding to relatively higher gravity, however, the NNW-SSE gravity high still exists.

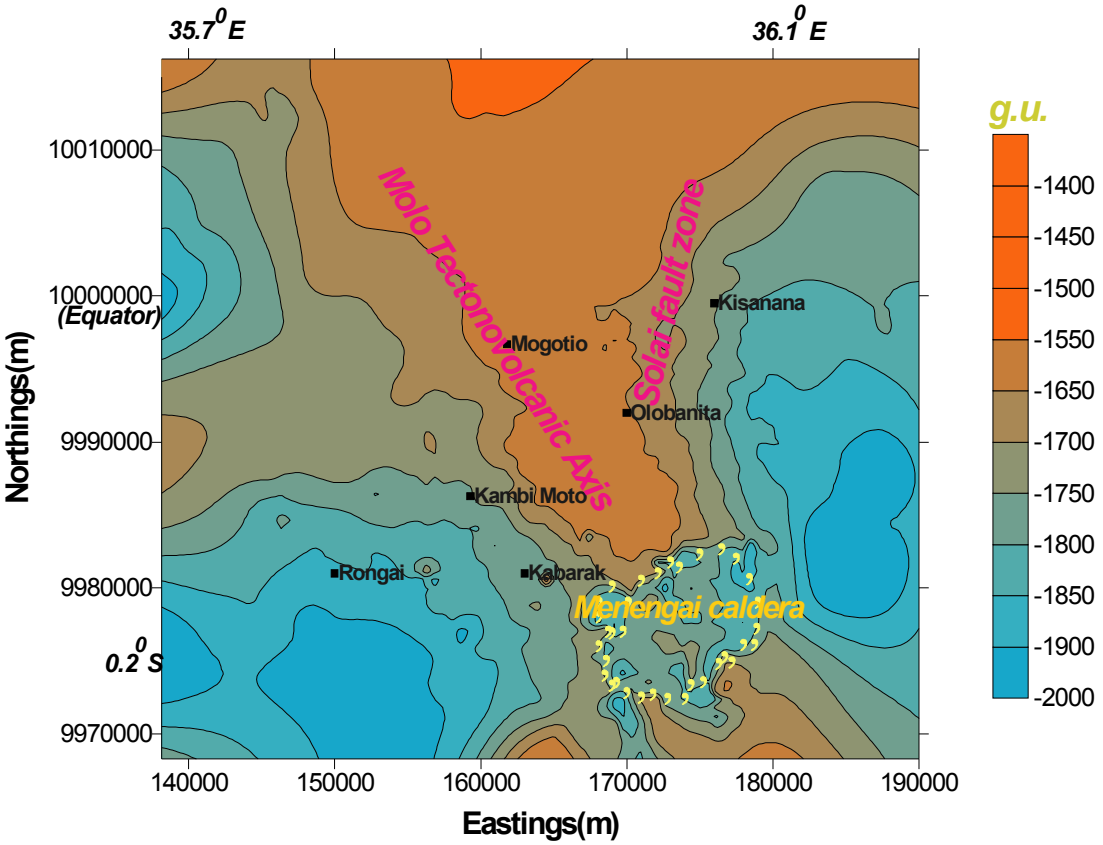

FIGURE 7: Menengai Bouguer gravity map

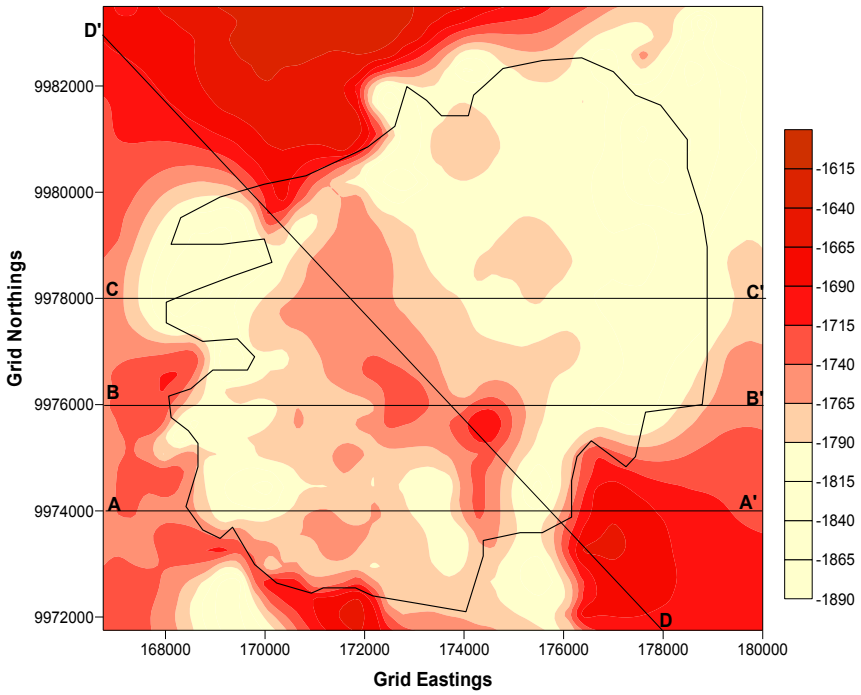

FIGURE 8: Bouguer anomaly map and analysed profiles through Menengai caldera

Parts of Olkaria and Menengai geothermal fields have ragged terrains with few or no access roads. The Menengai caldera is particularly challenging, the near fresh lavas making collection of data difficult or even dangerous.

Gravity data requires a lot processing techniques before being ready for interpretation. Interpretation can be completely objective or highly subjective. It can range from a simple inspection of a map or profile to a highly sophisticated operation involving skilled personnel and elaborate supporting equipment. Some interpretations require little understanding of the geology, but the quality of most interpretations is improved if the interpreter has a good understanding of the geology involved. Gravity data is also known for its ambiguity in interpretation unless compared with results from other methods such as seismology.

3. CONCLUSIONS

Given the site conditions and targets of investigation, the choice of a geophysical surveying method for geothermal energy should bear several factors in mind. First, the technique must be suited to detecting the necessary targets at the site imaged as anomalous features. Second, the technique must be appropriate for the conditions of the area, especially the subsurface geology and ground surface. If a particular method is conducted, it would best be used to complement it with another method of geophysical survey. Experience from geothermal exploration using magnetics and gravity around Olkaria and Menengai fields do suggest good indications of the likelihood of a geothermal resource and are best suited the methods to be utilized as first choices. These methods are often easy to carry out and are cost effective.

Gravity data is often complex and may not be interpretable. It could mean the data is possibly erroneous, but could also be accurate data requiring more sophisticated processing and interpretation. When this distinction is made, other reasons ruled out and no anomaly is seen then it can be concluded that the survey was not successful.

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APPLICATION OF MICRO-SEISMIC METHODS TO GEOTHERMAL EXPLORATION: EXAMPLES FROM THE KENYA RIFT

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ABSTRACT

Results from volcano-seismic studies of many geothermal fields show that they are possible resource-mapping tools for geothermal exploration and reservoir monitoring. They have been able to map the size and depth of possible shallow geothermal heat sources by analyzing data for seismic gaps, S-wave attenuation, reflected arrivals and converted waves. Analysis of shear wave split data for fracture density show high permeability areas that are potential targets for drilling high-producer wells. Variation of Vp/Vs ratios is related to reservoir fluid phases where low values are related to a decrease in P-wave velocity in the area with low pore pressure, high heat flow, fracturing and steam/gas saturation in the reservoir. High velocity ratios were found in the relatively liquid-saturated high-pressure fields that these ratios are useful tools for monitoring reservoirs under exploitation. The volcano-seismic approach can be useful as a stand alone tool for analyzing geothermal resource both at the exploration and exploitation stage that is cost effective in the long term

1. INTRODUCTION

The main objective of any scientific investigation for a geothermal resource is to locate a potentially attractive reservoir which can be economically exploited for electric power generation and other uses. Such indicators as a heat source, availability and characteristics of fluids, reservoir temperature and flow channels are the main parameters investigated. Most of these parameters are sometimes manifested on the surface whereas in other cases there are virtually no surface expressions though there is a resource lying underneath. To maximize on evaluation in the later 'blind resource' type of areas, different geological, geochemical and geophysical methods have been applied in various geothermal fields. Unlike in the oil industry where there are enormous financial resources, the geothermal industry has lacked the capacity to set up large seismic networks and develop techniques needed for resource evaluation using seismic methods.

However, numerous studies show that recent intrusions are associated with high levels of earthquake activity (e.g. Mt. St. Helen: Nevado del Ruiz, Lees, and Crosson, 1989, Zollweg, 1989; Fehler, 1983; Krafla, Iceland: Foulger, 1983; Stromboli, Italy: Ntepe and Dorel, 1990; Mammoth: Stroujkova & Malin, 1999). Spectral analysis of individual events shows that they are characterized by unique, low frequency source mechanisms. The events are often emergent, lack clear phases, and contain several

characteristic frequencies. These events give information on the dimensions of their associated magmatic and hydrothermal systems. In practical terms, these are the features that control the potential energy present in a given geothermal field.

A number of changes in the recent past have modified the capacity to use microearthquakes for geothermal studies. The cost of seismic instruments has been decreasing and the possibility of collaboration between institutions to work together by pooling resources including instruments has made it possible to carry out such studies.

Recent studies have focussed on the use of natural earthquake activity as a tool for geothermal evaluation of the heat source, fluid flow channels-permeability and reservoir properties. These are normally carried out following the objectives below:

a) Map the location of heat sources by using spatial seismic intensity, hypocenter distribution, shear wave attenuation and P wave reflection.
b) Map high crack density zones as an aide to siting high producer wells by inverting for three-dimensional crack direction and crack density in the target volume using the polarization angle.
c) Determine the fluid phase, reservoir size and characteristics by determining the variation in seismic velocity within the fields.

1.1 The Menengai prospect

Menengai-Olbanita area is located within a region of intracontinental crustal triple Rift junction. This is where the Kavirondo Rift joins the main Kenyan rift [Figure 1.1]. The Kavirondo rift has been inactive since at least upper Pliocene. The main rift is bounded by N-S running major rift scarps that depict different tectonic style on the two sides. Bosworth et al (1986) proposes that this part of the rift represent a breakaway section of major lithospheric detachments as evidenced by sharp scarps in the eastern side and gentle sloping one on the western side. Geotermica Italiana Srl (1987) proposes that this whole section of the rift is a crustal detachment generating a sequence of faults, which merge at a low angle at depth. This is a situation described structurally as a 'reverse drag' where differential spreading is maximum on the master fault and rotation of faulted blocks result in tilted blocks. The central ring structures of Menengai and Olbanita calderas represent collapses associated with emptying of shallow magma chambers underlying them. Menengai-Olbanita area is located within a region that is considered to overly a mantle plume (Burke & Dewey, 1973). The surface is comprised of several eruptive volcanoes with caldera collapses and concentration of tectonic grid faulting (block and fissure faults) in its northern reaches which are characteristic of extension faulting associated with spreading (rifting) at crustal boundaries. On the surface, the area comprises widespread pyroclastics cover from the large caldera and it is also characterised by heavy masking by Menengai eruptives. Grid faults expose older lava to the north, mainly trachytic and trachyphonolites belonging to the 'Hannington suite (McCall, 1967).

The composition of the lava-flows found in the area varies from phonolites, trachyphonolites and trachytes. Subordinate alkali olivine basalts also occur in the area. Phonolites and trachyphonolites form the older lava eruption in the Rift floor and are more exposed in the northern parts. Most of the Menengai pre-caldera shields building lavas are trachytic. Similarly the post caldera lava partially filing the caldera floor is also trachytic.

Huge amounts of pyroclastics cover the slopes of Menengai and areas around Olbanita. These vary from ash fall, pumice rich ash deposits, welded pyroclastic flows (Ignimbrites) and some proximal lithic tuff outcrops adjacent to Menengai explosive caldera. The source of the pyroclastic eruptives is obviously the explosive eruption accompanying formation of Menengai caldera.

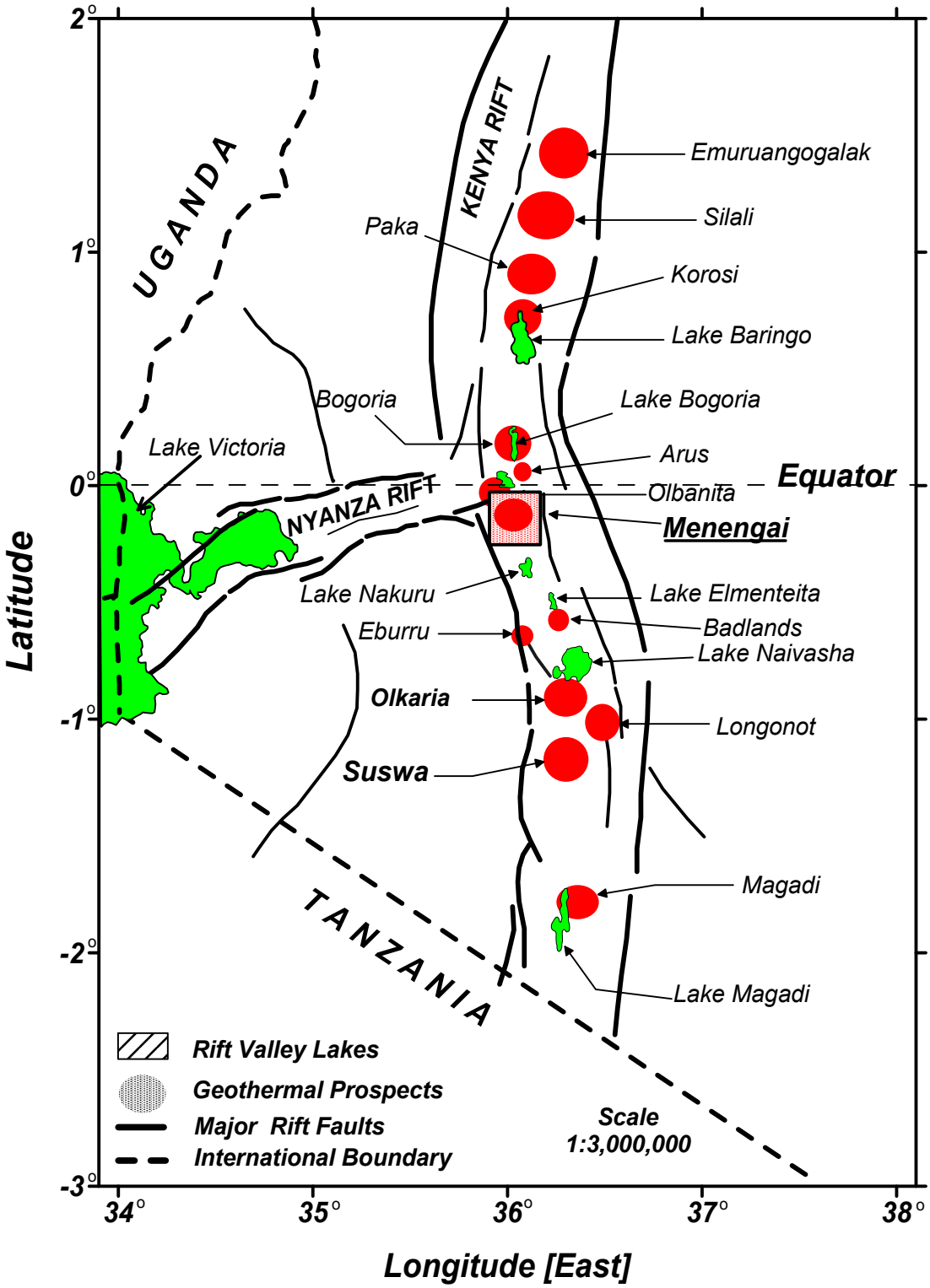

Figure 1.1. Map of the Kenya rift showing Lakes and Geothermal Prospects. The Menengai geothermal prospect is shown in a shaded box.

2. METHODOLOGY

Regional seismic refraction studies are normally carried out to identify areas with high seismic velocities that form targets for further detailed micro-seismic studies. For example, along the Kenya Rift, regional seismic studies of the crust [Henry et al., 1990; Mechie et al., 1994 and Mechie et al., 1997 and Simiyu and Keller, 2001] showed that there were significant differences in crust structure between the northern, Central and southern parts of the rift valley. The rift fill thickness varies from 1.5 km to 5 km underlain by basement material of velocity 6.05 km/s. They mapped high velocity bodies associated with the Menengai, Olkaria and Suswa Quaternary volcanic centres.

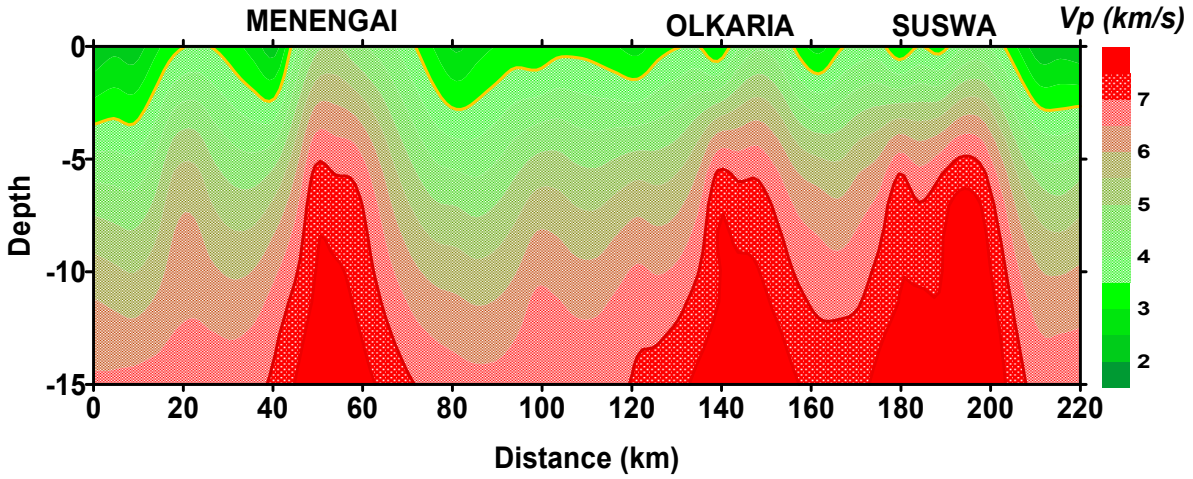

Figure 1.2. Seismic Velocity model along the Rift axis showing high velocity zones beneath Menengai, Olkaria and Suswa Volcanic centers based on the KRISP 1985-1990 axial model by Simiyu and Keller, 2000.

2.1 Data acquisition

2.1.1 Background noise monitoring

It has long been recognised that hydrothermal processes such as phase change within a geothermal reservoir radiate seismic energy [Whiteford, 1975]. High levels of ground noise has been detected at many geothermal sites and some evidence presented for existence of radiating sources at some depth, e.g. Long valley, California [Iyer and Hitchcock, 1976] and Grass valley, Nevada [Liew and McEvilly, 1979].

Background noise is recorded in the fields as a function of time over 24 hours where the instruments are programmed with a 5 seconds recording window that triggers every 30 minutes in order to monitor the variation of ground velocity amplitude. The root mean square (RMS) of the ground velocity (Amplitude) is then calculated over the 5 sec window in microns/sec. For example at Menengai, the noise levels oscillated around a mean as shown in representative plots of the RMS as a function of time [Figure 2.1]. The Menengai South West [MSW], Menengai South East [MSE], Menengai North East [MNE], Menengai Caldera Area [MCA], Menengai North West [MNW] and Menengai North Area [MNA] area have mean values of 2.5, 2.1, 1.5, 2.1,1.5 and 0.5 respectively.

An interpretation of the amplitude of ground velocity showed the value is highest in the MSW and MSE areas due to perturbation by cultural noise from the Nakuru town activity and traffic along the Nairobi-Nakuru-Eldoret highway. The MNE area shows very low noise levels during the night but

increases to the same levels as the MSW around mid-day when there is a lot of movement along the roads and town.

The MCA area has high mean noise level with a very large standard deviation mainly due to possible geothermal activities. The MCA has very limited cultural activities with the noise being mainly natural as opposed to the MSW and MSE. This is interpreted as possibly hydrothermal related radiating sources (Simiyu, 2003).

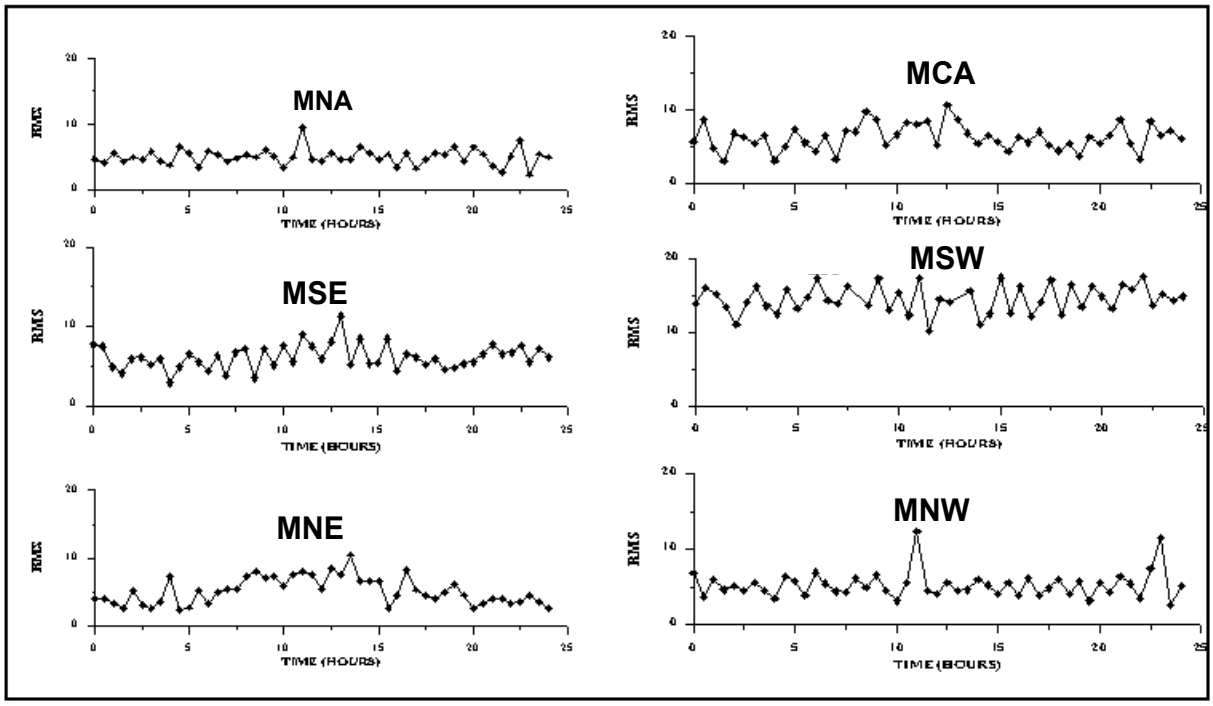

Figure 2.1. Background Seismic Noise in Menengai Area: MNA, MSE, MNE, MCA, MSW and MNW

2.1.2 Micro-seismic network

Months to years of continuous seismic monitoring using as many as 5 to 200 instruments are normally laid in a network to determine the locations and nature of the earthquakes within a given prospect area as shown in the Menengai Volcanic area [Figure 2.2]. A wider area network can also be deployed centred on the main prospect of interest with raypaths expected to cross the volcanic centres. The wider network is normally aimed to determine the variation in physical parameters that are associated with the heat sources, heat transfer and fluid flow.

The ideal seismograph network for the prospect is mainly comprised of stations with recorders equipped with three-component short period (1-2 Hz) sensors and digital GPS timing systems. Initially broadband sensors are deployed in a rectangle around the field within the wider area network with one instrument at the centre of the polygon. This earlier deployment has been used to assess the suitability of later methods used by analyzing for the instrument response, the source effect and site effects.

The main project network is designed to cover the potential geothermal area with instrument locations close enough to detect events of low magnitude. The network is typically designed to cover an area of about 20 km across centred on the main prospect. Thus, for shallow earthquakes [depth <5 km] the outer stations would record waves refracted through basement rocks and the inner stations would record direct waves travelling through the shallow layers.

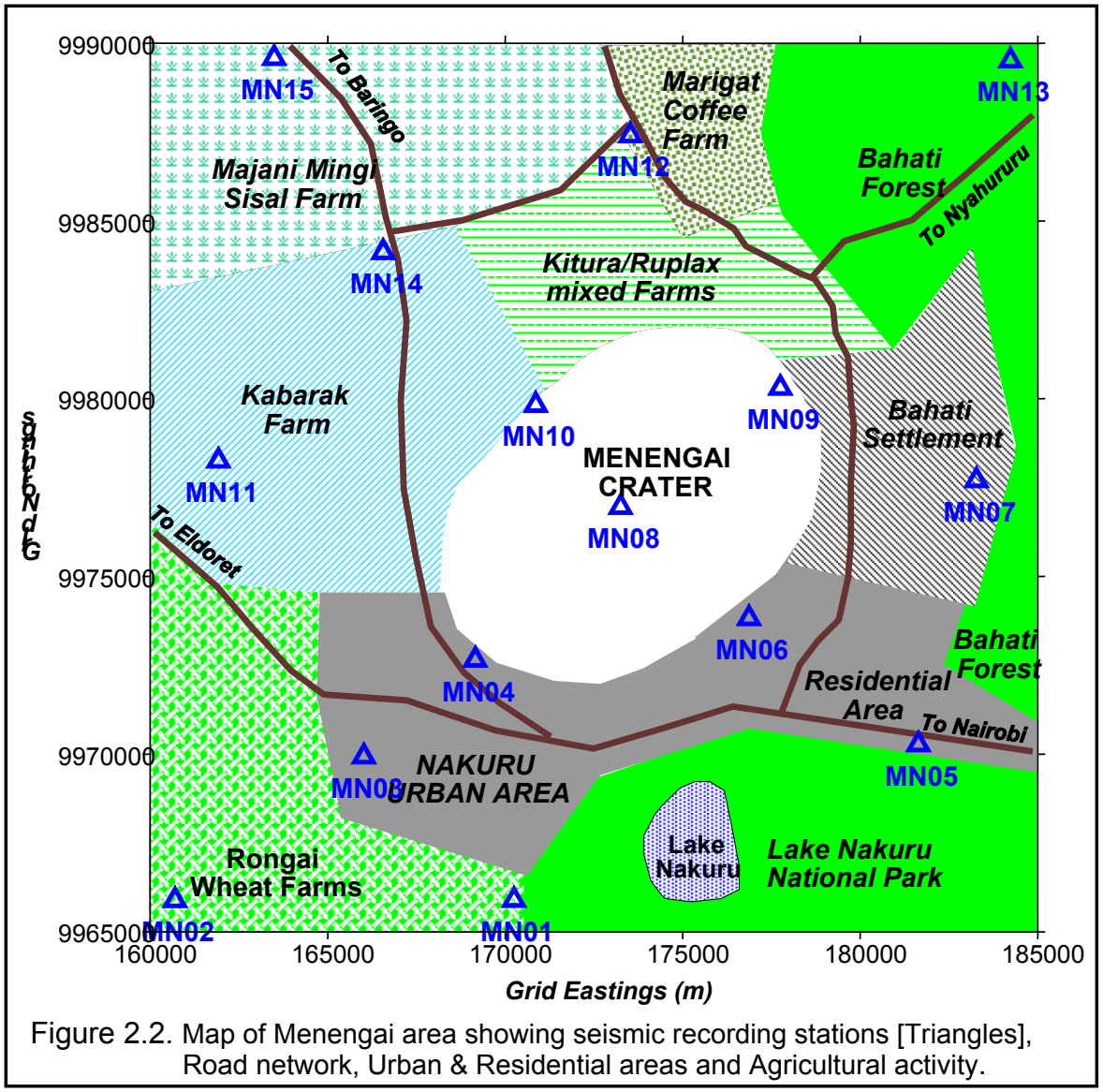

Figure 2.2. Map of Menengai area showing seismic recording stations [Triangles], Road network, Urban & Residential areas and Agricultural activity.

Seismometers are placed as close to outcropping rocks as possible in order to avoid noisy conditions and high attenuation associated with low velocity formations such as tuffs, soils and sediments. Pits are dug two to three meters deep for the seismometers through the loose cover to more consolidated material or base-rock where possible. A flat concrete base is then constructed with rock ballast and cement coupled onto the base-rock (country rock). For micro-seismics, instruments are programmed to sample at a rate of 250-500 samples per second on a data stream that can also be on trigger mode. A second data stream can be used at a different sample rate such as 50 samples per second but on a continuous recording mode. This second stream acts as security if there was a trigger parameter error. Also analogue recording instruments can be deployed alongside the digital ones to look at how the recording was going.

2.2 Data processing

2.2.1 Data picking

Data is downloaded directly onto a PC and processed using programmes such as PCSUDS and PITSA packages [Sherbaum and Johnson, 1994] where they are picked for the arrival times. When a P or S

arrival time is picked, the operator assigned that 'pick' a quality between 0 [good, error < 0.015 sec] and 3 [poor, large error-0.05 sec]. This relative waiting of picks is included as a contributor to the earthquake arrival time error given as;

$$\varepsilon_r = [\alpha^2+\beta^2]^{0.5}, \qquad [1]$$

where, ε_r = Reading/Arrival time error,
α = Picking error and
β = Instrument timing error.

2.2.2 Elevation corrections

The event location program assumes that recording stations are situated on a horizontal surface above a plane layered velocity model. To correct for this, a time delay based on the determined velocity of the shallow material within the topographic difference of the survey area was specified for each station and these were added to each set of arrival times. The reference levels are taken as the lowest station elevation within the survey area. Assuming near vertical incidence angles, the height difference between each station and the reference level is the travel path difference that is to be taken into account. To convert the height differences to time delays, the height was divided by the velocity of the material that makes the topography above the datum. The velocity defined for the top layer depended on the geology at the station. The elevation reference levels, maximum thickness and a determined velocity for the material above datum have to be determined and used for correction at each station.

2.2.3 Magnitude and event location

There are many packages used for event location and magnitude determinations. However, most of them are based on the HYPO71 package [Lee and Lahr, 1975]. The P and S arrival times read from the sections are entered manually into the HYPO71 (or hypoinverse) for preliminary epicentre and hypocenter location. The data are analyzed, events identified and then located. In a new area a 1 dimensional P-wave velocity model is initially made for the whole area consisting of a number of flat homogeneous layers the bottom of which is a half space and used to give an initial location of events. In Kenya, for example, the initial velocity models of the rift volcanic areas are based on regional seismic refraction data and used in the event location.

The resultant model is tested with well-located events and finally modified to make the observed and calculated velocities agree. The model was then used to get the initial /preliminary event locations for the area.

The next step is to make a combined P and S wave crustal velocity model for the whole area. This can be made consisting of flat homogeneous layers with vertical linear velocity gradient. The program used can also allow for horizontal velocity changes in the BLOCK DATA subprogram. In order to refine the event locations by using both P and S waves, it is necessary to develop a velocity model that incorporates both P and S wave velocity. First, an average Vp/Vs ratio for the whole area is estimated using Wadati plots. Earthquakes with an arrival time pick of quality 0 and 1 are used and to avoid bias towards the more active zones, the earthquakes chosen should be evenly distributed throughout the area. Plots of travel time versus distance are constructed and the average velocities for P and S-waves obtained by linear least squares fit [with focal depth consideration in the epicentre distance calculation]. The determined Vp is then divided by Vs to obtain the ratio.

To cross check the results, S-wave travel times are plotted against P-wave travel times for a number of earthquakes and the slope of a linear least squares fit gives the same the Vp/Vs ratio. These two

approaches should give comparable results. In most cases, the earliest S-arrival time is picked; hence the results of the analysis are in most cases biased towards the faster S-wave velocity. The new model combining P and S-waves is then used to relocate the events and then compared with the initial locations using a P only velocity model.

Using a combined P-wave and S-wave velocity model instead of the P-wave velocity model alone can reduce the location errors by 12-23 % horizontal and 13-28 % vertical. Normally the errors are lowest for those events from the centre of the network and highest for the events outside. A typical velocity model for Olkaria, Kenya (Simiyu 2000) is given below.

Layer	Depth [km]	V_p [km/s]	V_s [km/s]	Lithology
1	0 to 0.6	2.1	1.2	Pyroclastics
2	0.6 to 2.5	3.3	1.9	Trachytes/Tuffs
3	2.5 to 3.5	4.5	2.6	Lavas/Intrusives
4	3.5 to 4.5	5.2	3.1	U. granitic basement
5	4.5 to 8.0	6.4	3.8	L. granitic basement

The events are located and then classified according to arrival time differences into a number of categories such as an example below:

1) Local events [T_s-T_p<5 sec];
2) Regional events [5<T_s-T_p<40 sec];
3) Tele-seismic events [T_s-T_p>40 sec].

Commonly used is the formula given by Lee et. al., [1972] to evaluate the duration [coda] magnitudes.

$$M_c = 2\log[C] + 0.00325d - 0.97 \qquad [2]$$

where, d = epicentre distance [km],
C = duration of the earthquake coda [seconds]

The magnitudes of the earthquakes mostly recorded in geothermal areas are normally between M_c=1.5 and M_c=3.0.

Many studies in geothermal fields have shown that the velocity structure at most of the volcanic centres is heterogeneous from the surface up to 4 km. One velocity model that does not allow for lateral velocity variation is therefore not adequate for precisely locating earthquakes that span 2 of the regions. To reduce the problem of heterogeneity in such a case, each event can be located using the velocity model of the region of origin and stations within the region. Those stations close to the event are given more weight. During back projection, a laterally homogeneous velocity is assumed. The strong lateral variation in the upper zones [1-4 km depth] will not significantly affect the back projection if the rays used have hypocenters deeper than for example 4 km. Heterogeneity due to local anomalies may affect the ray paths more significantly such as lateral refractions around anomalously slow regions, which will produce a smaller image of the anomaly.

The next step in this approach is to break down the data into smaller hypocentre-station groups consisting of earthquakes originating from one part of the field [belonging to the same swarm]. It has been found in many fields that the seismicity patterns varied from one area of the field to another. Such a field can thus be divided into a number of areas. It has been found in many areas that the scatter greatly reduces with a standard deviation of 0.011 to 0.04.

2.2.4 Error analysis

The analysis program calculates the full 4x4-covariance matrix of the solution, and derives from it the error ellipsoid and the horizontal and vertical errors. The error calculation requires an estimate of the variance in the arrival time data, given as;

$$\omega^2 = \varepsilon_r^2 + \varepsilon_f * rms^2; \quad [3]$$

where, ω^2 = variance [standard error squared] of the arrival time data.
ε_r^2 = estimated reading error.
ε_f = weighting factor for including the effect of a poor solution.

The mean location errors calculated by HYPO71 using the combined P and S wave velocity model for the different fields in Kenya is on average typically; horizontal error of 0.3 km and a vertical error of 0.6 km.

2.3 Determination of detailed V_p/V_s ratio variations

Two typical detailed Vp/Vs ratio determination methods as applied for the Menengai area of Kenya is discussed next.

2.3.1 Using Wadati plots

The approach is to break down the data into smaller hypocenter-station blocks of 1x1 km. These blocks are made such that they are consisting of events originating from the same block of the field [belonging to the same group or clusters that are less than 1 km apart]. The Vp/Vs values are then determined for each divided block using the Wadati plots. The Wadati plot is a statistical method that is based on least squares fit approach.
The approach to this velocity ratios analysis for the Menengai prospect area was to determine;

1) an average overall V_p/V_s ratio for the whole of the Menengai area to use in Hypo71.
2) Spatial variation of the measured V_p/V_s ratio throughout the study area.

1567 well located earthquakes each with an arrival time pick of quality 0 and 1 were used. To avoid bias towards the more active zones, the earthquakes chosen were evenly distributed throughout the area. Simple plots of P and S wave travel time versus distance for the same data set were constructed and the average velocities for P and S waves obtained by linear least-squares fit [with focal depth consideration in epicentre distance calculation]. This was important as some of the events originated in areas localized velocity anomalies.

The determined Vp was then divided by Vs to obtain the ratio. To cross check the results, S arrival times were plotted against P arrival times for a number of earthquakes and the slope of a linear least squares fit gave the Vp/Vs ratio. It was found that these two approaches gave comparable results. In all cases, the earliest S-arrival time was picked hence the results of the analysis are probably biased towards the faster S-wave velocity. These plots for the whole area show very pronounced scatters. On the basis of these ratios, velocity models were developed for both the Olbanita area and Menengai caldera areas. [Figure 2.4a & 2.4b]

The highest Vp/Vs ratios were mainly for earthquakes outside the network and most of them were for earthquakes with an NE azimuth. Figure 2.5 shows the average distribution map of Vp/Vs ratios within the whole of Menengai area. This map shows that the caldera centre, north eastern caldera rim and the Olbanita area have the lowest average ratios. The MSW, MSE, MNE and other areas outside the caldera and Olbanita have the highest ratios.

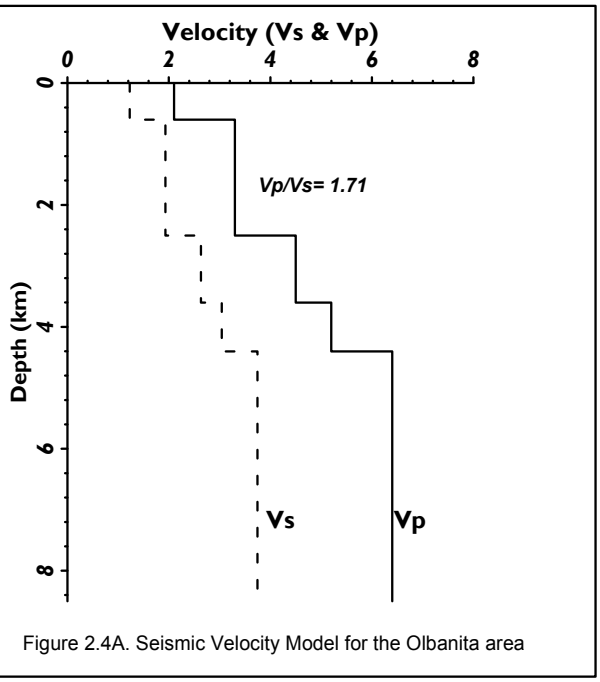

Figure 2.4A. Seismic Velocity Model for the Olbanita area

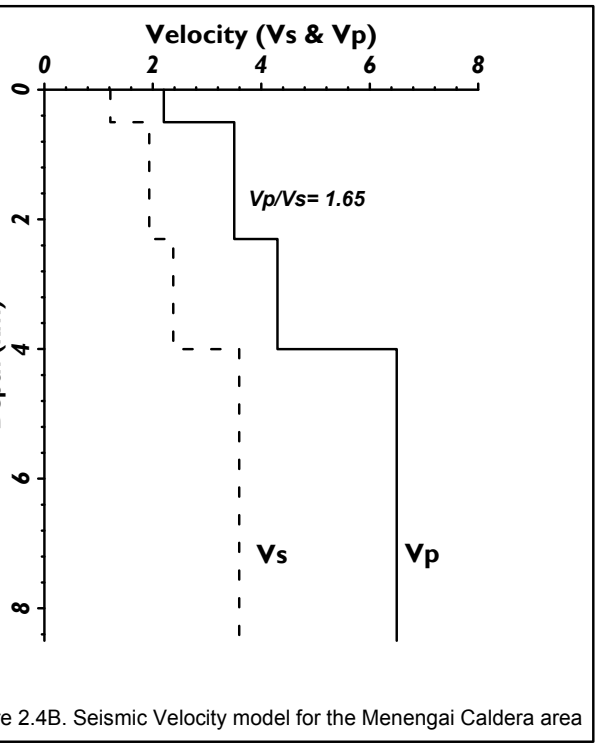

Figure 2.4B. Seismic Velocity model for the Menengai Caldera area

2.3.2 Direct V_p/V_s inversion method

The arrival times were inverted using the computer program SIMULPS12 [Evans et al., 1994]. This program is a modification of the original code by Thurber [1994] that uses raytracing. The modified program that we used solves simultaneously for earthquake locations and the crust structure [Vp and Vp/Vs] by the iterative damped-least squares method. At each iteration step, ray paths and earthquake locations are fully updated. The starting model was a 1D model determined earlier and used as a starting point for the inversion. The initial determined Vp/Vs ratio of 1.71 was used.

3D models were derived in a series of inversions in which starting with an initial course grid 100 notes at 5 km spacing. This was made progressively finer and the final grid has 1400 nodes and 0.5 km spacing with a final model giving RMS residuals of 0.03s P waves and 0.067s for S waves.

A resolution evaluation can carried out using the standard methods discussed by Foulger et al., [1995] by dividing the geothermal prospect area into blocks. The analysis results showed that the areas around the centre of the field are well resolved to a depth of 4.5 km. The developed ratios and velocities are then used to relocate the events.

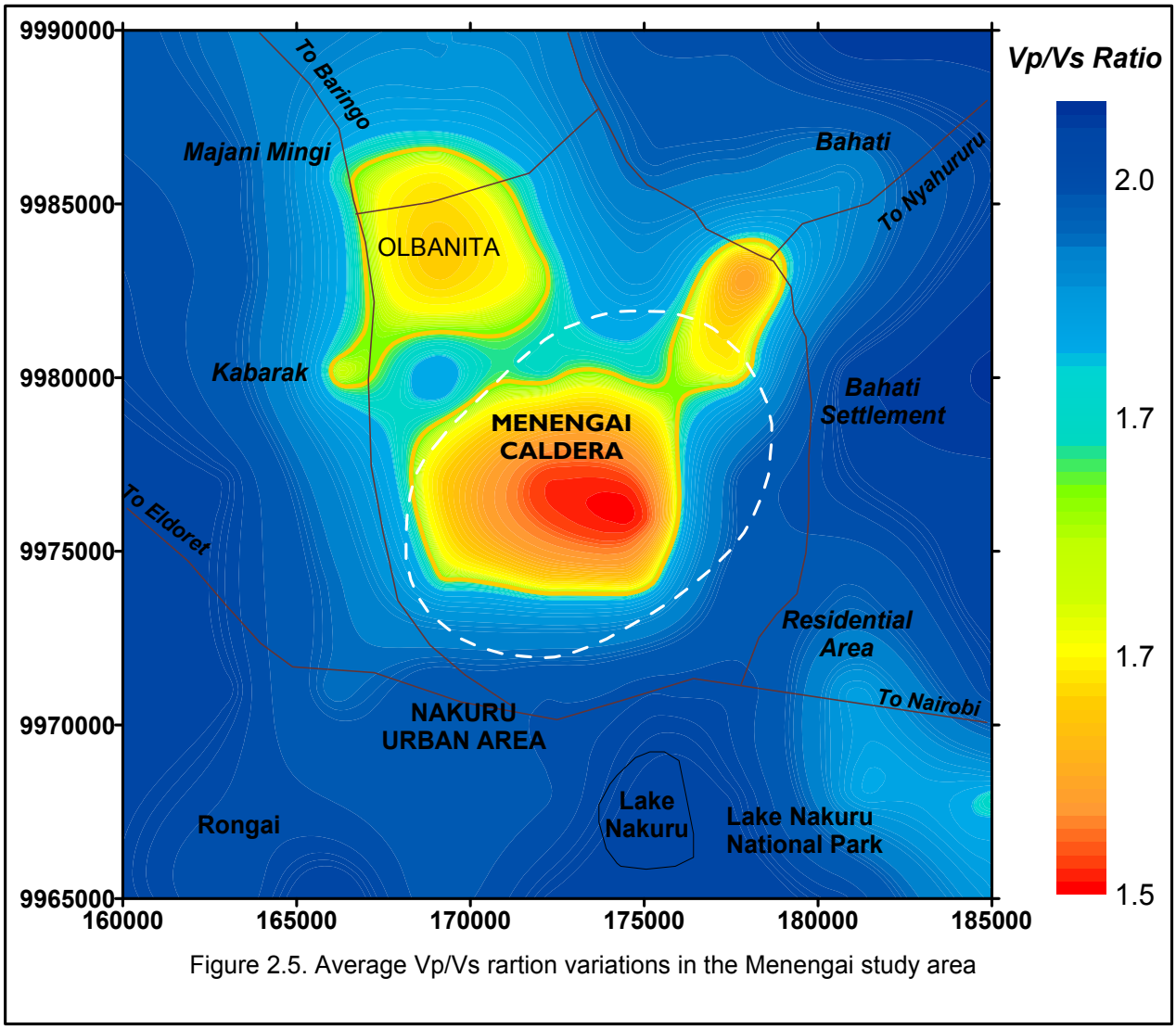

Figure 2.5. Average Vp/Vs rartion variations in the Menengai study area

3. RESULTS

3.1 Event distribution and magnitude variations

Figure 3.1a show the distribution of seismic events located within the Menengai prospect. Events are more concentrated within the Menengai caldera. This is the area around the central to the southern part of the caldera and on the NE caldera wall. Another area with a large cluster of events is within the Olbanita area to the central NW of the Menengai caldera where the events are also shallow [Figure 3.1b]. The dashed line represents a zone just above the brittle ductile transition. At a larger scale, the events occur along two trends. The first trend is along the rift axis in a NNW-SSE trend that starts from Majani Mingi through Olbanita, Menengai and dies out at Lake Nakuru in the South East. The second trend is parallel to the Nyanza rift axis in NE-SW direction along the major axis of the caldera with clusters from Bahati on the Aberdare ranges, through the caldera, Nakuru town and Rongai.

The Menengai caldera appears to be at an intersection of these two trends and thus at a triple junction. This shows that these fault zones along the rift axis and Nyanza Rift are still active and their point of intersection is therefore likely zones of magma injection and thermal fluid up-flow.

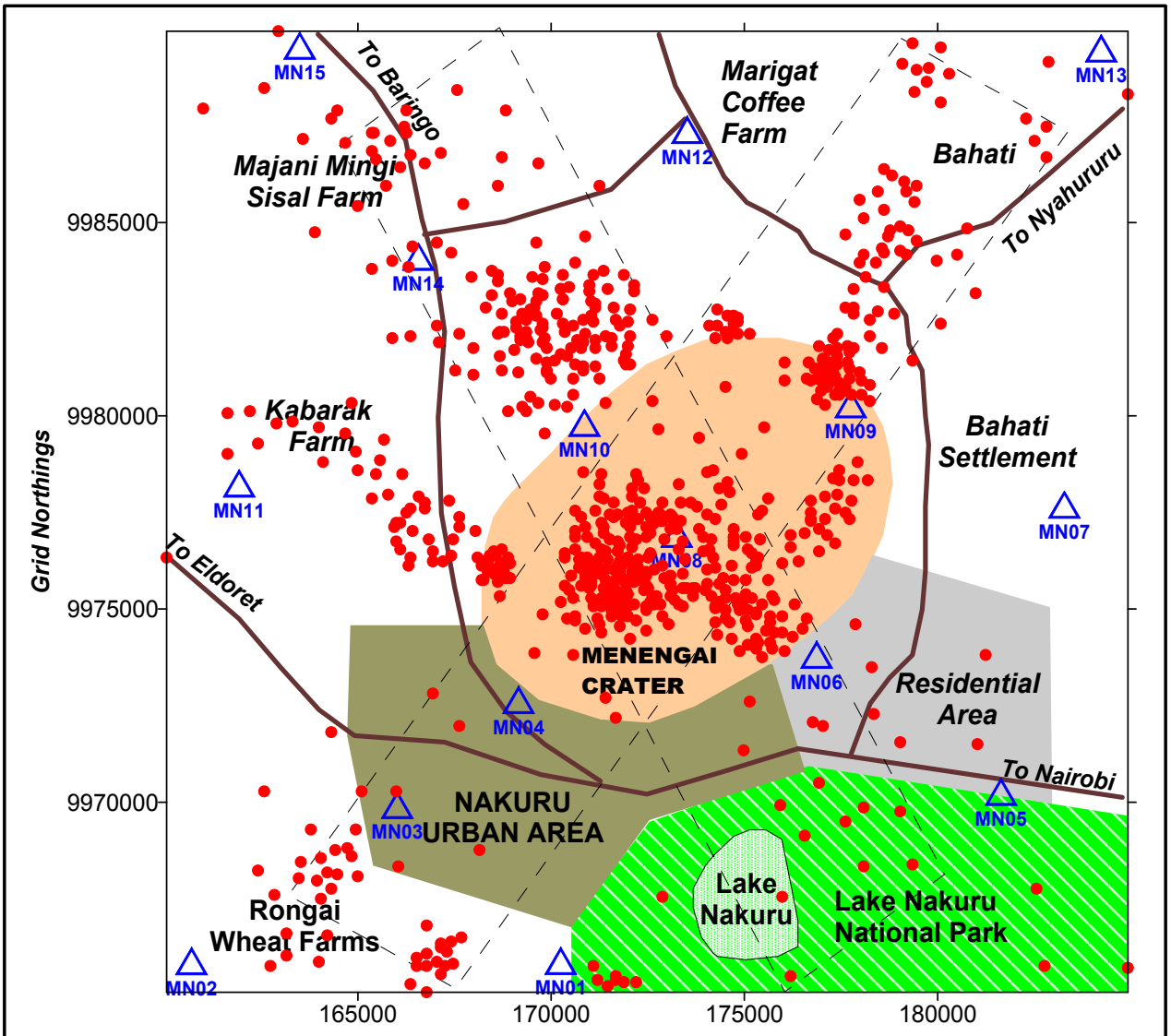

Figure 3.1A. Map showing recording stations [Triangles] and epicentres [circles]

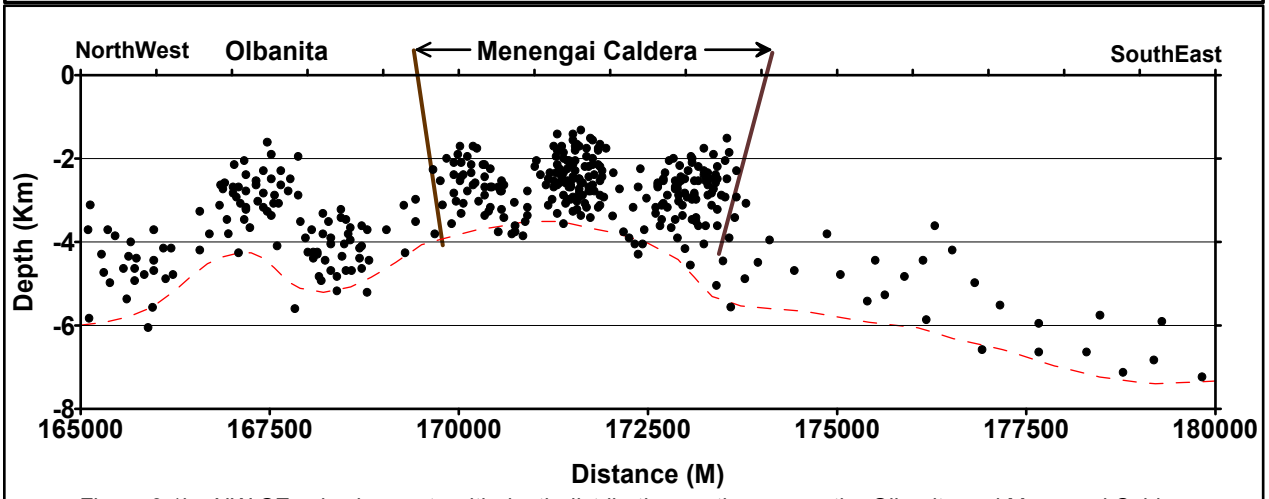

Figure 3.1b. NW-SE seismic events with depth distribution section across the Olbanita and Menengai Caldera

At Menengai, an averaged seismic distribution with depth map [Figure 3.2] shows that the area to the SW, SE, E and W are thermally under-privileged as the seismic cloud density decreases with depth. Around Olbanita and Menengai caldera, the events are smaller and shallower and deepen away from the caldera towards the SE, NW, North, West and East. The plots show a central area with intense seismic activity with shallow events centred on the Menengai caldera. It is therefore reasonable to assume that this zone of shallow events represent an area overlying the heat source for the geothermal system.

Magnitude-distance distribution for earthquakes located within the array [the prospect area] show that a greater proportion of the smallest earthquakes of magnitude 1.5 and less are recorded very close and within the network centre but fewer and larger magnitude 1.5 and greater on the periphery. This result is similar to recording in other high temperature and pressure geothermal fields such as Olkaria, Kenya [Simiyu and Malin, 2000], Mammoth [Stroujkova and Malin, 2000] and Geysers, USA [Combs, 1984].

In the absence of any specific magnitude formula determined for the southern part of the Kenya rift, we used the formula given by Lee et. al., [1973] to evaluate the duration magnitudes.

$$M_c = 2\log[C] + 0.00325d - 0.97, \qquad [4]$$

where, d = epicentre distance [km],
C = duration of the earthquake coda [seconds].

The magnitudes of local earthquakes show that there are no duration magnitudes for local earthquakes higher than 2.7 within the network, but magnitudes around 0.5-1.5 are regularly occurring. Figure 3.3 show the magnitude-distance distribution for earthquakes located within the array. This figure shows that a greater proportion of smallest earthquakes are recorded very close and within the network centre but fewer and larger magnitude earthquakes away from the network.

3.2. Heat source mapping

Although a number of studies have been carried out in the Menengai Geothermal Area, there has been no attempt to determine the presence and status of magma heat sources. A model relating the heat sources to the observed geophysical anomalies, volcanic evolution, reservoir characteristics and resource potential has not been developed.

3.2.1 The brittle-ductile transition zone

Under normal conditions, there is a linear increase in the crust strength with pressure [depth] and exponential decrease in strength with temperature. Peak strength is expected at a transition point from the brittle [pressure controlled] zone called the seismogenic zone to the ductile [temperature controlled] zone [Kohlstedt et al., 1995]. The amplitude and depth of the seismic activity peak is predicted to decrease with increasing geothermal gradient. Earthquakes represent a sudden slippage of rock along a fracture surface and generally should be restricted to a zone of brittle deformation. The maximum depth in a region at which earthquake intensity peaks will delineate the brittle-ductile transition zone [Meissner and Strehlau, 1982].

Chen and Molnar [1981] showed that temperature is a dominant factor in determining the maximum depth of earthquakes. Temperatures of less than 450^o C are required for an earthquake to occur in the crust rocks. At Menengai, the seismic activity depth relationship [Figure 3.2, 3.3 and 3.4] shows that the area within the caldera and Olbanita area is thermally privileged as the seismic cloud decreases with depth. Around these areas, the events are smaller and shallower and deepen away from the caldera towards the East, West and South. A contour map of averaged event depths shows a NE-SW

trend of the area with intense seismic activity with shallow hypocenters centred on the caldera. Another NNW-SSE trend through Olbanita is centred on the SE caldera edge. It is therefore reasonable to assume that these zones of shallow events within the two trends actually represent the areas overlying the heat sources for the geothermal system.

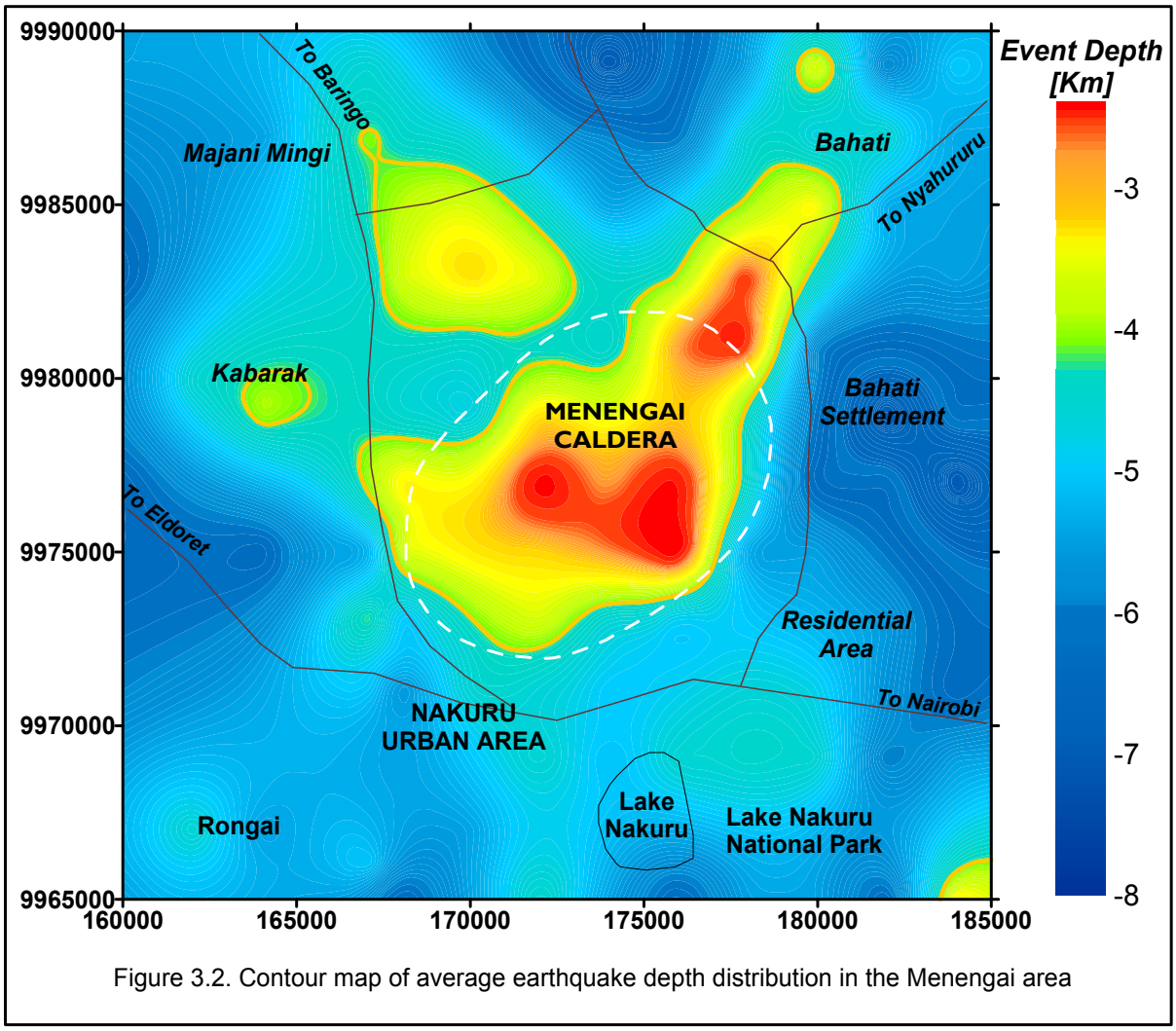

Figure 3.2. Contour map of average earthquake depth distribution in the Menengai area

Heat flow measurements in this area of the Kenya Rift (Wheildon et al., 1994) showed very high heat values (about 200 MWm^{-2}). In this area a change in seismic intensity at a depth of 5-7 km represent the brittle-ductile transition zone within the network. This depth is reasonable given the high geothermal gradient with temperatures of up to 340^{o} C measured in wells at a depth of 2 km.

These results are consistent with detailed analysis of gravity data [Simiyu and Keller, 1998] which show a positive anomaly with an amplitude of 30 mGal, half-wavelength of 15 km and a NW-SE trending anomaly interpreted to be related to the heat source. Band pass filtering indicated that the NE-SW trending anomaly has two maxima with amplitude up to 15 and 24 mGal. They also identified linear positive anomalies showing control of structures in the basement and shallow bodies related to Menengai volcanic activity. During this study, a basaltic melt magma body was postulated as the main heat source directly beneath the caldera.

All these data sets show that there exists a shallow high temperature body located directly beneath the caldera. This body is the likely heat source for the geothermal system. The distribution of epicentres in Menengai show more intense, smaller and shallower events are prominent in the centre of the field and

larger, deeper events on the periphery. 95 % of the events recorded having magnitudes less than M_c=2. This implies that the centre of the geothermal system is in a low stress state because stress is being released at a different rate to the surrounding areas with the rift flanks having the highest stress levels.

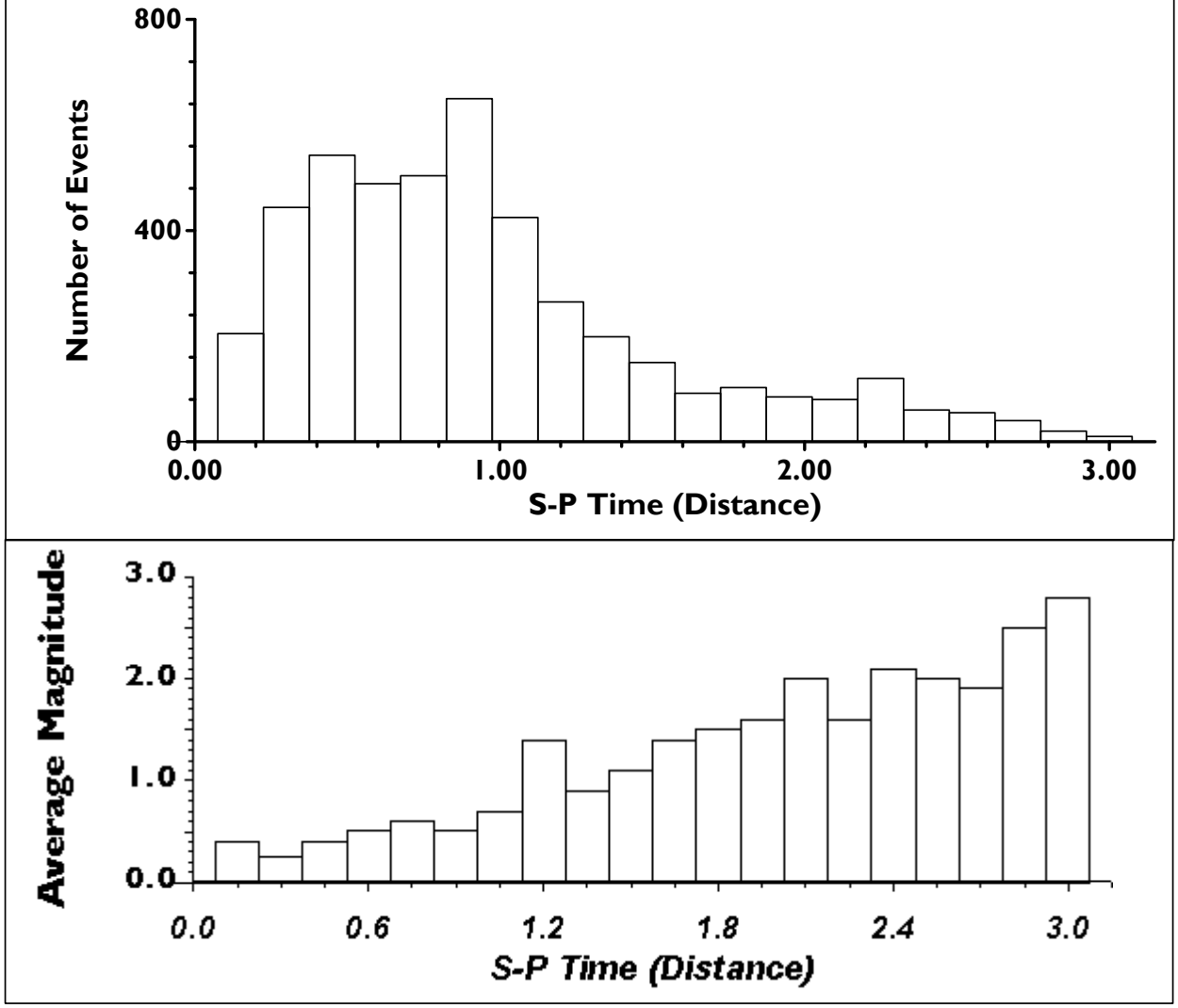

Figure 3.3. Plot of Frequency Vs Distance and Magnitude Vs Distance distribution from the center of the field for recorded events.

This implies that event depth is related to subsurface temperature and hot fluid flow patterns. Depth distribution may also be a reflection of the variation in the brittle-ductile transition depth within the study area as suggested by Meissner and Strehlau, [1982] and Simiyu and Malin [2000]. It seems reasonable to assume that the earthquake cut-off depth of 7 km [Figure 3.4] actually represents the start of the ductile zone. This depth is very important for determining the depth to the heat source, which is expected to be at a depth of about 7 km. outside the network, earthquakes deepen to the Southwest, South and Southeast away from the centre implying a deeper brittle-ductile transition zone.

[Fairhead and Stuarts, 1982] suggest that stress along the rift floor in the Central Kenya Rift [CKR] area is being released by micro-seismic activities in geothermal areas but by larger earthquake sequences along the rift boundary faults. This interpretation is also supported by recent seismic

intensity, magnitude and depth distribution analysis in Lake Bogoria and Olkaria by Young et al, [1994] and Simiyu, [1999]. Their results indicate that seismic activity is more intense in the centre of the volcanic fields [rift axis] where temperature is high, with smaller and shallower events that become larger and deeper on the periphery [rift flanks].

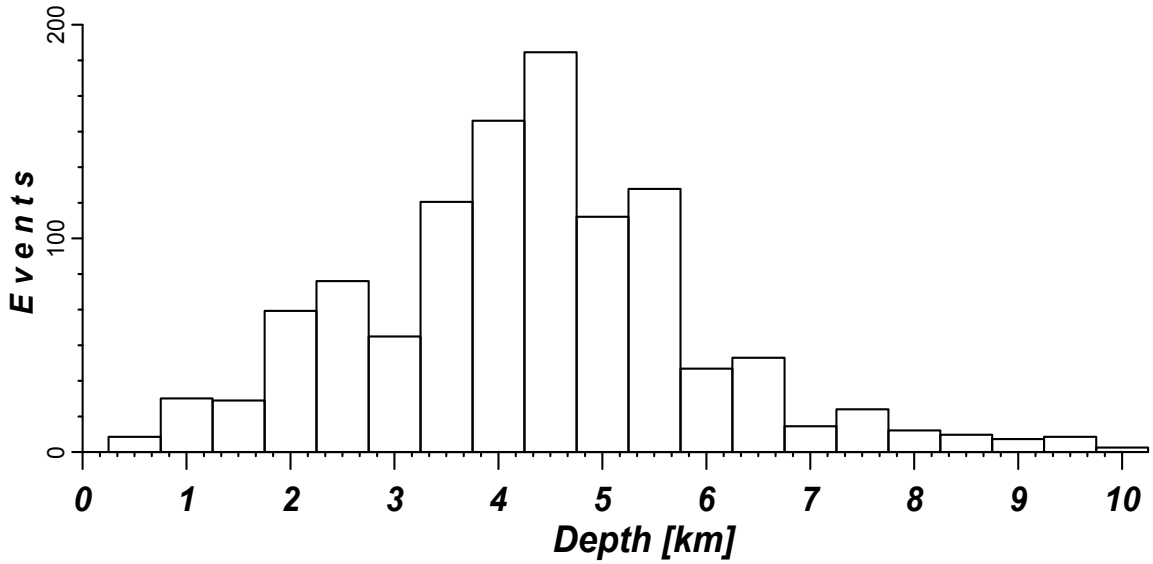

Figure 3.4A. Histogram of earthquake frequency distribution with depth

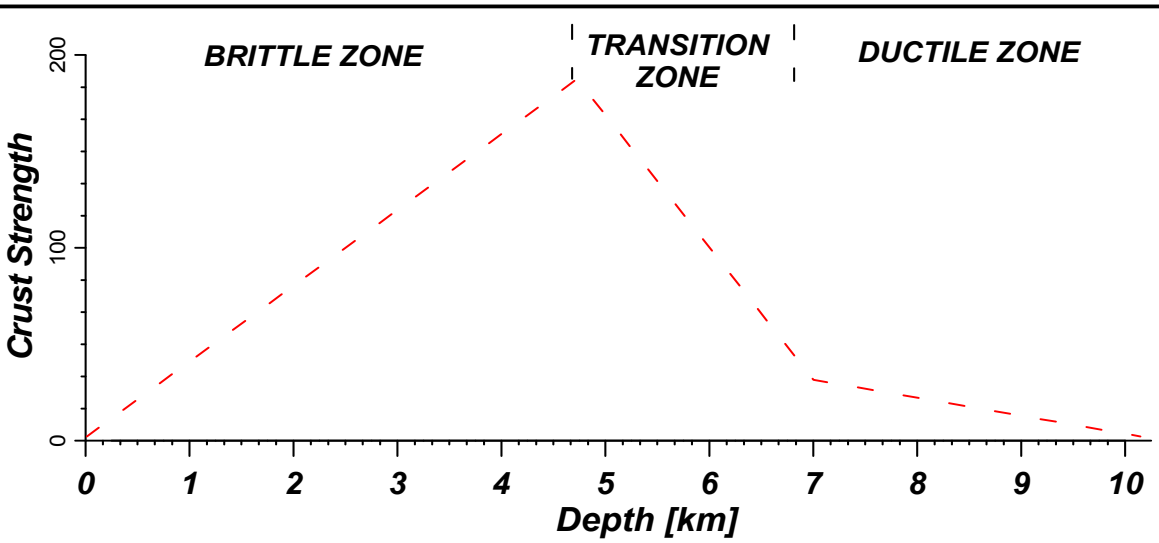

Figure 3.4B. Plot of crustal strength changes with depth showing the Brittle, Brittle-Ductile transition, Ductile Zone

3.2.2 Shear wave attenuation studies

Geothermal fields owe their existence to the presence of molten rock in the crust. The location of these bodies in many fields has been mapped by analyzing regions of high S_v wave attenuation [Sanders, 1984; Ryall and Ryall, 1981; Matumoto, 1971 and Einarsson, 1978].

During routine analysis of seismograms for arrival times and first motion [Simiyu et al., 1998], it was realized that some of the seismograms had diminished S_v wave amplitudes. Spectral analysis showed

that the signals were of low dominant frequencies [less than 3 Hz]. This was taken to imply that the rays were passing through a molten body or less compacted low velocity material near surface. It was therefore necessary to determine the real cause of the low dominant frequency whether it is a source, transmission, instrument or site effect.

There has been continuous monitoring during the last nine months that has objectives to analyze earthquake distribution and properties across the geothermal area. The purpose of this was to evaluate the presence of S-wave attenuating bodies that could constitute heat sources for the geothermal systems. The seismic network shown in figure 1.3 was used to study the attenuation effects beneath the Menengai volcano and the areas surrounding the geothermal prospect.

3.2.3 Event selection

The network records an average of 26 events per day and during this study, we chose events with at least 4 station readings, rms residuals <0.09 sec, horizontal error <1.0 km and vertical error <1.5 km. To avoid bias towards the dense network clusters, the area was divided into blocks of 2 km2 and maximum 2 events taken from each block, thus reducing the total events used to 147. Initially 433 events were selected then we chose seismograms with arrival time pick quality 0 and 1 for amplitude analysis. Maximum peak-to-peak P and Sv wave amplitudes were measured within the range of their expected arrival times on the vertical component record.

Amplitude determinations were done before the events were located to avoid possible bias. 147 events that showed attenuation effects have been used in the final analysis and location of attenuating bodies. 25 of the 147 events shown in table 4.1 have been chosen and are used here to show the ray paths and surface projections of normal and attenuated signals. Figure 3.5 shows the raypaths of events within the study area and outside used to study the attenuation. The outlines of the attenuating bodies beneath Olbanita and within the caldera are projected on the surface in this figure.

The events were grouped according to a scheme that had been developed during this study. This scheme is based on the relative attenuation of the S_v waves and similar to the methods used in the Long Valley caldera by Sanders, [1995] and at Yellowstone national park:

Type I	Severely attenuated S_v waves [S_v/A_p <0.4]. These are events whose ray paths have traversed attenuating bodies.
Type II	Moderately attenuated [0.4< S_v/A_p >0.8]
Type III	Slightly attenuated [0.8< S_v/A_p >1.2]
Type IV	Normal [S_v/A_p >1.2]. These are events whose ray paths have not crossed attenuating bodies

TABLE 3.1: The table is showing the seismic events used to map the location of bodies that cause the attenuation of waves. Also shown are the event location, hypocenter, magnitude, and date and origin time

Event	East	North	Hypo	Mag.	Date	Origin Time
01	172.0	9990.8	09	2.2	03/01/02	21 12 13.721
02	186.1	9978.7	11	2.4	20/05/02	18 23 11.817
03	191.8	9981.7	10	2.6	01/01/02	11 56 45.025
04	189.8	9981.8	08	2.2	13/04/02	02 31 05.312
05	173.4	9990.8	14	2.9	01/02/02	00 06 54.120
06	169.6	9992.2	15	2.6	26/05/02	17 51 32.314
07	172.0	9986.6	11	2.5	10/02/02	20 29 25.070
08	174.7	9981.1	12	2.1	23/03/02	12 05 43.201
09	185.8	9976.8	14	3.2	09/02/02	00 10 09.563
10	181.4	9961.9	09	2.5	08/03/02	16 43 08.774
11	192.1	9951.9	11	2.5	20/04/02	02 20 52.141
12	179.9	9960.0	13	2.2	12/03/02	23 21 33.992
13	174.7	9953.1	14	2.5	28/05/02	07.00 51.886
14	187.0	9963.9	17	2.3	27/01/02	09 52 12.864
15	191.2	9967.0	14	2.8	03/03/02	21 04 34.628
16	186.0	9969.0	17	2.3	13/01/02	13 59 55.332
17	184.5	9954.5	10	2.1	26/04/02	22 49 45.011
18	187.7	9987.0	11	2.3	10/03/02	01 55 23.346
19	185.7	9973.2	15	2.7	03/02/02	01 14 13.574
20	173.6	9969.9	13	2.6	11/03/02	02 43 39.642
21	191.4	9959.2	17	2.9	08/01/02	03 36 59.701
22	177. 9	9951.2	16	2.6	27/05/02	19 27 41.034
23	188.9	9952.8	12	2.7	19/02/02	16 11 22.736
24	192.9	9970.1	18	2.2	21/04/02	08 32 47.178
25	171.4	9970.1	16	2.2	02/05/02	03 25 18.004

3.2.4 Focal mechanism

Focal mechanisms were analyzed manually using patterns of the P-wave first motion for some of the events used in this study. The arrivals were plotted on equal area projections of the upper hemisphere using the take-off angle, polarities and azimuth calculated by hypo-inverse. In this case, only the best-located events with less than 1 km horizontal and 1.5 km vertical error were used. It was also ensured that the events used had clear P-arrival polarities. Seismograms from several events with well-constrained focal mechanisms were compared to test the possibility of source effects being the main causes of attenuation. In particular, two events that occurred at the same epicentre were used and showed that the low amplitudes recorded on some records is not due to source effect.

It is known that shear wave amplitudes may be related to the position of the recording stations relative to the pattern of S_v energy radiating from the earthquake source. Low amplitudes have therefore been in many studies measured near nodal planes. Events with constrained mechanisms are used to determine whether the low amplitudes recorded are due to the position on the S_v radiating pattern or propagation through attenuating bodies. It is therefore necessary to determine whether the attenuation of the S-wave energy could not be related to their positions on the nodal plane and not due to a high temperature related magma body.

The selective attenuation of shear waves indicates that some rays passed through a fluid, probably molten rock. The rays from some events were not as much affected along their travel path since the

origin depth is shallow and thus the seismograms would show normal amplitude. Postulated surface projection of all ray-paths for different event-station azimuth variations is shown in Figure 3.5.

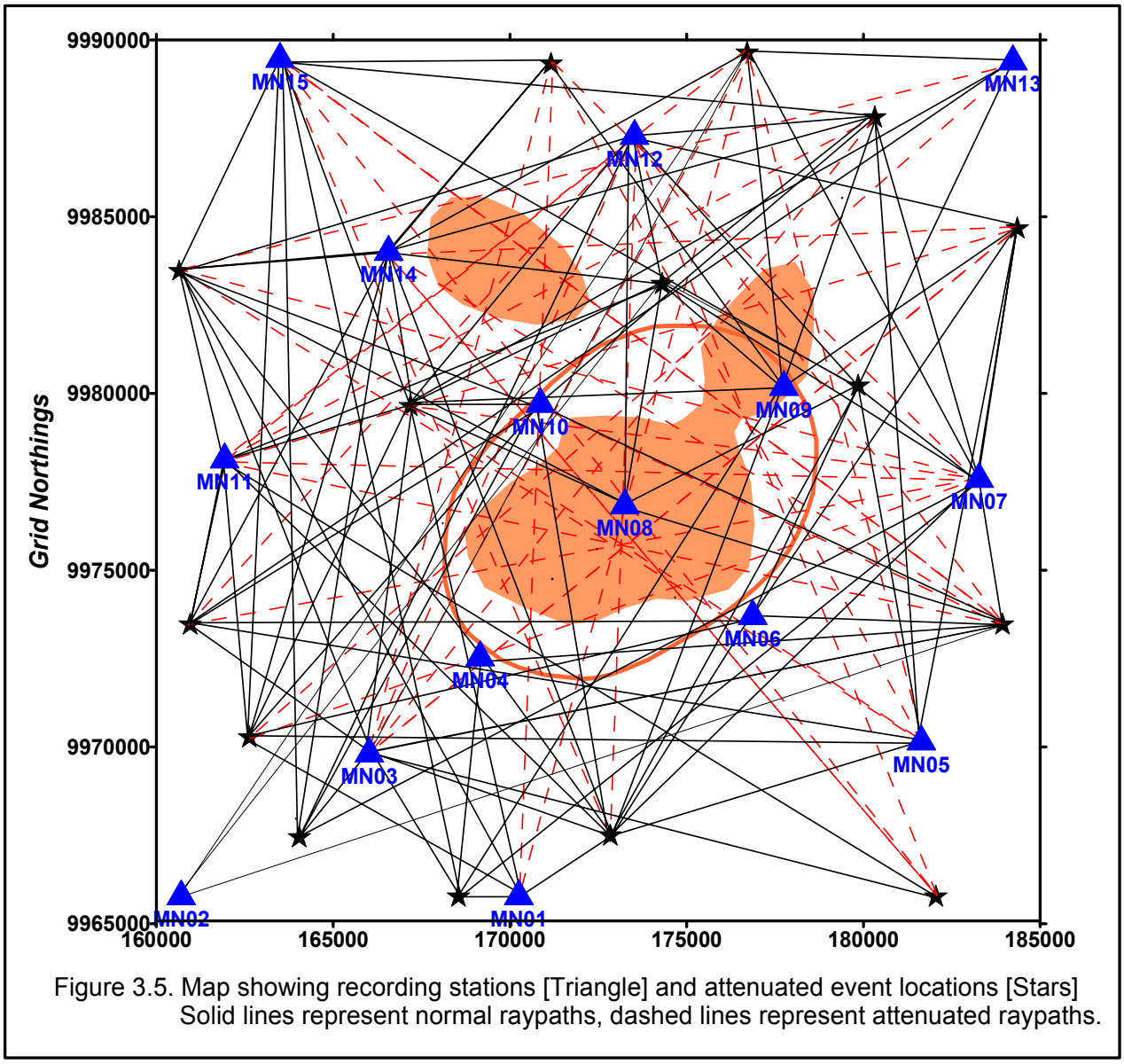

Figure 3.5. Map showing recording stations [Triangle] and attenuated event locations [Stars] Solid lines represent normal raypaths, dashed lines represent attenuated raypaths.

3.2.5 Spectral analysis

It has been shown in other studies [Aki et al., 1977] that the dominant frequency in hydrothermal and volcano-tectonic events if measured close to the source of origin could be related to the source effect and has nothing to do with propagation effects.

To determine the spectral content of events at Menengai required a great deal of attention. The recording was done such that the event to be analyzed must have been recorded close to the source of the signal to avoid mis-interpretation. It was found that events, which appear with low frequency content at a longer distance, are sometime high frequency events at the source. The higher frequencies are removed by attenuation during wave propagation through poorly compacted low velocity rocks. This was mainly evident for events with source that have near surface origin. However there were

recorded deeper events that mostly originated from outside the volcanic area whose ray-paths crossed the area at a depth of more than 7 km. These events had also diminished S-wave amplitude.

During this study, the seismograms showed that a single event had different waveforms and a spectral content that varied from one record station to another depending on azimuth and take-off angle. The seismic signal records were divided into two groups.

I. Show high levels of S-wave attenuation characterized by a weak emergent phases for both the P and S-wave window followed by a phase of near uniform amplitude but at the same frequency. A strong dominant frequency is observed at 2-3 Hz.
II. This group involved seismograms that did not show any attenuation of the S-wave. They had clear P and S wave arrivals. The records have a relatively sharp onset of the signals with a wide range of frequencies. A mixture of dominant and sub-dominant frequencies varied from 2.5 Hz, 3.2 Hz, 3.5 Hz, 5.5 Hz and 8.6 Hz.

3.2.6 Attenuating sources

Geologists have over the years argued for the presence of highly evolved material beneath the Menengai volcanic field. Results from the present study show that there is no evidence for attenuating bodies to a depth of less than 6 km throughout the entire area. All the attenuating signatures come from events that have traversed the area deeper than 6 km. The attenuating bodies could not be fractured rocks saturated with hydrothermal fluids because:

I. It would have been detected throughout the entire circulation system from near surface down to the heat source.
II. It would have had a concave upward shape. The shape of attenuating bodies is concaving downwards consistent with the shape of a magma body.
III. Attenuation would have decreased with depth due to fracture sealing as a result of hydrostatic pressure.

Studies in Olkaria [Simiyu et al., 1998] show that complete sealing of fractures in this area occurs by 4-5 km depth. The picture we therefore get is that of off-shots of magma bodies coming off a main deeper body and penetrating the crust to shallow levels.

3.2.7 Olbanita area magma

The magma body is situated in the Menengai west area directly beneath Menengai volcanic centre. Figure 3.5 show normal and anomalous ray-paths beneath the Menengai caldera and Olbanita area to different stations spread within the area. Analysis of ray-paths through the Olbanita area anomaly shows that the boundary is constrained to the south by rays from the western area to station MN09, MN07 and MN13. The northern boundary is also well constrained by rays to station MN11, MN12 and MN15.

The western boundary is also well constrained. NS ray-path sections through the Menengai caldera show anomalous records at station MN04, MN15 and MN03. Depth to the top of the body is constrained at about 7 km. The Olbanita body peaks directly beneath the area of the postulated buried Olbanita caldera [Mungania, 1999].

3.2.8 Menengai caldera body

Distant events recorded at stations were picked at large spacing intervals in the whole area across the rift stretching from the two rift flanks on the Aberdare range and the Mau escarpment. These stations have been used to monitor deep events from both sides of the rift flanks with ray-paths that seem to

have crossed the rift floor within the Menengai geothermal area. These events have been used to determine the nature of the root of the seismic attenuating bodies beneath the Menengai caldera.

Rays that are projected to have passed beneath the volcanic field at a deeper level have been used to map the magma root. The boundary of the attenuating body is well constrained to the north by deep attenuated and normal ray paths recorded at stations MN11 and MN07 for events from the two adjacent rift flanks. Ray paths recordings at station MN11, MN04, MN06, MN05 and MN07 were used to define the southern boundary. The ray-paths and section show that there is possibly a single deep body that is feeding the shallow magma centres at both Menengai and Olbanita.

Some raypaths north of the caldera and Olbanita area also show some limited effects of attenuation. The presence of these attenuated rays outside the caldera shows that there is a possibility that there could be other attenuating sources outside the caldera structure to the north. To the south of the caldera, there is no sign of attenuation on the recorded events.

3.3 V_s/V_p analysis and reservoir characterization

It is important to know the reservoir condition before committing a field to more expensive exploration drilling. Advance reservoir knowledge will aid in decision making whether to go ahead with exploration drilling and the drilling techniques to be used. This is because a geothermal system life span depends on the dominant fluid phase and management strategies such as injection/re-injection adopted right from the start of extraction. Phase separation, which is a function of temperature, pressure and fluid saturation, produces different classes of vapour plus fluid and vapour only dominated systems. It enhances convection as it removes heat more efficiently than fluid circulation alone while at the same time, accelerating cooling of the heat sources.

It can also cause rapid expansion of the fracture network, thus enhancing permeability. Thus geothermal systems in which phase separation has not occurred persist ten times longer than those with evidence of phase separation [Ito et al., 1979]. For sustainable geothermal power production, it is necessary to know whether phase separation has taken place and the rate as it has implications on reservoir management strategies to be adopted.

O'Connell and Budiansky [1995] have shown that a rock's bulk modulus is affected by the degree of water saturation. The ratio of P-wave velocity to the S-wave velocity [Vp/Vs] increase with pressure increase and temperature decrease from vapour saturated [low pore-pressure] conditions to liquid saturated [high pore-pressure] conditions [Ito et al., 1979].

Studies on these ratios have been contacted in different geothermal fields [McEvilly et al., 1978; Majer and McEvilly, 1979; Combs, 1980; Julian et al., 1996, Simiyu, 1999 and Simiyu and Malin, 2000]. These studies show that water dominated systems such as East Mesa [California], Cerro Prieto [Mexico], and Olkaria North East [Kenya] have high values 1.7-2. These fields also have low reservoir draw down during exploitation. Steam dominated fields such as Geysers, Coso Hot Springs [California] and Olkaria East [Kenya] have low values, 1.5-1.7 and high reservoir draw-down.

Vp/Vs ratios are known to be sensitive to phase changes in geothermal systems. Water and steam filled pore spaces affect both P and S wave transmission differently. Vp/Vs ratios normally increase from vapour saturated [low pore pressure] condition to liquid saturated [high pore pressure] condition. It is also known that S waves are more adversely affected by anisotropy than P waves and thus Vp/Vs ratios are also expected to vary with azimuth. This is important in delineating geological structures with contrasting physical properties within the reservoir. The highest Vp/Vs ratios were mainly for earthquakes outside the caldera and most of them were for earthquakes from the northeast and the western edge of the area. The caldera, Olbanita area and Northwest areas have the lowest average ratios while the far NE, SW, SE and the area outside the caldera have the highest ratios. This implies

that the low ratio areas in the caldera could be having the highest temperature, highly fractured and vapour dominated.

3.4 Hazards analysis

3.4.1 Seismic/earthquake risks

A cumulative magnitude frequency distribution was plotted for the whole area. Earthquakes within the centre of the network with accurate picks [quality 0 & 1] were chosen and checked to ensure that they were not clipped. The cumulative magnitude-frequency relation was plotted for these earthquakes. The magnitude-frequency relation in a particular area obeys the following relation;

$$\text{Log}_{10}\, N = a - bM_c \qquad [5]$$

where, N =the number of earthquakes with a magnitude at least M_c,
a = is related to the length of time under consideration, normalized to 1 year.

Most of the earthquakes with magnitude 1.5 and more are on the periphery of the geothermal field and outside. This implies that stresses within the geothermal field are being released at a different rate to the surrounding areas.

This is consistent with the regional stress analysis studies [Sass and Morgan, 1987] that suggest that the stress along the rift floor is released by micro-seismic activities in geothermal areas but by larger earthquake sequences along the rift boundary faults. This means that the physical-chemical effects of high temperature and fluids-rock interaction have weakened the crust in the geothermal area.

The value of 'b' parameter in the relationship is relatively high at around 1.05. This implies that the reservoir rocks are in a low stress state with less likelihood of a large earthquake occurring within this volume of the rocks within the field than outside. This value is within the limits usually found within geothermal fields [McEvilly, 1985]. The high value implies that there is high heat flow and stress is being released through a high frequency of small magnitude earthquakes.
The corresponding 'a' value is 3.4, which gives a magnitude-frequency expression in equation 5 as; $\text{Log}_{10}\, N = 3.4 - 1.05M_c$. This expression is used to predict the potential for a number [N] of different sized magnitude [M_c] earthquakes occurring within the study area.

Although monitoring of seismic activity in an area requires to be carried out for many years to be able to assess the seismic risk potential, this expression was used to calculate a preliminary risk of potential destructive magnitude $M_c > 5$ earthquake occurring within the geothermal field. The calculations yielded predictions given in table 3.1;

TABLE 3.1: Predicted earthquake risk analysis in the Menengai area

$M_c > 3$	1 event	every 7 months	not felt	not destructive
$M_c > 4$	1 event	every 6.3 years	slightly felt,	not destructive
$M_c > 5$	1 event	every 71 years	moderately felt	destructive
$M_c > 6$	1 event	every 794 years	strongly felt	very destructive
$M_c > 7$	1 event	every 9,000 years	extreme	disastrous

This shows that there is no likelihood of a destructive magnitude $M_c > 5$ earthquakes occurring within the study area. This is because most of the energy is being released through the occurrence of many small earthquakes.

3.4.2 Volcanic eruption risks

Menengai area is located within a region of a triple rift junction that is considered to overly a mantle plume (Burke & Dewey, 1973). The surface is comprised of several eruptive volcanoes with caldera collapses and concentrations of tectonic grid faulting (block and fissure faults). These are characteristic of extension faulting associated with spreading at crustal boundaries. Such areas are tectonically unstable and are thermally privileged with huge supply of magma reservoirs.

Our study shows that a large magma body underlies the Menengai area that extends from within the caldera to the NE walls and the Olbanita area. That means that in the event of an eruption, it might not be confined within the existing caldera. Shear wave attenuation and the brittle –ductile transition depth show that the molten material is at a very shallow depth of about 6 to 8 km. At such a depth, any new injection into the magma chamber from the mantle will lead to volcanic eruptions. Velocity ratio analysis shows that this is a very strong heat source, which is unlikely to be cooling.

Geochemical analysis by Omenda [1998] show that the magmatic materials of this volcanic centre [including Olkaria, Longonot and Suswa] is highly evolved and is therefore bound to be explosive thus its ejected material cover expansive areas. The fact that it is located within a triple junction means that there is a rich supply of mantle derived magmatic gases that are bound to be very poisonous.

Considering the high human population, commercial activities, farming and animal conservation within the area. There is need to have a continuous monitoring of the magma activities beneath the area by seismic methods and gas chemistry. Such monitoring will form a basis for an early warning system.

4. DISCUSSION

The distribution of epicentres in Menengai show that more intense, smaller and shallower events are prominent in the centre of the field and larger, deeper events on the periphery. Seismic activity gaps mapped within the Menengai prospect mark zones of hot magma intrusions that have raised the temperature.

Ray paths from deep events through the centre of the field show that there is a deep attenuating body directly beneath the central part of the caldera structure and taking on geometry with a NE-SW major axis that is consistent with the structure. At shallow depth, the location of individual bodies occur along NNW-SSE and NE-SW trends that could be controlled by the Nyanza rift and Kenya rift axial fault structures along which there has been magma injection. This shows very clearly that the arcuate nature of structure within the Menengai Volcanic Complex can be attributed to caldera-related activities and Nyanza rift. There could also be limited influence from strike slip fault interaction with the rotation of regional stress fields. The lateral extent of the heat sources for the geothermal system at Menengai could be confined within the caldera at deeper level.

The developed Vp/Vs ratios show the caldera areas to have lower velocity ratio formations with deeper horizons suggesting high temperature, low pore pressure and vapour dominated system A decrease in P-wave velocity with constant S-wave velocity results from a change in the compressibility of the rocks. Intense fracturing of the upper crust in areas of high heat flow is a plausible explanation based upon analysis of these data. The values are higher to the SW, SE, East, NE and NW because it could be a possible recharge zone for the system. This zone is water saturated with less steam and high water saturation pressures within the reservoir.

Theoretical estimates of the Vp/Vs anomalies that would be caused by differences in pore-fluid phase, temperature, and pore pressure, for rocks with different porosity. For zero porosity, the Vp/Vs ratio

equals that of the rock matrix, and the effects of temperature and pressure are much too small to contribute significantly to the observed anomaly. At finite porosity, the compressibility of the pore fluid strongly affects Vp/Vs. The largest effect is caused by the contrast between liquid and steam. On the other hand, the dependence of vapour's compressibility on temperature is also important. The Vp/Vs anomaly is caused probably by vapour domination. This means that the reservoir is vapour rich in its natural state, while the surrounding rocks of the area outside the inner caldera, especially to the south, NE and west is not. This means that the reservoir has a Vp/Vs anomaly before exploitation. The magnitude of this anomaly can be explained entirely by the difference between water vapour in the reservoir and liquid water in the surrounding rocks.

We have therefore been able to map in Menengai a low-pressure/high temperature steam dominated reservoirs region and a high-pressure water dominated reservoir region.

5. CONCLUSIONS

This study has been able to show that there exists a high temperature geothermal system within the Menengai prospect area that can be exploited to generate electricity. Figure 5.1 shows a summary of results from this study and proposed sites for drilling of the production wells.

5.1 The heat source

This study has mapped the spatial seismic intensity, hypocenter distribution, event magnitude, depth of clusters with time and shear wave attenuating structures. All these results, combined with gravity and magnetics show that a large high temperature body at a depth of at least 6.5 km beneath the caldera and 7.5 Km beneath Olbanita area underlies the Menengai volcanic area.

5.2 Reservoir size, fluid phase, and characteristics

Three-dimensional seismic travel-time tomography of the prospect shows a strong Vp/Vs anomaly that corresponds to the most highly intruded part of the field. This anomaly indicates low pore pressure and dry conditions caused by boiling of pore water due to limited fluid inflow. The low values correspond to a decrease in P-wave velocity due to high heat flow, fracturing of rocks and steam saturation.
The reservoir is mainly steam dominated in the central caldera area, the immediate NE and part of the NW within the caldera. It is water dominated to the MNW at Olbanita. The geothermal reservoir area that is based on the 1.71 velocity ratio contour (Figure 5.1) is about 80 km^2 and the main productive zone would be in the depth range of 1200-2500 m.

5.3 Recharge for the system

A major water-dominated area has been mapped mainly to the NE from the Aberdare escarpment and a minor one to the NW of the caldera system along the rift axis. Other minor recharge regimes are from the SW, SE and west. These water-dominated areas represent the cold fluid recharge corridors for the geothermal system.

5.4 Sitting of wells

Figure 5.1 show three proposed drill sites. One is within the caldera, in the low velocity ratio zone and above the mapped high temperature heat sources. The second one is at Olbanita where a buried caldera has been inferred [Mungania, 1999].And the third one is on the caldera wall to the NE but has been sited outside the rim in order to validate the caldera control on the geothermal system. Drilling of these wells will validate the method and give a clear indication of the reservoir size and heat source

estimates. This study suggests that the high temperature system is controlled by the calderas and any future development should be confined in the area defined by them.

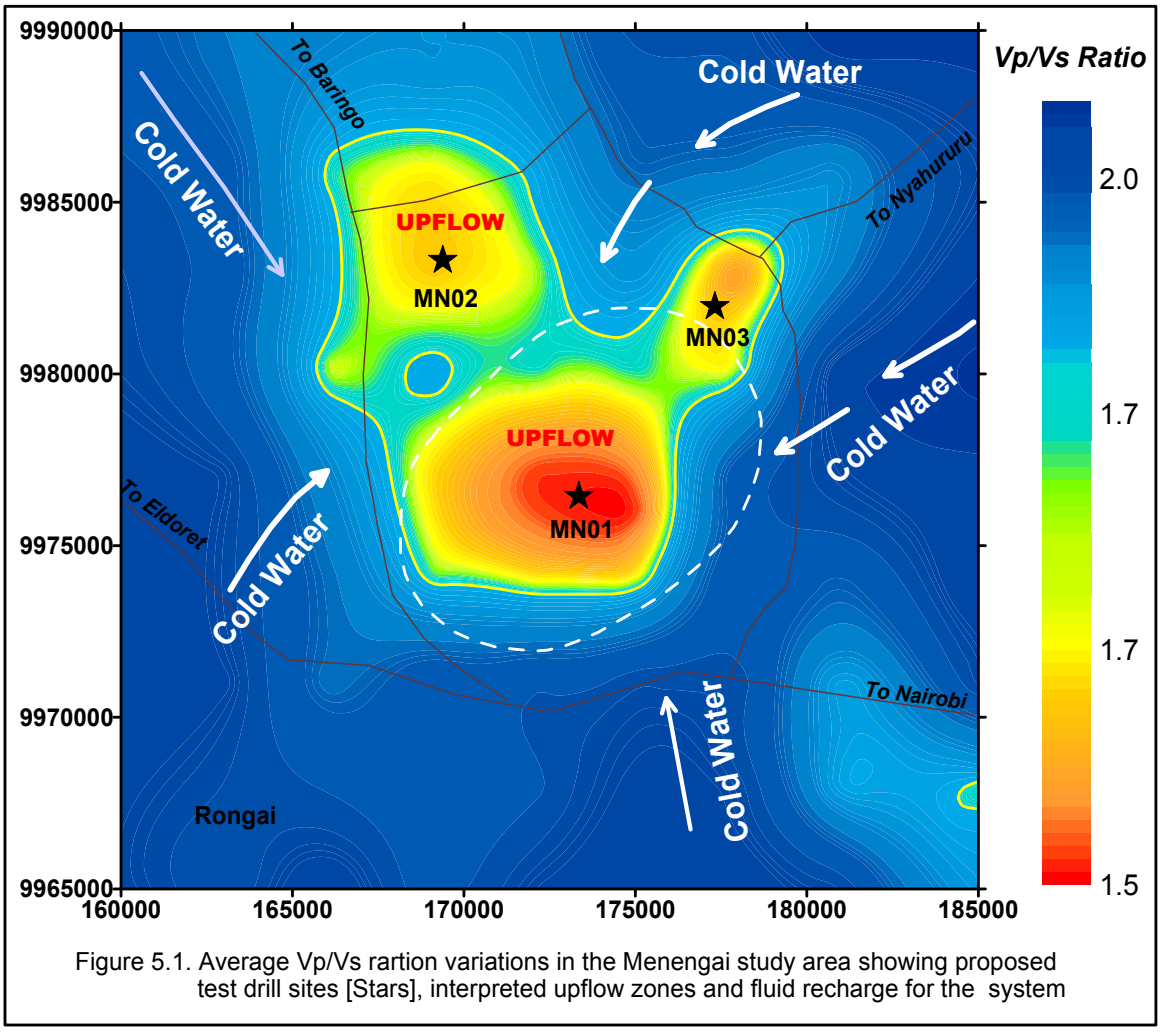

Figure 5.1. Average Vp/Vs rartion variations in the Menengai study area showing proposed test drill sites [Stars], interpreted upflow zones and fluid recharge for the system

5.5 Earthquake risk analysis for the area

The value of 'b' parameter in the relation is high around 1.05, which is within the limits found in geothermal fields. A high value implies that there is high heat flow and stress is being released through a high frequency of small magnitude earthquakes. This leads to reservoir rocks being in a low stress state with less likelihood of a large earthquake occurring within this volume of rocks. The magnitude thresh-hold for this area is M_c =1.4. This shows that there is less likelihood of having a large destructive earthquake within the study area.

5.6 Volcanic risk assessment

Heat source analysis shows the existence of a high temperature molten body directly beneath the Menengai volcanic centre. During this study, there has been no direct monitoring of magma activity. However, the presence of this large magma body beneath a central volcano such as Menengai is a major risk. This volcano has also a unique volcano-tectonic origin [plume driven triple junction], which means that it can release large volumes of ejector and mantle derived poisonous gases.

The risk assessment for this area is made in view of the expansion in the area's rich agriculture, wildlife conservation [Nakuru Park] and commercial activities in Nakuru town. The influx of people into the area surrounding the volcanic centre makes them directly exposed to these high potential volcanic hazards. Since we cannot stop a volcanic eruption but we can predict it, there is need to have a volcano-seismic risk-monitoring program for the area. This will be important for continuous resource evaluation and risk monitoring that can form a basis for an early public warning system

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GEOPHYSICAL SURVEYS OF HIGH TEMPERATURE FIELDS – A CASE FOR OLKARIA AND MENENGAI GEOTHERMAL FIELDS, KENYA

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ABSTRACT

The occurrence of surface manifestations in the country's rift valley regions encouraged various people to carry out various geophysical investigations to establish the subsurface structure with a view of establishing its geothermal potential. Various levels of success have been achieved with each of the techniques. The activities resulted in drilling geothermal wells at Olkaria. Eburru and Menengai Geothermal fields. Power plans have been commissioned at Olkaria and Eburru. Changes in technology have seen the deployment of modern geophysical techniques that included transient electromagnetics (TEM) and magnetotellurics (MT) which made it possible for shallow and deep conductors to be accurately imaged and thus more accurate geothermal models developed. This article provides a general introduction to the most important methods of geophysical exploration that have been employed at both Olkaria and Menengai Geothermal fields, Kenya, the results obtained and recommendations made.

1. INTRODUCTION TO GEOPHYSICAL METHODS

For earth scientists, a wide range of geophysical, geo-chemical and geological surveying methods exist for geothermal energy investigations. For each of these methodologies, there is a typical physical/chemical property to which the technique is sensitive to. For geophysics, location of a geothermal reservoir may be determined by use of seismic velocity, electrical conductivity, magnetic or/and gravity methods. Effects of exploitation of a geothermal reservoir can be monitored using micro-seismic, micro-gravity, geo-chemical and temperature/pressure techniques. Though these may require complex methodology and relatively advanced mathematical treatment in interpretation, much information may be derived from simple qualitative assessment of the survey or monitoring data. Often many of these methods are used in combination to obtain a plausible inference. At the interpretation stage, ambiguity arising from the results of one survey may often be removed by consideration of results from a second or third survey method. A wide range of geophysical surveying methods have been employed for exploration for geothermal energy in Olkari and Menengai, as well as the monitoring of geothermal reservoirs under exploitation in Olkaria (Ndombi, 1981; Mariita, 1995; Simiyu and Keller, 1997). The type of physical property to which a method responds dictates the application. In both fields, these methods include seismic, gravity, magnetics, electrical resistivity, Transient Electromagnetic (TEM) and Magnetotelluric (MT). The end results are geared to obtaining information on whether a resource exists and propose sites for exploratory drilling, and develop a geothermal conceptual model of the area.

2. GEOPHYSICAL SURVEYS IN OLKARIA GEOTHERMAL FIELD

Olkaria Geothermal Field covers an area of about 256 km2 divided into seven fields based on structure and reservoir characteristics (Figure 1). These are; the East production field (EPF), North East (NEF), Olkaria Central (OCF), Olkaria West (OWF), Olkaria South East (OSE), Olkaria South West (OSW) and Domes (Olkaria 4). This is the first geothermal field to be developed in the Kenyan part of the East African Rift Valley where over 150 wells have been drilled. The field has been assessed to have total potential of 500 MWe. Drilling and reservoir studies have been going on for the last 30 years and research has reached a stage where the system characteristics are well understood. A conceptual reservoir model for the Olkaria geothermal field has been developed, and is reviewed from time to time as new data is obtained. Over the years, it has been possible to strengthen the model and add confidence to the understanding of the characteristics of the field and reservoir. Much of this information has been collected by use of Geophysical methods.

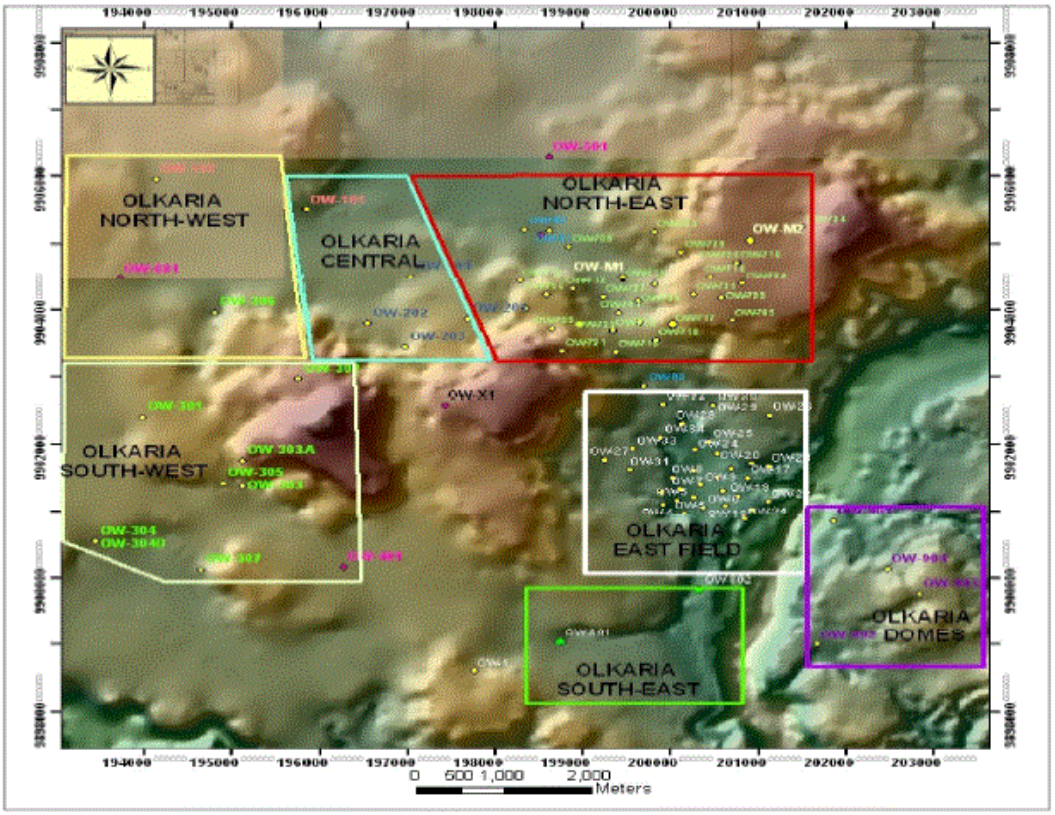

FIGURE 1: Sectors of the Greater Olkaria Geothermal field

2.1 Previous works

Exploration efforts for Geothermal Energy in Kenya before the 1970s is discussed in detail by Tole (1996) and JICA (1983). In the early fifties two wells (X1 and X2) were drilled at Olkaria (Figure 2). The results were not encouraging. In 1960's, more geophysical work was carried out between Lake Bogoria and Olkaria under the UNDP project. They identified several areas of low resistivity and positive gravity anomalies associated with Quaternary volcanic complexes. These areas that were found suitable for geothermal exploration were found to be associated with surface manifestations and they have been targets for detailed geothermal exploration.

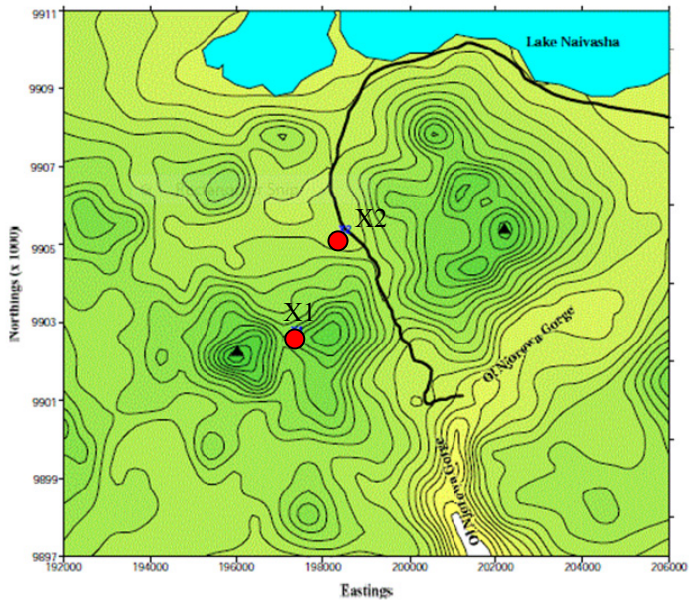

FIGURE 2: Location of the first 2 geothermal wells (X1 and X2) to be drilled in Kenya

A wide range of geophysical surveying methods has been employed at Olkaria over the years including seismology, resistivity, gravity, magnetics and electro-magnetics (Mwangi, 1984). Various levels of success have been achieved with each of the techniques.

2.2 Resistivity measurements in Olkaria geothermal field

At Olkaria, direct current (DC) resistivity methods have been used for many years to carry out reconnaissance mapping, location of faults for drilling targets and to define the boundaries of geothermal reservoirs. Interpretation of DC Resistivity data from the Olkaria geothermal field shows that the low resistivity (less than 20 Ωm) anomalies at depths of 1000 masl that define the geothermal resource boundaries are controlled by linear structures in the NE-SW and NW-SE directions. The near surface difference in resistivity is caused by contrasts in the subsurface geology. Drilled wells show that the low resistivity anomalies at 1000 masl define a geothermal system with temperatures in excess of 240°C. Some of the high resistivity regions coincide with recharge areas associated with NE and NW trending faults that act as conduits for cold water flow from the Rift Valley scarps. The geothermal fluid up-flow zones occur at the intersections of these regional faults in the vicinity of a heat source.

In recent years, Transient Electromagnetic (TEM) and Magnetotelluric (MT) have been favoured against the DC sounding methods. This was mainly due to logistical considerations and the depth of penetration.

Transient electro-magnetics (TEM)

Of the DC resistivity measurements, the Schlumberger array was the most preferred configuration for good vertical resolution at depth down to 1 km. However due logistic constraints this technique was abandoned and TEM method was introduced in the mid-1990s. The TEM method serves the same purpose as Schlumberger but it gives better resolution at depth. The depth of penetration is dependent on how long the induction in the receiver coil can be traced in time before it is drowned in noise. However, for the Olkaria situation the depth of penetration of TEM is limited to about 700 m depth depending on the resistivity structure. This is similar to that of Schlumberger soundings with a maximum distance of 3 km between the current electrodes.

Over one hundred TEM sounding stations have been covered in the greater Olkaria area. The method involved the passage of a large current through an ungrounded loop of wire measuring 300mx300m square. An EM receiver at the centre of the square measured the ground TEM response. The data was processed, inverted and produced in apparent resistivity plots in form of contours maps at various elevations. The data shows that the low resistivity anomalies are controlled by linear structures in the NE-SW and NW-SE directions and that the geothermal resource is confined within an area with a low resistivity value of less than 15 □m at an elevation of 1400 Masl (Figure 3).

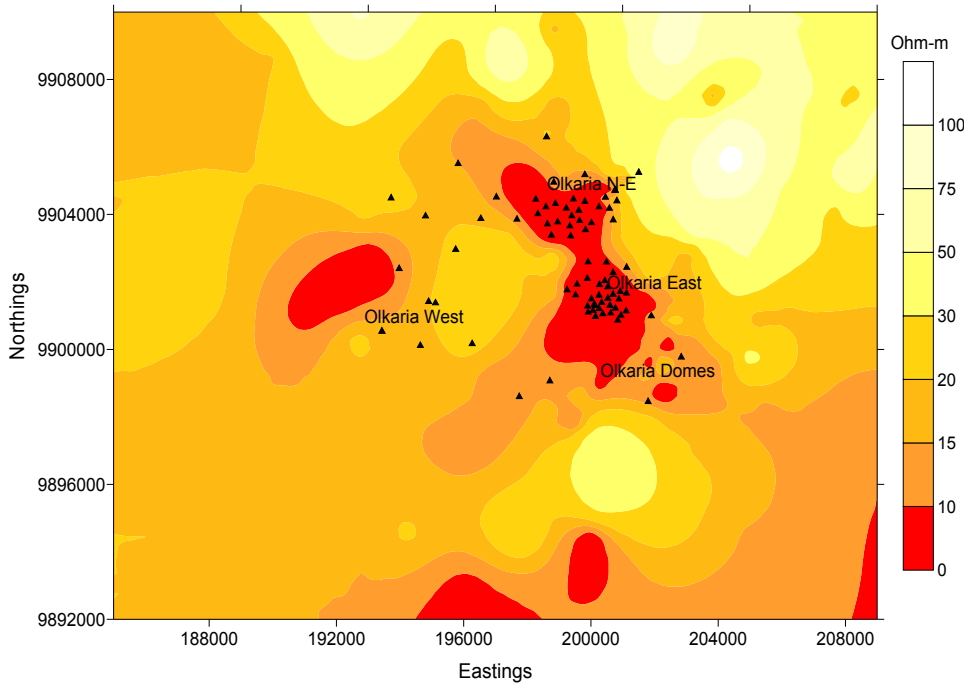

FIGURE 3: Resistivity distribution at 1400 masl from TEM measurements at Olkaria

The resistivity is lower around Olkaria West Field (OWF) than the area around East (EPF) and North East Fields (NEF). The near surface difference in resistivity is caused by contrasts in the subsurface geology. An altered thick surficial layer of pyroclastics occurring in the Olkaria West field is the cause of the near surface low resistivity in the field (Omenda, 1994, 1998). A thicker layer of pyroclastics up to an elevation of 1500 masl covers the Olkaria West area. Drilled wells show that the low resistivity anomalies at 1000 masl define a geothermal system with temperatures in excess of 240°C. Some of the high resistivity regions coincide with recharge areas associated with NE and NW trending faults that act as conduits for cold water flow from the Rift Valley scarps. The geothermal fluid upflow zones occur at the intersections of these regional faults in the vicinity of a heat source (Onacha, 1989, 1993).

Magnetotellurics (MT)

The magnetolluric resistivity technique is the latest method that has been acquired for geothermal energy exploration in Kenya. The method uses natural current fields induced in the earth by time variations in the earth's magnetic field. Both the electric and magnetic fields are measured. Due to this, the technique does provide more information on subsurface structure, as its depth of penetration is much larger than TEM. The depth is dependent on frequency and the resistivity of the subsurface. Consequently, depth penetration increases as frequency decreases and the apparent resistivity varies with frequency. The calculation of the apparent resistivity for a number of decreasing frequencies thus provides resistivity information at progressively increasing depths.

Though the MT method has the capability for probing several tens of kilometres, the data may be affected by galvanic distortions manifesting as frequency-independent static shifts of the apparent resistivity curves when small-size surficial heterogeneities are present, as can be expected in the weathered and volcanic-covered basement terrain of Olkaria. The TEM technique provides a logical shallow-depth (< 1 km) compliment to MT and also serves for correction of MT static shifts. The combined TEM-MT approach has therefore been selected as the technique with optimum potential in Olkaria. Preliminary analysis of MT data from the region suggests the presence of significantly enhanced conductivities below Olkaria (Figure 4); however, no quantitative modelling of the data has been undertaken and the actual physical parameters of the suggested zone of enhanced conductivities are not known.

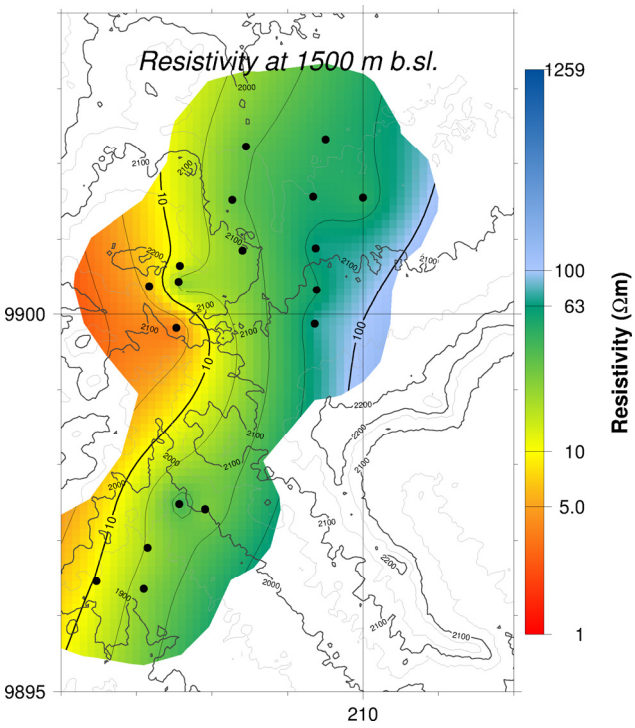

FIGURE 4: Resistivity distribution at 1500 mbsl from MT measurements at Greater Olkaria Area

2.3 Potential field measurements in Olkaria geothermal field

Gravity survey of the shallow crust beneath Olkaria indicated a volcanic zone of three layers that appears down-faulted in the Olkaria West area and showing low density (Ndombi, 1981). Gravity further revealed the presence of dense dike material along the Ololbutot fault zone. However, it is now known from geology that the N-S Olkaria Hill fault marks a major east-dipping fault that has down-thrown the Mau formation to more than 3 km in the eastern area. The developed eastern graben was later in-filled with late Pleistocene - Holocene volcanism that was dominated by trachyte, basalts and rhyolite lavas and relatively minor pyroclastics, thus resulting in higher gravity (Omenda, 1994, 1998). A Bouguer anomaly map using a density of 2.5 g/cm^3 (Figure 5).

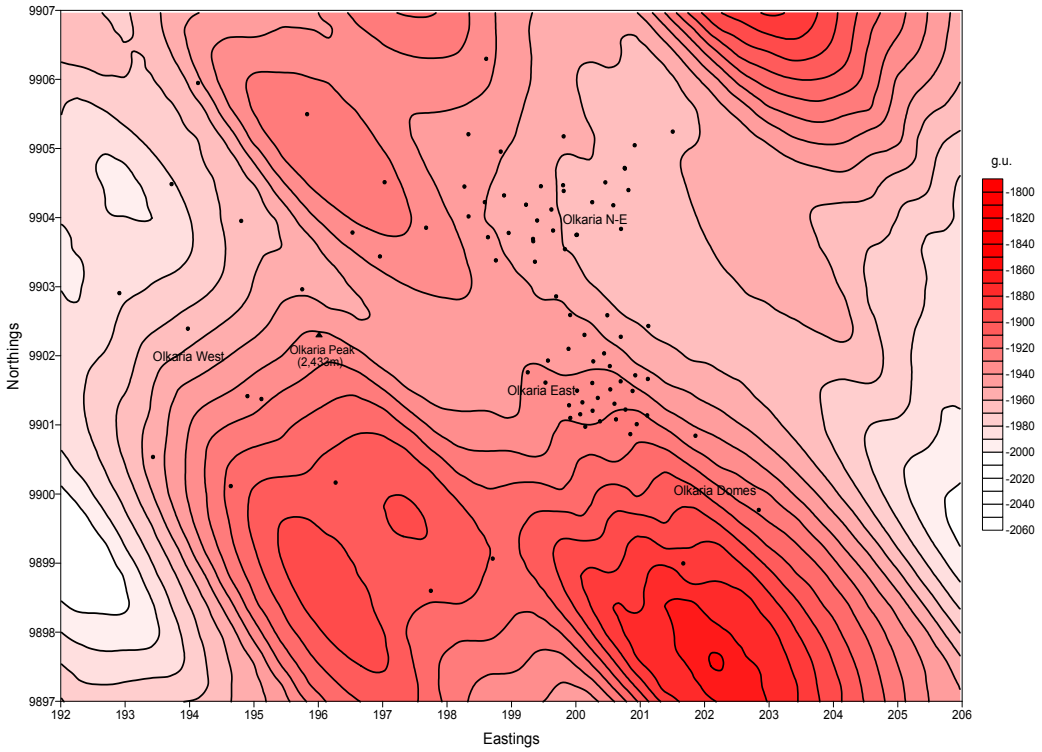

FIGURE 5: Directionally filtered gravity data of the greater Olkaria geothermal field. Note the NW-SE trend of the gravity anomaly through Olkaria, corresponding to the regional geological structure in the central rift segment. A low gravity anomaly occurs in the west with towards the Mau escarpment. Another gravity low occurs in the eastern Olkaria Domes area and extends to Longonot volcano.

In Olkaria, both ground and aero-magnetic data have been used to investigate the presence of a geothermal resource in combination with gravity. From the aero-magnetic maps several of the anomalies can be clearly correlated with surface expressions of volcanism such as craters, domes or cones, localised basaltics lavas or plugs (Figure 6). From these maps most of the volcanic centres tend to lie in areas with magnetic highs (positives). Sometimes a superimposed magnetic low (negative) exist; but this is generally weak or zero.

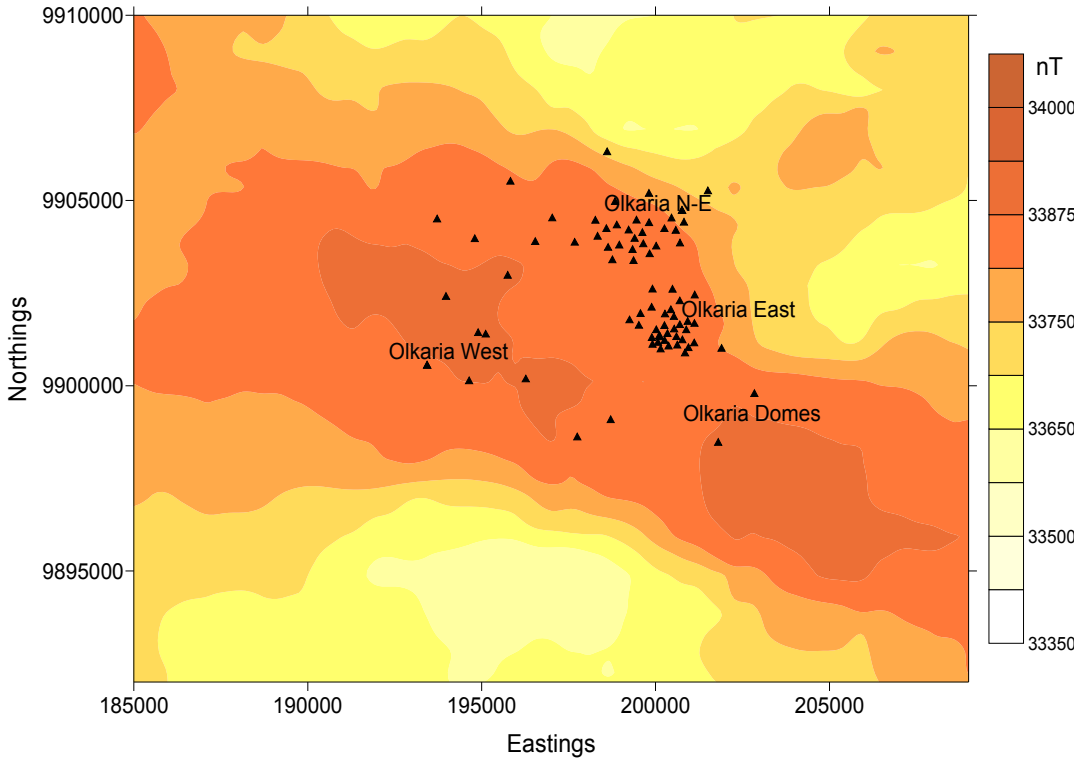

FIGURE 6: Total magnetic intensity over Olkaria and surrounding areas

Bhogal and Skinner (1971) analysed residual draped aeromagnetic data flown at 300 m above ground surface within the Olkaria area. Their results showed that the central geothermal area had a positive magnetic anomaly trending NW-SE. This anomaly is superimposed on a broad regional negative anomaly that covers the entire southern Lake Naivasha region and corresponds to normally magnetized rocks. The positive anomaly oriented NW was interpreted to occur in a demagnetized zone corresponding to the main heat source with a temperature above the curie point of magnetite (575°C) and a depth of about 6 km. A minor trend in the magnetic anomaly is in a NE-SW direction corresponding to the Olkaria fault zone.

2.4 Seismic measurements in Olkaria geothermal field

Both passive and active source seismic studies have taken place in Olkaria. These were contacted by the United States Geological Survey (Hamilton et al., 1973) using an eight-station network. They located 87 events of magnitude 2 and less restricted mainly within a 4 km wide zone parallel to the NS trending Ololbutot fault zone. Time distance plots indicated that the area is characterized by a three layer volcanic sequence of about 3.5 km thick underlain by a granitic layer with a P-wave velocity of 6.3 km/s.

A 2-year seismic monitoring program was carried out in Olkaria between 1996 and 1998 (Simiyu 1999; Mariita et al., 1996). The main objectives were to carry out analyses of the wave parameters so as to determine earthquake location and to relate these locations to the presence of structures that allow reservoir fluid flow patterns. During this period more than 4800 local earthquakes originating within the study area were recorded (Figure 7).

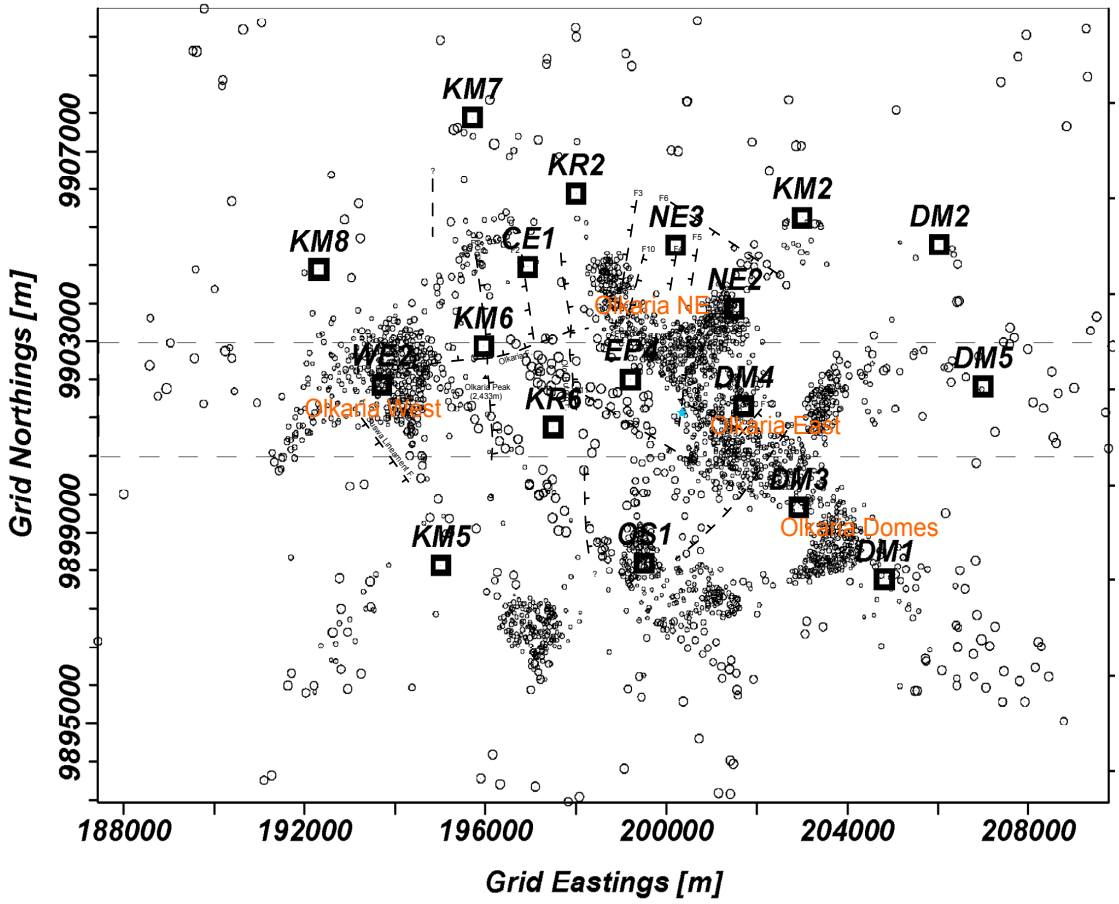

FIGURE 7: Micro-earthquake event location around Olkaria. Thick square boxes represent the locations of seismic receivers

The results show that seismicity is more intense in the centre of the field where temperature is high, with smaller and shallower events. On the periphery and outside of the field, where drill holes show low temperature, events are large and deeper.

Outside of the geothermal field, earthquakes deepen to the northwest, north and northeast away from the geothermal system. Seismic gaps were mapped within the Olkaria field (OWF and NEF) and found to mark zones of hot magmatic intrusions that have raised the temperature above 450°C. Anomalous low S wave amplitudes beneath the young volcanics of the Olkaria geothermal area were determined and then back projected to map the position of attenuating anomalies in the region by using source-receiver ray path overlap density. It was possible to image an attenuating (possible heat source) body directly beneath the Olkaria geothermal area that also showed a gap in seismicity above it.

2.5 Integration of geophysical data for Olkaria geothermal field

Many of the geophysical methods used at Olkaria have aided in understanding reservoir conditions. The Olkaria geothermal system is closely associated with the Quaternary silicic volcanism in the segment of the rift which was active from late Pleistocene to Holocene. Results from seismics and magnetics indicate the presence of attenuating bodies at 6-10 km depth which are also demagnetized within the Olkaria geothermal field thus, corroborating geological. The seismic data is also in agreement with recent geological models that indicate that the bodies are discrete; fault controlled and experienced different evolutionary histories.

The gravity survey of the shallow crust beneath Olkaria shows a general gravity high trending NNW and in line with the regional geological structure in the area. However, there are local highs that trend NE in line with the recent fault trends. These local gravity highs are interpreted as dike intrusions which are heat sources in some areas while in others, e.g., along the Ololbutot fault zone they act as hydrological barriers between fields. The occurrence of magnetic and gravity anomalies at the intersections of NE and NW rift faults, is an indication of distinct near surface heat sources controlling the reservoir characteristics of the geothermal systems.

Micro-earthquake monitoring for epicentre and hypocentre locations show that Olkaria is a high temperature geothermal field characterized by a relatively high level of micro-earthquake activity. The Olkaria West area has shallow high frequency events and deep low frequency events. The shallow events occur at the intersection of the Olkaria and Suswa faults. The shallow events are associated with an up-flow zone in Olkaria west. Shallow high frequency tectonic events and deep low frequency volcano-tectonic events occur within the EPF and NE Olkaria along a NW-SE linear trend. The shallowest high frequency events related to shallow fluid movement and volcano-tectonic events occur at the intersection of the Ololbutot fault zone and the Olkaria fault. Deeper to medium depth events occur along the Ololbutot fault zone and they are interpreted to be due to fluid movement at depth. The Ololbutot fault zone has also been modelled as a recharge zone from resistivity, down-hole temperature measurements and geochemical signatures. The deep events occur away from the up-flow zones and signify tectonic movements along the main faults.

At Olkaria, the resistivity methods have been the most consistent and extensively used geophysical method with very good results. Initially the DC resistivity type was employed. However, this has been abandoned in preference to TEM and MT methods due to the efforts required to penetrate depths greater than 1 km. Resistivity methods have been capable of mapping the reservoir itself and that makes them more attractive to use.

An integrated E-W cross sectional plot through Olkaria geothermal field incorporating gravity, DC, TEM and MT data (Figure 8) shows high resistivity and low gravity anomalies in the western escarpment which is interpreted as the recharge for the geothermal system. However, a deep low resistivity occurs in close proximity of Olkaria Hill and is postulated as the heat source for the Olkaria West geothermal system. A major dike intrusion is modelled to occur along the Olkaria Hill fault and the zone shows as a high resistivity zone.

3. GEOPHYSICAL SURVEYS IN MENENGAI GEOTHERMAL FIELD

3.1 Previous works

The Menengai-Olbanita area is located in a region of intra-continental triple junction where the Nyanza rift joins the Kenya rift and is considered to overly a mantle plume. The surface is comprised of several eruptive volcanoes with caldera collapses and concentration of tectonic grid faulting. The Menengai complex is dominated by a central volcano with a large caldera of about 12km in diameter. The Olbanita volcanic complex consists of the remnants of an old caldera 8 km north of Menengai. The surface in both areas is covered by mainly pyroclastics, tuffs and minor occurrence of trachyte and basalt. Although there are few surface manifestations, shallow boreholes in this area have encountered steam at depths of about 70 m. Pyroclastics and tuffs cover the area outside the caldera. The floor of the caldera is covered by post caldera collapse trachytes. The northern rim of the caldera is cut to the west by NS trending faults, which form a small graben, and to the east by NNE trending faults that form the Solai tectono-volcanic axis. Geothermal manifestations occur on the floor of the caldera and along the NS trending faults (Dunkley et al., 1993). The Menengai Geothermal Field has a rugged terrain and very few geothermal manifestations, which makes it quite difficult in terms of exploration using both geophysical and chemical methods. The few geothermal manifestations present

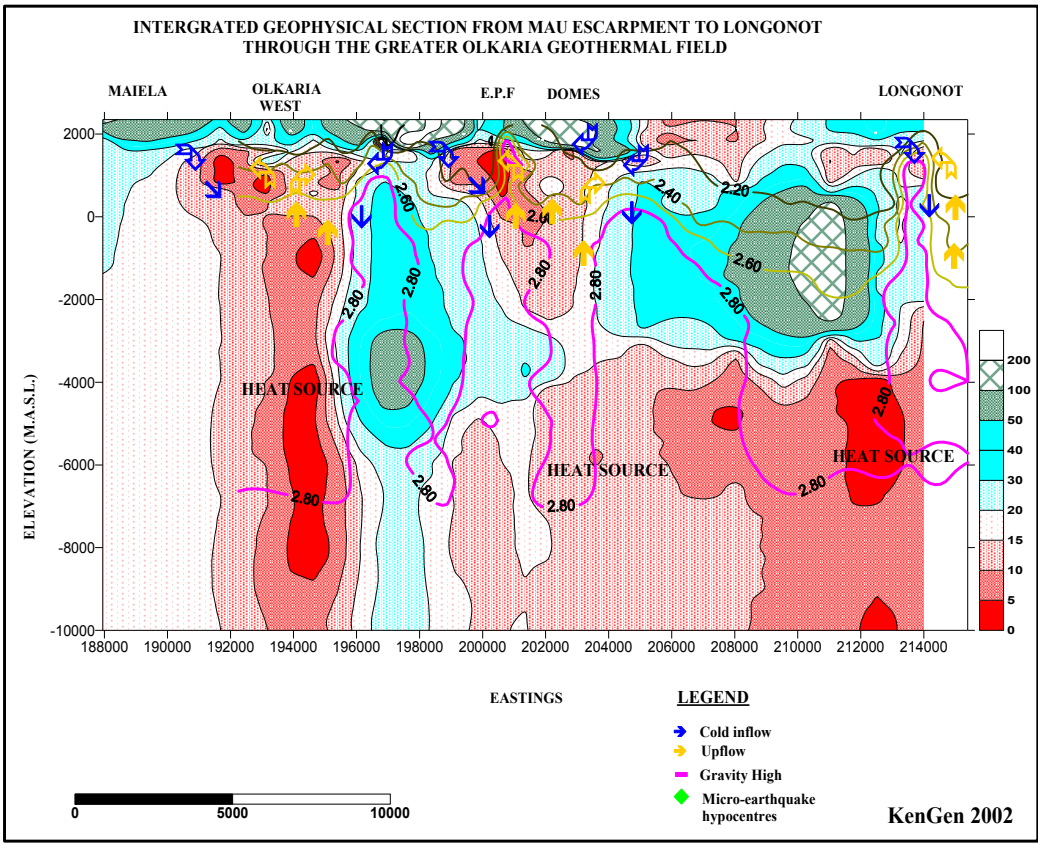

FIGURE 8: Integrated geophysical model across Olkaria

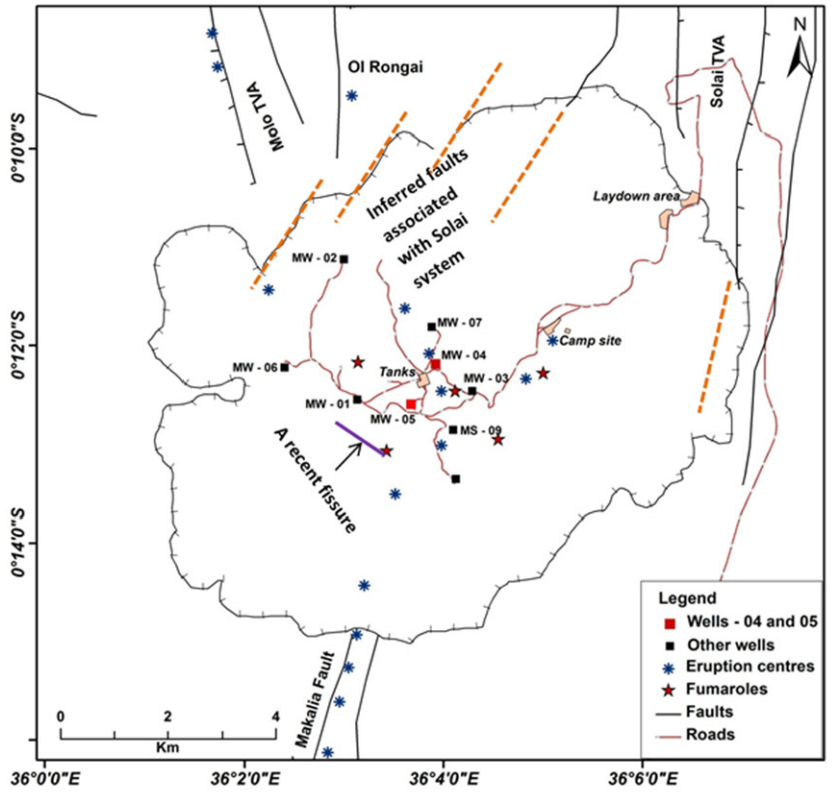

FIGURE 9: Menengai structural map and surface manifestations

Several Geophysical Methods have been used in Menengai, namely Resistivity, Seismics and Potential fields. The resistivity methods have been Schlumberger, MT and TEM. Previous geophysical investigations of this area were carried out by Geotermica Italiana Srl, (1987), the British Geological Survey (Dunkley et al., 1993) and Ministry of Energy in 1985-1986 under the auspices of the United Nations Department for Technical Development (DTCD). The work covered the area from Menengai caldera to Lake Bogoria to the north. The work involved gravity and resistivity measurements. Later in 2004 more geophysical work using (resistivity, gravity and heat flow) better methodologies were done by KenGen through funding by the Ministry of Energy. The Menengai caldera has extensive young lava flows and boreholes drilled to 300 m depths have recorded temperatures of 4°C to 60°C. Heat loss features encountered are hot grounds and fumaroles. No hot springs were encountered.

3.2 Heat flow measurements in Menengai geothermal prospect

Results from Heat flow work done by KenGen in 2004 using shallow gradient holes is shown in Figure 10. It is demarcated by the 40°C isotherm. Observation of the results indicate a high temperature anomaly in a NNW-SSE direction, suggesting a major fault/fracture zone in this direction allowing deep hot fluids to travel close to the surface causing localised heating. Another possible structure seems to occur in NE-SW direction. Areas around Olongai and Banita have low heat flow possibly because the geothermal system in this area is older.

Total heat loss estimated from the Caldera alone is in excess of 2,690 MWt indicating possibly a big hot body underneath which can be explored further for production of steam. From the heat flow measurements it was concluded that over 3,536 MWt of natural heat loss occurs in the Menengai/Olbanita geothermal prospect. 2,690 MWt is lost from the Menengai Caldera out of which 2,440 MWt is by convection through fumaroles. It was concluded that this large heat loss could be an indicator of a huge heat source underneath this prospect.

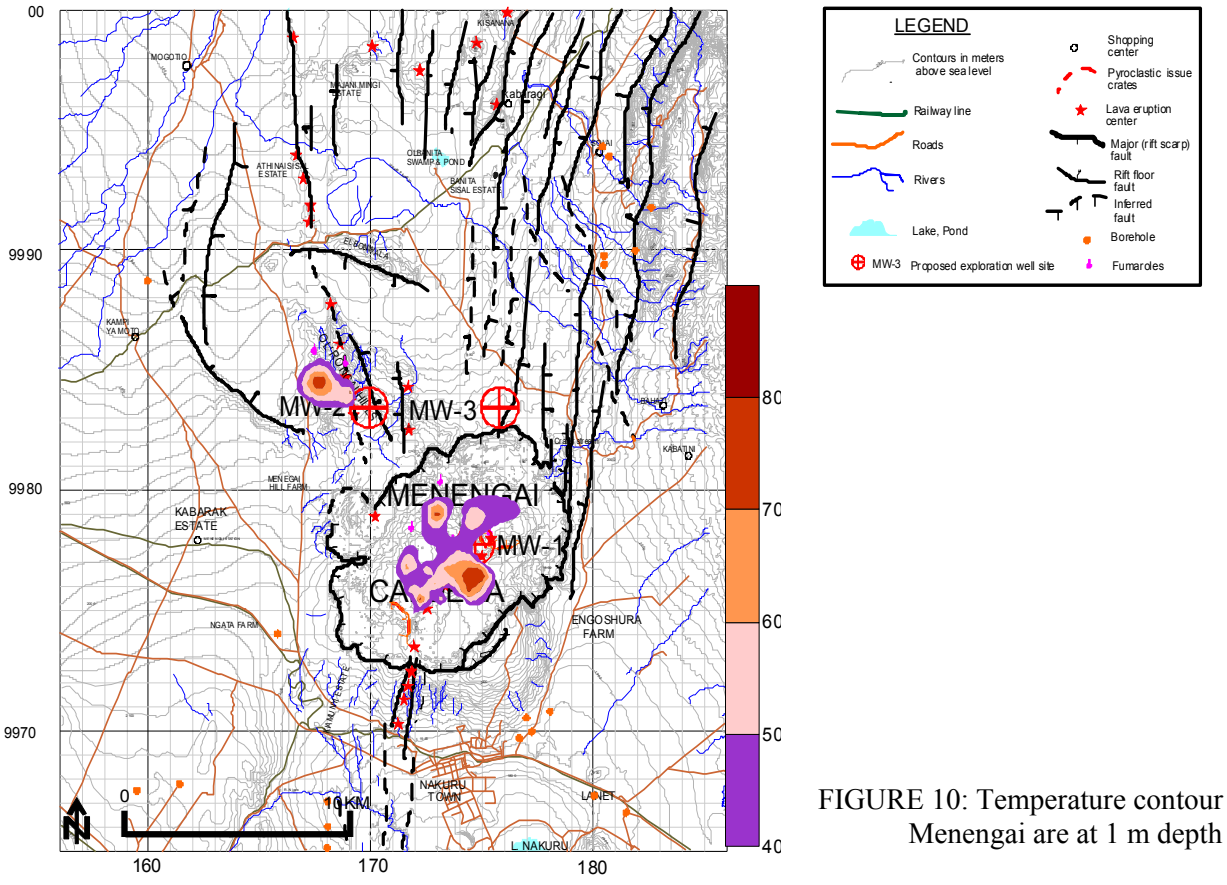

FIGURE 10: Temperature contour map of Menengai are at 1 m depth

3.3 Resistivity measurements in Menengai geothermal field

Geotermica Italiana Srl (1987), under the auspices of United Nations/Government of Kenya project KEN/82/002, carried out resistivity studies using the Schlumberger method. These studies were aimed at providing data for interpretation of the geothermal system. KenGen in the year 2004 and GDC in 2011 and 2012 have used Magnetotullics in conjunction with Transient Electromagnetics. Figure 11 is Iso-resisitivity Map at Sea Level of Menengai area from the MT/TEM data. Figure 12 is a cross-section across the caldera.

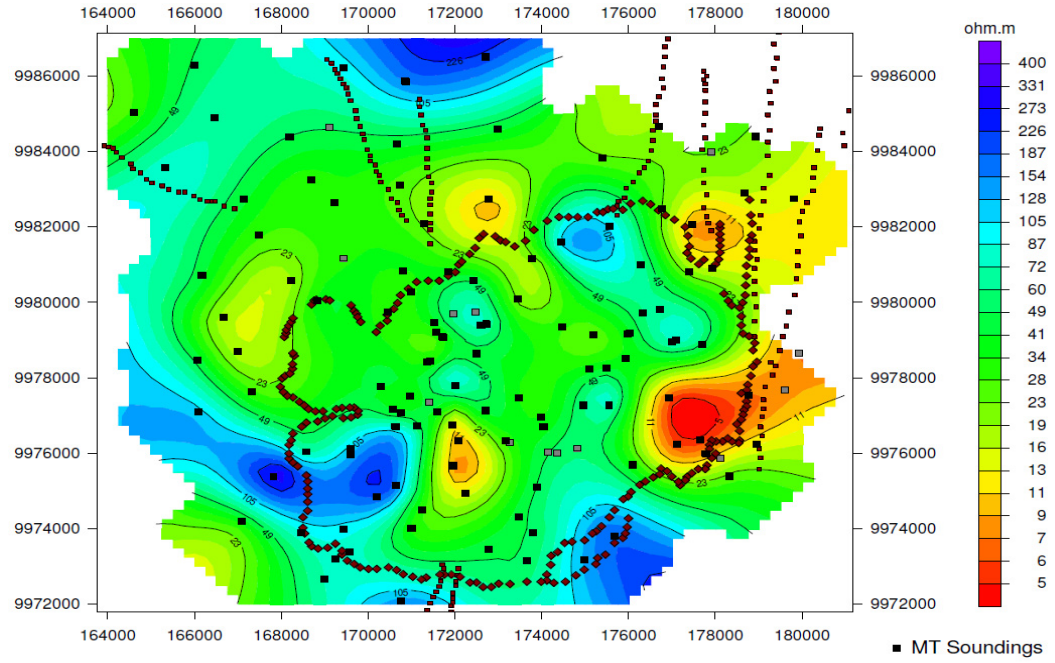

FIGURE 11: Iso-resisitivity Map at Sea Level of Menengai area from MT/TEM data analysis

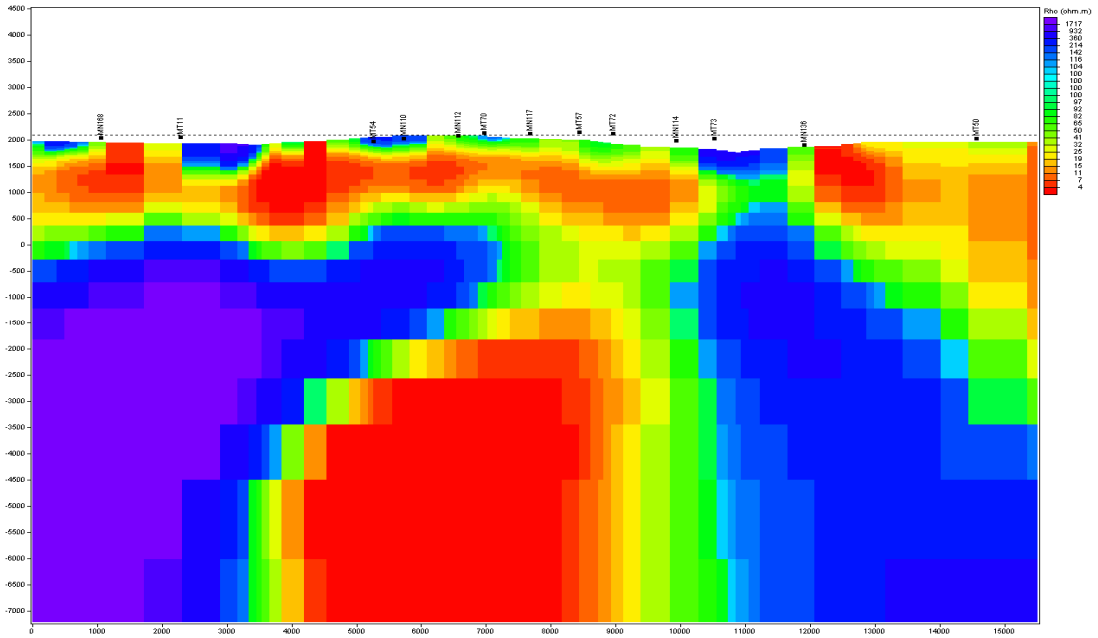

FIGURE 12: Resistivity cross-section across Menengai caldera.

3.4 Potential field measurements in Menengai geothermal field

A sizable amount of gravity data has been collected over the area. Interpretation of this data has been done in conjunction with aeromagnetic data from the Kenya National Oil Corporation. Gravity studies by Geotermica Italiana (1987) under UN/GOK project KEN/82/002 collected some 1400 data points. Analysis of this data showed a large positive anomaly, located in the central part of the area. They interpreted this anomaly to be related to a dense body located some 3.5-4 km deep and a density of 2.8 g/cm^3 that could be a heat source for the geothermal system. This anomaly coincided with the Molo Volcanic Axis, which is intruded by a series of dikes (Simiyu and Keller, 1997; Simiyu 1998). Gravity data interpretation by KRISP (Simiyu, 1998) along a regional profile that runs across Menengai, show a gravity high with an amplitude of 40 mGal and an EW wavelength of 35 km. This anomaly was modeled as an intrusive body, about 13 km wide and coming to within 4 km of the surface.

3.5 Seismic measurements in Menengai geothermal field

The Kenya Rift Seismic Project (KRISP) set up a Seismic work in this area in 1990. Results from the effort indicated the presence of high velocity material lying directly beneath the north of Menengai Caldera. Simiyu (1996) modeled this body with a P-wave velocity of 6.8 km/s in an area of 6.05 km/s basement velocity Micro-seismic monitoring show that some events originate from the Menengai-Olbanita area along the Solai axis. These seismic results together with geology showed that the Solai axis is still the most tectonically active system characterized by normal grid faulting with blocks generally tilting towards the east.

3.6 Integration of geophysical data for Menengai geothermal field

The Geophysical data from the three methods discussed above were integrated in order to infer the presence or absence of a heat source, reservoir and permeability. Results indicate the presence of deeper denser bodies. Seismic data from KRISP experiments suggest the presence of high velocity/high density material within the upper 10 km of crust along the rift axis located below the volcanic centres and low resistivity areas. The seismic activity confined to within 4 km imply that a magma body exists at shallow depth and may be forming the heat source for the area. This investigations culminated in recommending that the field be put under exploratory drilling. Figure 13 shows the initial proposed exploratory wells.

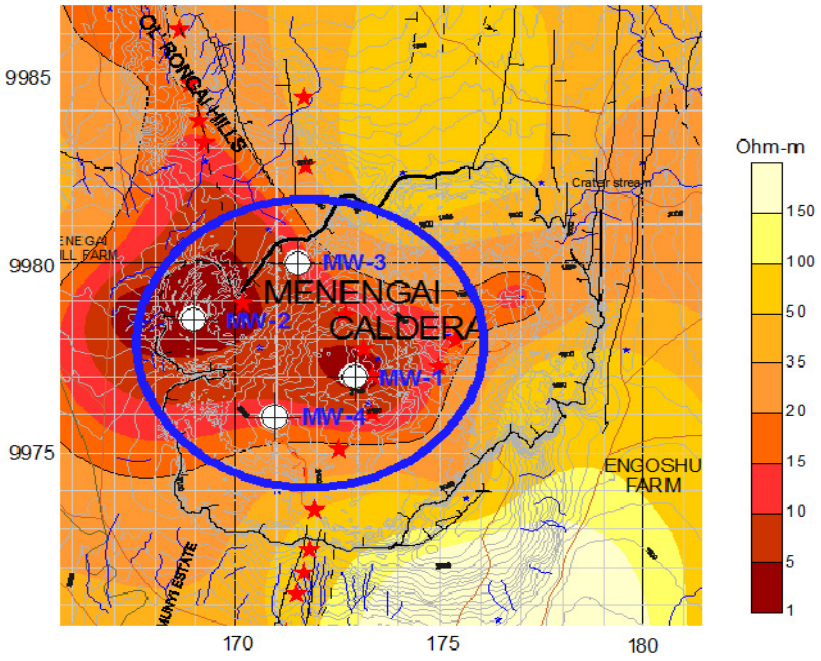

FIGURE 13: Initial proposed best well sites based on integrated geophysical studies

4. CONCLUSIONS AND DEVELOPMENT FOR MENENGAI FIELD

The Menengai geothermal field has a potential for existence of geothermal system(s), giving priority to caldera for further exploration since it represents the most recent volcanism and existence of centralized magma body, which is assumed to be the heat source.

The formation of the Geothermal Development Corporation in January 2009 by the Kenyan government has accelerated the development of the geothermal resource at Menengai. The company has carried out several investigations in Menengai which have involved Structural Mapping; geophysical surveys; geochemical surveys and heat flow measurements. All these methods have indicated an exploitable resource. The Comprehensive Geothermal Conceptual Model developed and currently in use to site productive wells in this field, recommends that 4 exploratory wells be drilled within the Menengai caldera and step out subsequent wells to delineate the resource area.

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A COMPARISON OF 1-D, 2-D AND 3-D APPROACHES OF INTERPRETING ELECTROMAGNETIC DATA OF SILALI GEOTHERMAL AREA

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ABSTRACT

With development of MT interpretation codes and advancement in computer hardware, 3-D electromagnetic data interpretation has become attainable. This study therefore seeks to compare results of Electromagnetic data using different interpretational techniques in order to provide reliable information about the presence, location, and size of geothermal systems in Silali field. Resistivity study of the Silali area in Kenya was carried out by the combined use of TEM and MT soundings. Joint inversion of the EM data was used to correct for static shifts in the MT data, which can be severe due to large near-surface resistivity contrasts. Joint 1-D inversion of 102 TEM/MT sounding pairs and a 3-D inversion of a 97 sounding subset of the MT data were performed. Additionally 2-D inversion of the same data set was done and results are compared with those of 1-D and 3-D inversion models. The resistivity models resulting from the 3-D inversion were elevation corrected and smoothed and are presented as planar maps and cross sections. The inverted model of electrical resistivity reveals the presence of highly resistive near surface layer, identified as unaltered formations, which covers a low resistivity cap corresponding to the smectite-zeolite zone. Beneath this cap a more resistive zone is identified as the epidote-chlorite zone (the resistive core) and interpreted as the host of geothermal reservoir. Further at depth of about 6 km an electrically conductive feature has been imaged, and has been tentatively interpreted as a heat source for geothermal system in this field. The aim of modelling EM data using all the three interpretational techniques is to compare results and establish which resistivity anomalies stand out irrespective of the dimensional inversion used. In this study results from 1-D, 2-D and 3-D models recover near surface resistivity structure fairly well but differ somewhat at depth. The 3-D inversion however reveals much more consistent details than the 1-D and 2-D inversion confirming that the resistivity structures in the area are highly three dimensional. At depth below 6 km the three approaches give different results implying that the models do not resolve deeper structures. This has been attributed to noise in the data at long periods.

1. INTRODUCTION

The electromagnetic methods that include magnetotelluric (MT) and transient electromagnetic (TEM) are techniques of choice when it comes to geothermal exploration. This is because they give indirect information about the sub-surface, in terms of the resistivity structure of geothermal systems that may

be connected to temperature and other components that are of interest. A total of 102 MT soundings and an equal number of TEM soundings are used in the interpretation. This report describes a multi-dimensional inversion of static shift corrected MT data set from Silali area.

The MT method suffers from the static shift problem. This is an inherent uncertainty in the MT data, caused mainly by local near-surface resistivity heterogeneities close to the sounding site (Sternberg et al., 1988; Árnason, 2008). This phenomenon cannot be resolved using MT data alone. The static shift is expressed by scaling of the apparent resistivity by an unknown factor (shifted on log scale), so that apparent resistivity curves plot parallel to their true level. This may lead to very wrong and misleading interpretation of MT data if the static shift is not corrected. The TEM method does not suffer this problem, therefore joint inversion of TEM and MT soundings done at the same location has been used to determine and correct for the static shift in the MT data.

Joint 1-D inversion of MT and TEM recovers resistivity variation only with depth, from which models have been stitched together to produce spatial resistivity variation and cross-sections in the area of interest. 2-D inversion models presents resistivity cross-sections where resistivity is assumed to vary with depth and in one horizontal direction, but being constant in the other orthogonal horizontal direction. Data has been interpreted by use of TE, TM and combined TE+TM modes with the aim of evaluating which of the modes recovers the resistivity structure more accurately. TE-mode describes current flowing parallel to strike whereas TM-mode describes current crossing the structure. Recent developments of inversion codes and computer hardware (computer clusters) have made 3-D inversion of MT data practical. The real Earth is 3-dimensional where conductivity varies in all directions, $\sigma(x, y, z)$. In this regard the 3-D MT inversion of the off-diagonal impedance tensor has been performed resulting in much more reliable and detailed results than previously attained. The results are compared with the results of the joint 1-D inversion of the TEM and MT data and those of the 2-D inversion models.

2. LOCATION OF SILALI GEOTHERMAL AREA

The Silali volcanic system is located within the East African rift system (EARS) consisting of a central volcano with a caldera aligned in NW-SE direction and fissures and faults trending in NNE-SSW (Figure 1). This area has experienced immense volcanism and faulting which has motivated investigation of its geothermal potential. Kenya's Geothermal Development Company (GDC) has explored for geothermal resource in this prospect and is in the process of initiating development soon. Extensive geophysical surveys including resistivity (TEM and MT) have been done to delineate the geothermal anomaly. This study seeks to examine the resistivity distribution within the Silali volcanic region in order to define the magmatic, geothermal, and structural features of this active volcano. Recent fissure eruptions occurred about 200-300 years ago in the eastern sector of the Silali volcano. At volcanoes where there has been recent eruption activity, like Silali caldera, magma remnants at depth can be imaged using resistivity investigation.

3. JOINT 1-D INVERSION OF TEM AND MT SOUNDINGS

The one-dimensional joint inversion is performed simultaneously for both TEM and MT data by fitting both data sets to obtain one model. This is achieved by use of an algorithm which determines the appropriate shift factor to be used to constrain the MT data to fit the TEM response. Both the MT and TEM data collected on approximately the same location are brought together in a joint inversion which also determines a static shift multiplier to correct for static shift that is inherent in MT data.

Joint 1-D Occam inversion has been done for the rotationally invariant determinant apparent resistivity and phase of all the MT soundings and their nearest TEM soundings in the Silali field. Determinant data is preferred because it is rotationally invariant and averages out all "dimensionality" of data. It is

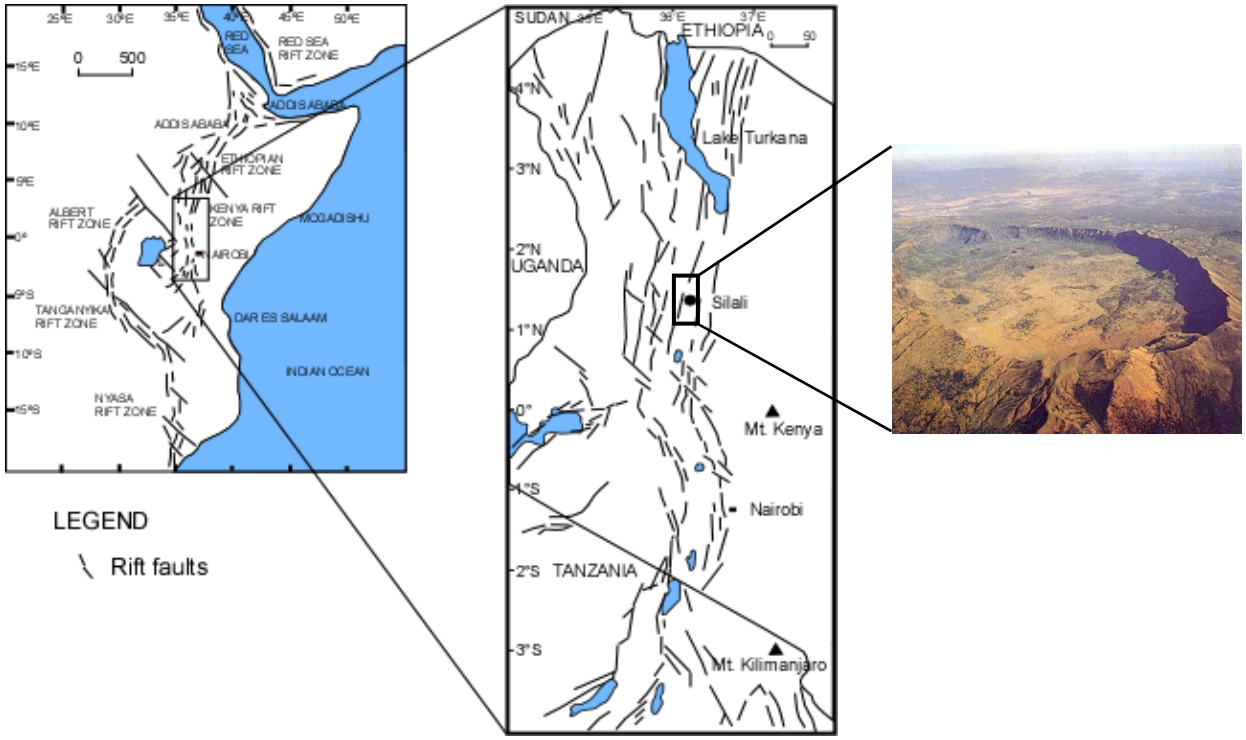

FIGURE 1: Map showing the Kenya Rift and the volcanic centres and lakes; Silali (rectangular box) is the volcanic centre of focus for this study

unique and independent of the strike direction. An example of a 1-D joint inversion of MT and TEM data is shown on Figure 2. The shift multiplier is shown in the upper right hand corner of the apparent resistivity panel. The best fit for this pair was achieved with a shift parameter of S = 0.716. This means that the MT apparent resistivity has to be divided by this value to be consistent with the associated TEM sounding.

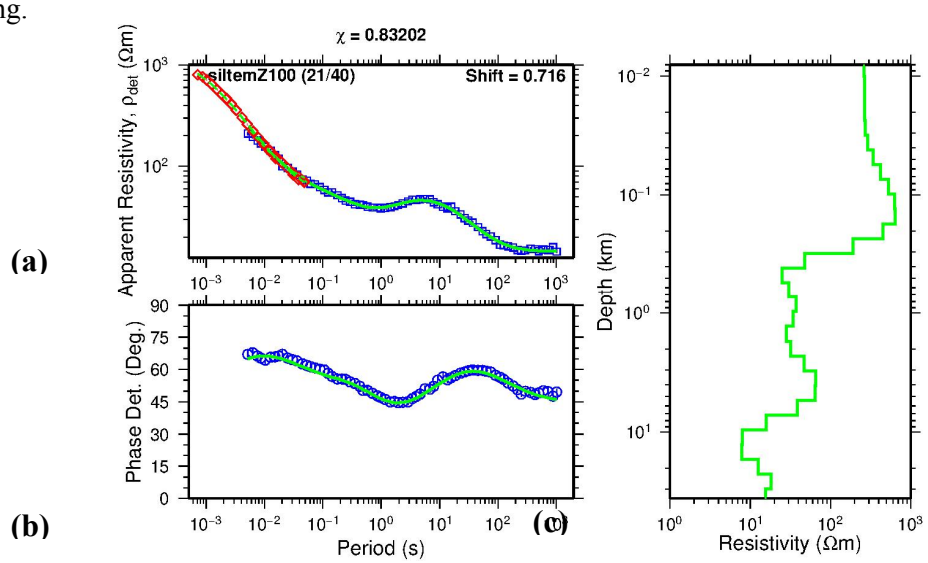

FIGURE 2: Typical result of a joint 1-D inversion of TEM and MT soundings; where the red diamonds in Figure 1a are measured TEM apparent resistivities and blue squares are the MT apparent resistivities and phase Figure 2a and 2b). Solid lines show the response of the resistivity model on Figure 2c. The shift multiplier is shown in the upper right corner of the apparent resistivity panel in Figure 2a

3.1 Joint inversion 1-D results

3.1.1 1-D cross-sections

Resistivity cross-sections (see location map in Figure 3) are plotted for results obtained from 1-D inversion by a program called TEMCROSS (Eysteinsson, 1998), developed at Iceland Geosurvey. The program calculates the best line between selected soundings on a profile, and plots resistivity isolines based on the 1-D model for each sounding. It is actually the logarithm of the resistivity that is contoured so the colour scale is exponential but numbers at contour lines are actual resistivity values. Cross-sections were made through the survey area and profiles were positioned perpendicular to the inferred geoelectrical strike direction (N10°E). Cross-sectional maps are shown in Figures 4a and 5a.

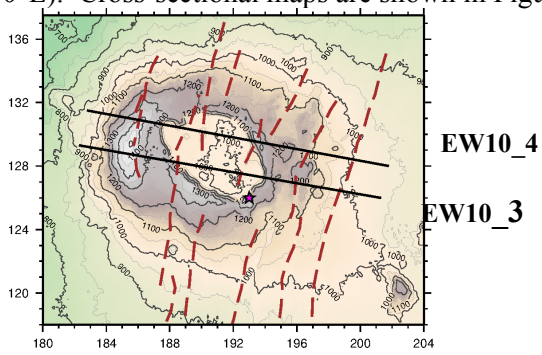

FIGURE 3: Location map showing cross-sections through the study area

3.1.2 1-D iso-resistivity maps

Iso-resistivity maps are made by a program known as TEMRESD which generates iso-resistivity maps at fixed elevations derived from the 1-D Occam models (Eysteinsson, 1998). The resistivity is contoured and coloured in a logarithmic scale. The general elevation of the Silali volcano is about 1000 - 1200 m a.s.l. The maps show that resistivity varies considerably both laterally and with depth (see maps in Figure 6a and 7a)

3.1.3 Discussion of 1-D inversion results

Joint inversion of TEM and rotationally invariant determinant MT data reveals a resistivity structure consisting generally of a shallow low-resistivity layer particularly around the caldera, in the uppermost 1 km, underlain by high resistivity. At greater depth, a second conductive layer is observed in the northeast, southeast and in the west of the caldera. The upper low-resistivity layer presumably reflects conductive hydrothermal alteration minerals formed at temperatures between 100 and 240 °C. The resistive core reflects the change in alteration to resistive high temperature minerals which could be hosting the geothermal system in Silali field. The nature of the deep conductive layer is not as clear in absence of other geophysical data, but could be attributed to magmatic heat sources.

4. 2-D INVERSION OF MT DATA

The inversions of MT data was performed by use of REBOCC program along profiles running perpendicular to the regional strike. The program finds a minimum structure model subject to a desired misfit level. The starting model used in the 2-D inversion was a 10 Ωm homogeneous half-space, and the iterations were set to 10 with RMS misfit of 1. It should be noted that the desired RMS achieved in all profiles was in the range between 5 and 11, this was as a result of the model responses not fitting well to the data which imply that the data was not fully 2-dimensional. For each profile two data responses and their corresponding error responses for both apparent resistivity and phase were generated each for TE and TM-mode and used as input to REBOCC. A total of 73 periods ranging from 0.0031

to 877 seconds were included in the data file for each profile. Several half-space initial models were used to check model convergence and fitting to the data and 10 Ωm homogeneous half-space was found to be the best. REBOCC is very fast and converges to a reliable inversion with minimal memory usage.

4.1 2-D inversion Results

This section describes results from two profiles running perpendicular to the strike direction. Each of the profiles present three cross-sections for TE-mode, TM-mode and a combined TE+TM-mode. Two-dimensional models usually have anisotropic responses. For instance inverting each mode separately yields two different resistivity structures. This difference in modes is due to different sensitivity to complex structures and does not always imply anisotropy.

4.2 Discussion of 2-D inversion results

2-D inversion were carried out to define subsurface conductive structures but a single model that explains both TE and TM models may not exist. The TM-model provides better resolution of higher resistive blocks, which can be explained in terms of boundary conditions. The electric field in the TM-mode is perpendicular to strike and thus, discontinuous across lateral changes in resistivities. In this case the TM-mode is more robust for the presence of 3-D structures (Wannamaker, 1991).

The main result from inversion of profiles presented in Figure 4b and 5b can be summarized as follows: four main resistivity layers are revealed from the 2-D inversion. These are a thin surface layer of high resistivity ($\geq$ 100 Ωm) followed by conductive layer of about 10 Ωm, underlain by a high resistivity core of about 100 Ωm and a deep low resistivity of $\leq$ 10 Ωm. The surface high-resistivity layer can be correlated to unaltered basaltic lava flows and other eruptive materials. The second layer is very conductive and can be associated with altered formations and clays (smectite-zeolite or mixed layer clay alteration zone). The high resistivity core below the conductive layer can be correlated to chlorite-epidote alteration zone down to a depth of about 3 km. This high-resistivity zone below the conductive layer could be related to the reservoir of the geothermal system. At depth of 5-6 km a deeper conductor appears on mainly the TM and TE+TM-mode cross-sections. This deeper conductive structure, if real, could be the heat source of the geothermal system. Although the results of the inversion model seems to reproduce main structures, the poor fit of the model responses to the some data would not guarantee enough confidence in the inversion model obtained. 2-D inversions are known to introduce spurious features in the interpretation when they cannot resolve the features due to off-profile 3-D structures (Siripunvaraporn et al., 2005). Moreover, the resistivity distribution of real geological structures is often very complex and does not satisfy the 2-D assumption. Therefore to solve this problem, 3-D MT inversion of the MT data is essential.

5. 3-D INVERSION OF MT DATA

5.1 Data interpretation

With the development of MT interpretation codes and advances in computer hardware 3-D electromagnetic data interpretation has become attainable. Dimensionality analysis of the MT data from Silali field show non one-dimensional resistivity structure mainly at long periods. It is therefore necessary to carry out 3-D inversion to determine the correct resistivity structure. This is achieved by use of a 3-D inversion program, WSINV3-DMT version 1.1.0 (Siripunvaraporn et al., 2005) which seeks to find a model with a response that fits the data. This inversion code uses finite difference forward algorithm and formulates the inversion problem in data-space rather than the more computationally demanding model-space approach. Therefore this scheme significantly reduces the computational time and memory required for the inversion making the 3-D inversion of MT data possible.

5.1.1 Data preparation

The modelling data used for the 3-D inversion are: 97 MT soundings, 30 periods and 4 impedance tensor elements. The MT soundings chosen were those that were less noisy and with long period data points and evenly distributed over the entire area. All the MT impedances were rotated to N10°E which is the strike direction. In order to minimize the computational time and memory the impedance data was sampled at 30 periods equally spaced on a log scale, ranging from 0.0031 to 700 seconds. This not only reduces the data size but also makes the data to be more smooth. If there are any noisy data points in the resampled data set a skipfile is prepared to be used during inversion to skip those noisy data points so that they were not included in the inversion.

5.1.2 3-D Model mesh grid design

When setting up a 3-D model grid, it must be ensured that it is accurate for the resistivities and frequencies to be used. In designing the mesh a trade-off is sought between the size of the grid and the computational time it would require to obtain reasonable solutions to the models. This is because the finer the grid the larger the time and memory resource required. Forward modelling solutions depend significantly on the mesh grid discretization used. The finite difference code for the forward problem requires a cubic grid, in this case a grid of 73 x 86 x 28 in x, y, and z directions was used. This gave a total model size M to be equal to $73 \times 86 \times 28 = 175{,}784$. At the centre of the grid a uniform model discretization with a cell width of 350 m for 49 x 62 grid squares in x and y directions was used within the area containing MT stations. This grid increases exponentially in size to 139.4 km and 141.8 km in the x and y directions respectively. In the z direction the grid planes are dense at shallow depth with the first layer set at 16 m and then increased progressively by 1.4 times of the overlying block to depths of 160.8 km.

5.1.3 3-D modelling parameters and initial models

The 3-D model size represents the number of unknowns in the forward modelling problem. If the inverse problem was to be solved in the model-space this would present a huge computational problem. In the given data set of 97 stations at 30 periods and 4 impedance responses, the problem reduces to N=97 x 30 x 4 equal to 11,640 which can be solved with achievable computational cost and memory done by data-space 3-D inversion. The inversion program was run using a parallel processing version of the WSINV3DMT code using the Message Passing Interface (MPI) parallel computing environment. This was setup on a special machine cluster at ÍSOR running on 32 cores and 132 GB of memory to be able to deal with a big data set like this one.

A 10 Ωm homogeneous half-space initial model was used as the base models for the 3-D inversions starting at initial RMS of 11.5 and reducing to 1.5 after 15 iterations. The RMS defines the data misfit between the measured and calculated values of the off diagonal tensor elements (real and imaginary parts), weighted by the variance of the measured values.

For the initial model three runs were performed and 5 iterations were allowed for each run. After every run the inversion was restarted with the model that gave the best fit as the initial model for the successive runs. Through these step-runs the inversion gradually relaxes the limitation of the prior model, until the data fit can no longer be improved. This is achieved by regularization where a reference (prior) model is used to constrain the inversion model not to deviate too much from the prior model. Each iteration took 27 hours, yielding a total computing time of 405 hours for 15 iterations. Most of the CPU time is spent in constructing the sensitivity matrix for solving inverse problems.

5.2 3-D inversion results

This section describes 3-D inversion results derived using the smoothed 10 Ωm homogeneous half-space initial model. Ordinarily the 3-D program assumes flat surface, but as mentioned earlier the MT data were static shift corrected prior to the inversion and this correction considerably removes topographic

effects in the data. The resistivity models resulting from the inversion were elevation corrected, and results are presented as smoothed iso-resistivity maps (Figure 4c and 5c) and cross-sections (Figure 6c and 7c).

5.2.1 Discussion of 3-D inversion results

The 3-D MT inversion of the off-diagonal impedance tensor for the 97 MT sites and 30 periods revealed the main parts of the subsurface resistivity structures at the Silali geothermal field. The resistivity models revealed a typical resistivity structure for a high-temperature geothermal field as found elsewhere, i.e. a low-resistivity cap underlain by a resistive core which presumably is related to the geothermal reservoir (Eysteinsson et al., 1994; Árnason et al., 2000).

The low-resistivity anomaly observed at shallow depth particularly around the caldera and to the south of the caldera is attributed to low temperature alteration minerals. Underlain high resistivity is related to the change in alteration minerals to higher temperature mineralogy within the caldera spreading to south of the caldera. At depth of about 6 km a conductive segment dominates; this deep low-resistivity region could be associated with presence of partial melt which has been interpreted as the heat source for the geothermal system in this field. It should however be noted that the resolution of MT data at long period may not be trusted due to noise, this therefore underscores the importance of collecting good data particularly at long periods. Results from the above models show that resistivity structure up to a depth of 6 km is stable but below that the models may not be entirely correct.

6. COMPARISON OF 1-D, 2-D AND 3-D RESULTS

Results for two profiles will be compared for the 1-D, 2-D and 3-D inversion of MT data. Both 1-D and 3-D are elevation-corrected but 2-D is not. From the evaluation of the 3-modes of 2-D inversion, TM-mode result are preferred to be compared with both 1-D and 3-D models.

The 1-D, 2-D and 3-D vertical resistivity cross-sections of Profile EW10_4 (for location see Figure 3) are shown in Figure 4a, 4b and 4c). All the three resistivity cross-sections generally show a three layer resistivity structure down to depth of 6 km, with a high resistivity surface layer (> 100 Ωm) underlain by a low resistivity layer (< 10 Ωm) and a third high resistivity zone (> 70 Ωm). The deeper basal layer differs somewhat with 1-D model smearing low resistivity across the entire section rising to shallow depth at the western most end of the profile and at the eastern edge of the caldera below site slmt172. On the other hand the 2-D profile shows low resistivity on the western half of the profile rising to shallow depths on both sides of the caldera. The 3-D model shows low resistivity at depth of 6 km b.s.l beneath the caldera with a fairly low resistivity elongation towards the surface. In all the models there is a low resistivity linear structure between the high resistivity anomaly in the intermediate depths. It should be noted that the 3-D model reveals the resistivity structure reliably well particularly the high resistivity zone where the two anomalies are clearly resolved.

Similarly resistivity structure for profile EW10_3 (for location see Figure 3) is compared in Figure 5. Likewise this profile shows a resistivity structure with a top high resistivity underlain by a low resistivity second layer followed by a higher resistivity structure. However the 3-D model has better resolved resistivity geometries both at the shallow low resistivity and the underlying high resistivity core. Of special significance are the two high resistivity anomalies separated by a lower resistivity linear structure below the caldera. At depth of 5 km b.s.l both 1-D and 2-D models present a deeper low resistivity smeared all across the entire profile. The 3-D model presents a localized deeper low resistivity beneath the caldera and extending to the west of the caldera. From this comparison it seems reasonable to conclude that the anomalies revealed are real.

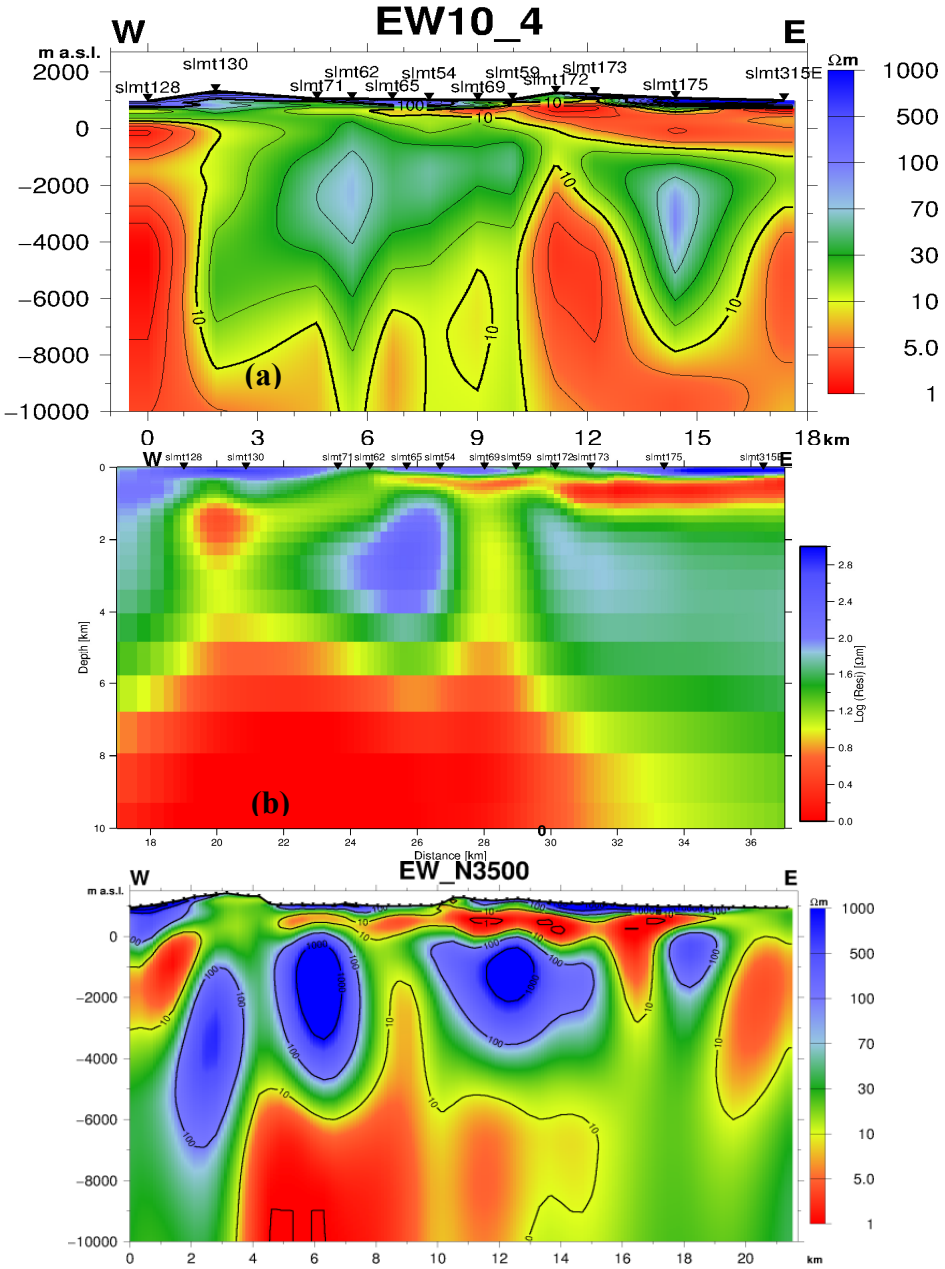

FIGURE 4: Comparison of 1-D, 2-D and 3-D vertical resistivity cross-sections for profile EW10_4: (a) from joint 1-D inversion of TEM and determinant MT data. (b) 2-D inversion of TM-mode and MT data (c) 3-D model at EW_N3500

The next section compares iso-resistivity maps of 1-D and 3-D developed using Linux program with 2-D maps from WinGlink program. 2-D cross-section shown above are made using REBOCC. It should be noted that colour scales for 2-D WinGlink maps differ from those of 1-D and 3-D model maps. On the WinGlink maps the caldera structure and the faults are marked by brown and black symbols respectively whereas on the other maps faults are marked by brown broken lines.

Figure 6 shows resistivity at 1000 m a.s.l for 1-D, 2-D WinGlink and 3-D models respectively. For all the three models there is a striking correlation between the low resistivity which has been attributed to the low temperature mineral alteration and the surface manifestations at shallow depth encircling the caldera. Elsewhere a high resistivity is seen on the outer margins all around the low resistivity. Similarly

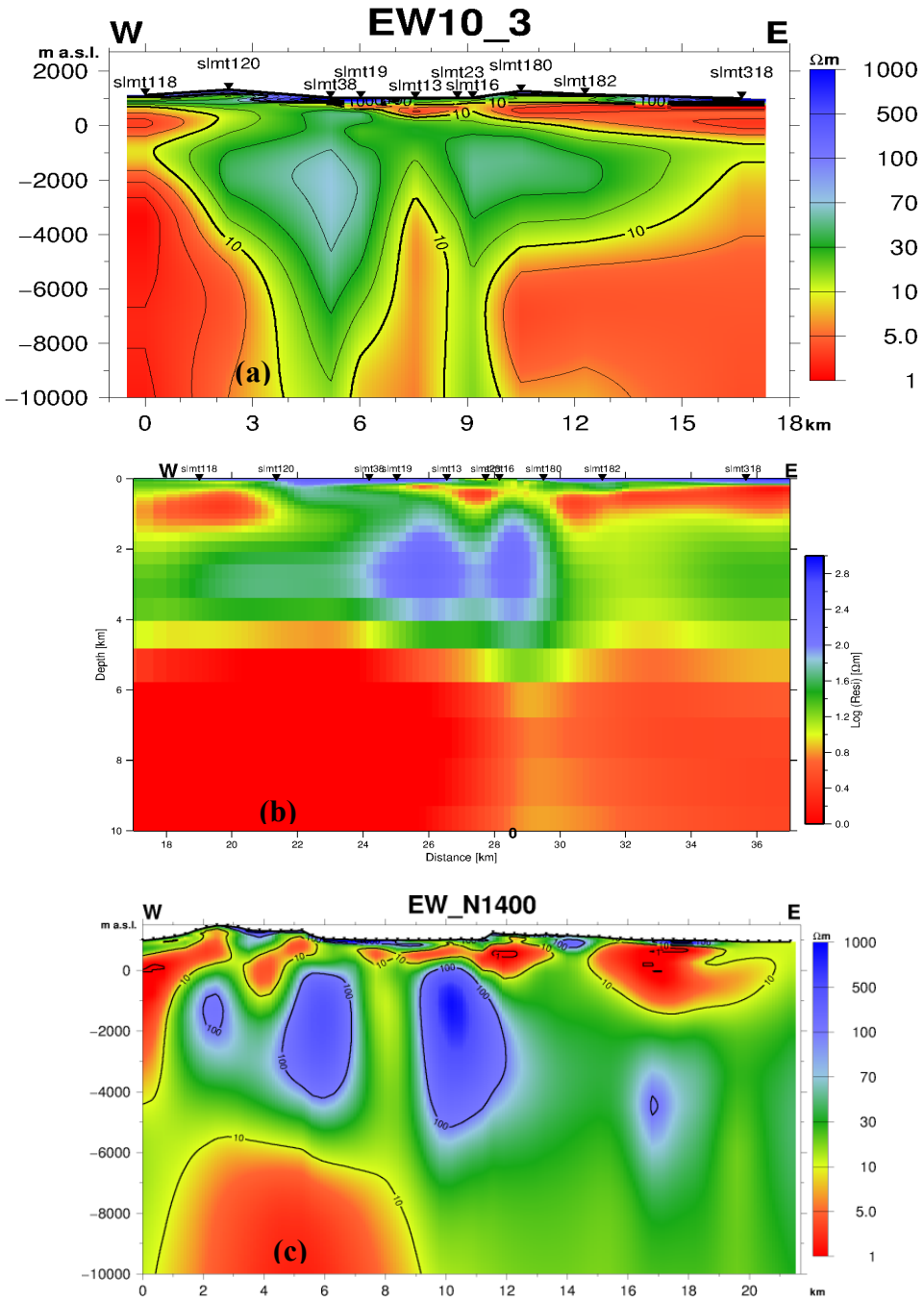

FIGURE 5: Comparison of 1-D, 2-D and 3-D vertical resistivity cross-sections for Profile EW10_3: (a) from joint 1-D inversion of TEM and determinant MT data. (b) 2-D inversion of TM mode MT data. (c) 3-D model at EW_N1400

Figure 7 shows resistivity at sea level with a generally high resistivity trending in a NE-SW direction from the caldera to the extreme SW end. This high resistivity zone, maps high resistivity core of the geothermal system in this field. 1-D and 2-D models smear the resistivity indiscriminately while 3-D models seems to sharpen the resistivity structure much better as seen in Figure 7c showing the two high resistivity anomalies inside the caldera.

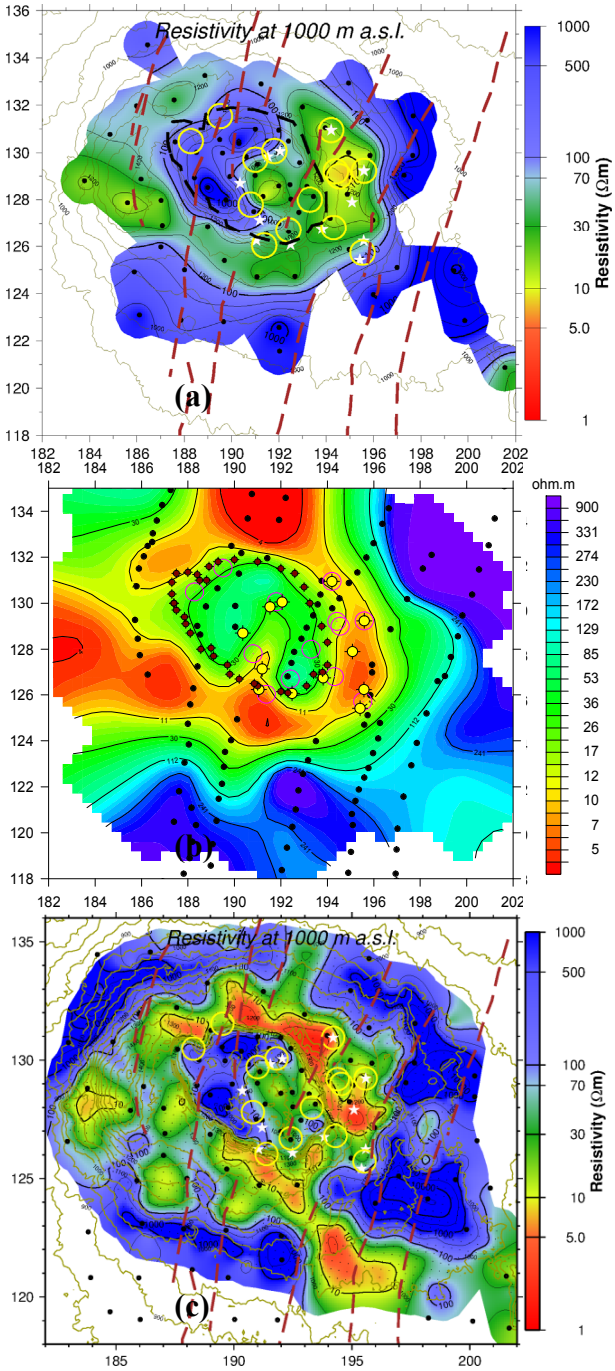

FIGURE 6: Comparison of 1-D, 2-D and 3-D horizontal resistivity map at 1000 m a.s.l (a) joint 1-D inversion of TEM and determinant MT data. (b) 2-D resistivity map from WinGlink. (c) 3-D resistivity map from 10 ohm-m initial model

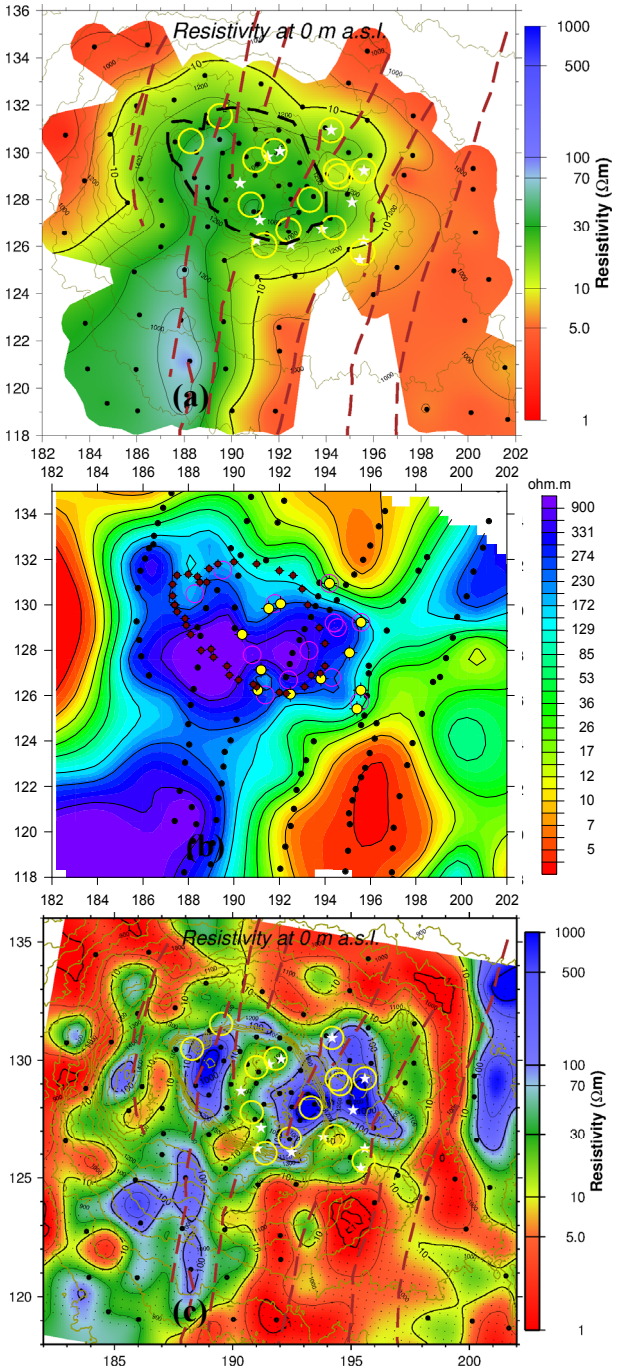

FIGURE 7: Comparison of 1-D, 2-D and 3-D horizontal resistivity map at sea level (a) joint 1-D inversion of TEM and determinant MT data. (b) 2-D resistivity map from WinGlink. (c) 3-D resistivity map from 10 ohm-m initial model

6.1 Discussion of 1-D, 2-D and 3-D comparison

The 1-D and 2-D inversion of MT data on the two profiles (Figures 4 and 5) show three main resistivity structures down to a depth of 6 km. A high resistivity surface layer associated with fresh basaltic lava, a very low resistivity second layer (< 10 Ωm) of variable thickness was observed along the vertical cross-sections. The conductive layer is presumably associated with smectite and mixed layer clay

alteration. A high resistivity (> 70 Ωm) is observed underlying the conductive layer along the cross-sections, more resolved in the 3-D model both for Figure 4c and 5c. The high resistivity could be related to high-temperature alteration (chlorite-epidote alteration zone) down to a depth of about 4 km. The 3-D inversion revealed a more resolved deeper conductive structure than the 1-D and 2-D inversion models. The deep conductive body is presumably associated with the heat source of the geothermal system. Generally 1-D models give a rough picture, 2-D models can be difficult to resolve but 3-D resistivity models sharpen the resistivity structure.

It should however be noted that due to noise in the data at long period the results from 1-D, 2-D and 3-D differ widely and may not resolve the anomalies deeper than 6 km. This is because the noisy portion of the data can be fitted by different models. Therefore the depth of resolution is limited to 6 km.

In conclusion, it must always be remembered that in the real earth there are no such components as 2-D anomalies, all anomalies are 3-dimensional. Again since two-dimensional (2-D) interpretations frequently cannot explain important features present in field data sets from geologically complex regions, then it is inevitable that 3-D inversion has to be carried out. Often a 2-D inversion is undertaken of data that exhibit weak 3-D effects because of the inadequacy of spatial coverage (only a single profile of data rather than a grid) or because of the complexity of 3-D modelling. 2-D techniques applied to 3-D data are merely indicative and can be misleading if interpreted without consideration.

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APPLICATION OF GEOCHEMICAL METHODS IN GEOTHERMAL EXPLORATION

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ABSTRACT

Subsurface waters have been classified into meteoric water, ocean water, evolved connate water, magmatic water and juvenile water. Geothermal water is mostly meteoric and oceanic water although andesitic waters near subduction areas often contain significant proportions of evolved connate and magmatic waters. Geothermal waters have been classified with respect to their anion and cation contents into alkali-chloride water, acid sulphate water, acid sulphate-chloride water and bicarbonate water. Acid waters are generally unsuitable for elucidation of subsurface properties. Conservative constituents are used for tracing origin and flow of geothermal fluids, stable isotopes (especially ^{2}H and ^{18}O) along with B and Cl being most important. Radioactive isotopes and chlorofluorocarbons (CFCs) have been used for dating. Rock forming constituents (e.g. SiO_2, Na, K, Ca, Mg, CO_2, H_2) are used to predict subsurface temperatures and potential production problems such as deposition and corrosion. Triangular diagrams and log(Q/K) diagrams are introduced as powerful tools in the interpretation of geothermal geochemistry.

1. INTRODUCTION

The major goals of geochemical exploration are to obtain the subsurface composition of the fluids in a geothermal system and use this to obtain information on temperature, origin, and flow direction, which help locating the subsurface reservoir. Equilibrium speciation is obtained using speciation programs and simulation of processes such as boiling and cooling to get more information to predict potential deposition and corrosion. Environmental effects can be predicted and the general information is used as a contribution to the model of the geothermal system.

2. CLASSIFICATION

Subsurface waters: It has proved difficult to obtain a genetic classification of subsurface waters. The waters that have been studied in detail are mostly those that are of economic interest as potable water. Water also tends to flow away from its point of origin and also undergo water-rock interaction during its travels making it increasingly difficult to decipher its origins. White (1986) attempted a classification which is reproduced here.

- Meteoric water circulates in the atmosphere, co-existing with near-surface, uncemented sediments, can circulate in subsurface rocks and dissolve constituents, e.g. evaporites.
- Ocean water is partly evaporated products of meteoric water.
- Evolved connate water forms in young marine sediments. It is initially 10-50% oceanic or pore water mixed with combined water. Upon increased burial depth more interaction takes place at modest temperatures, and compaction leads to lower pressure environments. Variable salinity is observed and may be due to filtration, evaporation or dissolution of evaporites.
- Metamorphic water is contained in or driven from rocks undergoing metamorphic dehydration reactions. Being over pressured at depth, it may escape in response to lithostatic load.
- Magmatic water is derived from oceanic and evolved connate waters subducted along with oceanic crust into the mantle. At deep crustal level it is mostly due to rocks undergoing metamorphism.
- Juvenile water is classified as water that has never circulated in the atmosphere. If it exists it must be extremely rare. Juvenile ^3He and CO_2 of mantle origin exist and thus suggest that juvenile H_2O may exist too but it has not yet been identified conclusively.

Geothermal waters: Ellis and Mahon (1978) classified geothermal water into four categories based on major ions.

- Alkali-chloride water: pH 4-11, least common in young rocks, e.g. Iceland. These are mostly sodium and potassium chloride waters although in brines Ca concentration is often significant.
- Acid sulphate water: These waters arise from the oxidation $H_2S \rightarrow SO_4$ near the surface and most of its constituents are dissolved from surface rock. Thus such water is generally not useful for prediction of subsurface properties.
- Acid sulphate-chloride water: such water may be a mixture of alkali chloride water and acid sulphate water, or it can arise from the oxidation $H_2S \rightarrow SO_4$ in alkali-chloride water or dissolution of S from rock followed by oxidation. Sulphate-chloride waters need not be very acid and may then reflect subsurface equilibria and be used for prediction of subsurface properties.
- Bicarbonate water: Bicarbonate water may derive from CO_2 rich steam condensing or mixing with water, it is quite common in old geothermal waters or on the peripheries of geothermal areas in outflows. They are commonly at equilibrium and may be used to predict subsurface properties.

A good way of distinguishing between the differences between the different types of geothermal water is the use of the chloride-sulphate-bicarbonate ternary diagram described by Giggenbach (1991). An example from Uganda is shown in Figure 1, where the geothermal water from one area, Kibiro, is a typical alkali-chloride water, the water from another, Buranga is a relatively alkaline chloride-sulphate-bicarbonate water, but the geothermal water from the third one, Katwe, is a sulphate water. The cold groundwater in the areas is scattered.

The dissolved constituents of geothermal water may originate in the original meteoric or oceanic water, but more likely they are the result of water-rock interaction and possibly modification by magmatic gas. They are divided into rock forming constituents, e.g. Si, Al, Na, K, Ca, Mg, Fe, Mn and incompatible constituents, e.g. Cl, B, Br.

Products of geothermal alteration are controlled by temperature, pressure, chemical composition of water (e.g. CO_2, H_2S), original composition of rock, reaction time, rate of water and steam flow, permeability and type of permeability and these products in turn control the chemical composition of the fluid. Some of the effects are that the silica concentration depends on the solubility of quartz/chalcedony, temperature dependent Al-silicate ion-exchange equilibria control Na/K, Na/Rb ratios, pH is controlled by salinity and Al-silicate equilibria involving hydrogen and alkali ions, Ca^{+2}

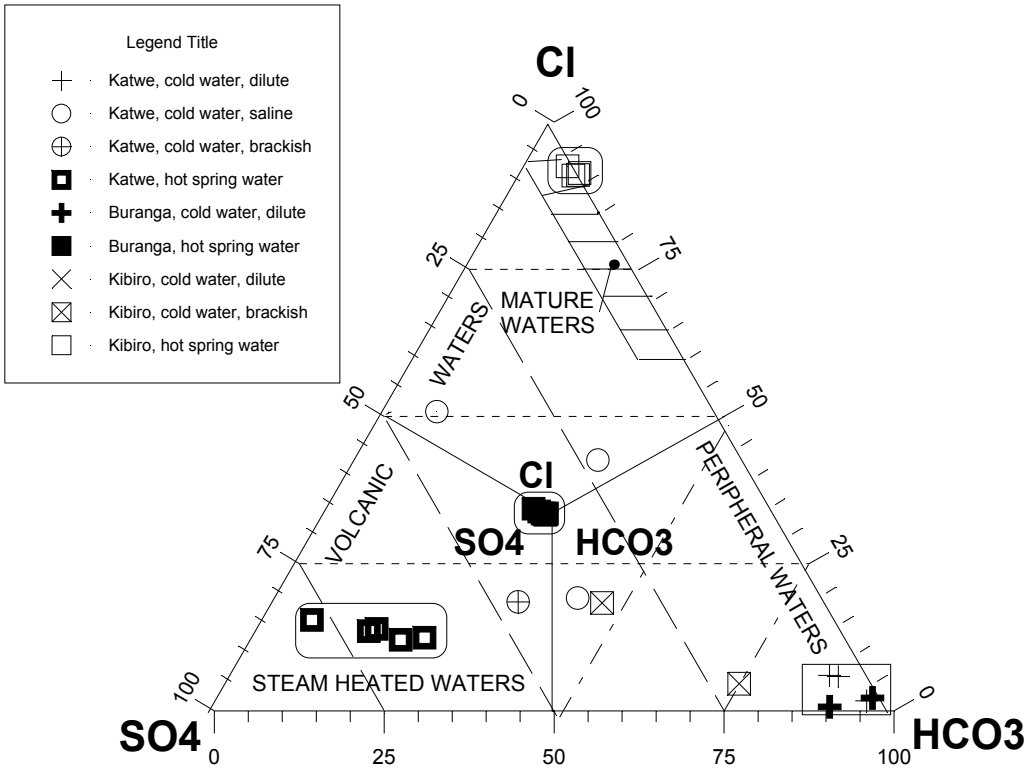

FIGURE 1: A ternary Cl-SO_4-HCO_3 diagram showing the characteristics of waters from different Ugandan geothermal systems

and HCO_3^- concentrations depend on pH and CO_2 concentration because of equilibrium between the fluid and calcite, F^- and SO_4^{-2} concentrations are related to that of Ca^{+2}, limited by solubility of fluorite and anhydrite and temperature and salinity dependent silicate equilibria control a very low Mg^{+2} concentration. The results of alteration studies show that the chemical composition of geothermal fluids originates in controlled reactions dependent on temperature, pressure and rock composition. Therefore it is possible to deduce the properties of subsurface water from the chemical composition of water which has been collected at the earth's surface.

3. TRACING THE ORIGIN AND FLOW IN GEOTHERMAL SYSTEMS

Stable isotopes and conservative constituents making use of ratios, e.g. Br/Cl, B/Cl and/or ternary diagrams, e.g. Cl-Li-B, are the most powerful tracers of the origin of geothermal systems. The relationships of major ions, e.g. seen in ternary diagrams such Cl^--SO_4^{-2}-HCO_3^- give an insight into the origin of the constituents of the water.

3.1 The use of stable isotopes

In sea water δD and $\delta^{18}O$ are close to 0‰ (SMOW). Evaporation subsequently causes the formation of clouds into which light isotopes preferably find their way. The clouds are eventually precipitated and the relative concentration of light and heavy isotopes depends on several factors, i.e. latitude as lower isotope ratios are found at high than low latitudes, altitude and distance from sea shore where relatively lower isotope ratios are found in precipitation at higher than lower altitudes and greater than shorter distances from the shore. Temporal effects may cause variations in isotopic composition at the same place. Single showers may travel different distances and their composition depends on the origin of the cloud and the temperature of condensation. Seasonal changes are observed with lower isotope

ratios in winter than summer. This effect is more pronounced at high than low latitudes. Long-term climatic changes produce a similar effect with low isotope ratios in precipitation from cold climates but higher ones from times of warmer climate. A quantitative effect is sometimes observed as an inverse relationship between isotope ratios and quantity of precipitation. This effect is more pronounced at low than high latitudes (Truesdell and Hulston 1980).

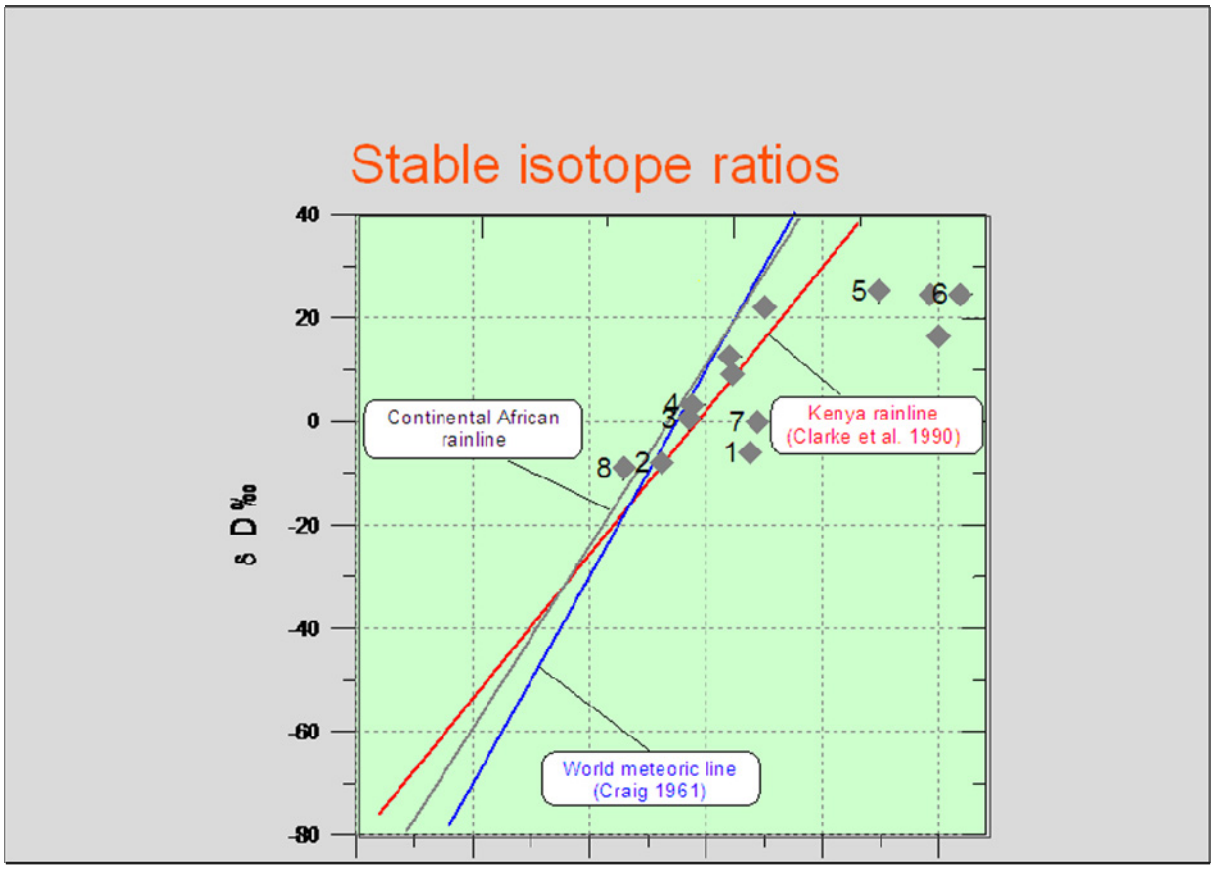

FIGURE 2: World meteoric line, Continental African rainline, Kenya rainline. Samples from Ugandan areas plotted and show variation. The oxygen isotope shift is probably due to poor permeability

The reason for the usefulness of stable isotope ratios for tracing water origin is that after precipitation there is little change in them although the water may travel long distances. Local annual means for precipitation have been established and (Craig 1961) showed that a meteoric line describing the relationship between δD and $\delta^{18}O$ applies all over the world although deviations are known and local lines have been described. However geothermal water values suggest its origin but mixing, water-rock interaction, condensation and age may have to be accounted for.

3.2 The use of conservative constituents

The boron concentration of sea water and thus precipitation is low but that of rocks and of volcanic steam is relatively much higher and boron is extremely soluble. The chloride concentration of sea water and thus evaporation is high but in rocks and some magmatic steam relatively low. Thus the B/Cl ratio can be used to trace mixing of sea water or magmatic steam with precipitation.

3.3 Dating

One way of studying the origin of geothermal water is by dating. For this two types of methods have been used, i.e. determination of radioactive materials and chlorinated fluorocarbons. Of radioactive

substances ^{3}H with a half life of 12.43 years has been extremely useful for relatively young waters. It is measured in tritium units (1 TU = 1.185 Bq/L). The natural cosmogenic level in precipitation is a few TU but rose to ≈ 2000 TU from the nineteen fifties to 1963/1964 but is down to ≈ 10 TU at present For older waters dating with ^{14}C with a half life of 5730 years has been used. It is present in atmospheric CO_2, the living biosphere and hydrosphere after production by cosmic radiation but underground production negligible and therefore it cannot be used for carbon from a magmatic source. The ^{14}C content is often presented as % modern carbon (pMC), grown in in 1950. Fallout ^{14}C (in CO_2) has been used to date water with mean residence time less than 150 years. Organic compounds of chlorine and fluorine are man-made and first appeared in 1928. They are unreactive and non-toxic. CFC-11, CFC-12 and CFC-113 are the most common of these. The release of CFC-11 and CFC-12 to the atmosphere rose in the 1930s. Deviations in the release were first noted following 1974, when possible ozone depletion by chlorine-containing species was first announced, but much more significant ones after the signing of the Montreal Protocol in 1987. Release of CFC-113 increased significantly through the early- and mid-1980s until the Montreal Protocol was signed, after which production significantly diminished.

TABLE 1: Atmospheric lifetime of chlorinated fluorocarbons

CFC	Lifetime
CFC-11	45±7
CFC-12	87±17
CFC-13	100±32

3.4 Geothermal gases

The origins of geothermal gases are diverse and can be magmatic, in rock dissolution, organic, atmospheric and radiogenic. Studies of isotopes, inert gases, and thermodynamic calculations help elucidate the origin in each case. The $\delta^{13}C$ signatures for CO_2 of different origins are -10 - -1‰ in magmatic gases, -2 - +2‰ in gas derived from marine limestone, <-20‰ for CO_2 of organic origin and -5 - -8 ‰ in atmospheric CO_2. Sulphur isotope ratio ($\delta^{34}S$) for H_2S leached from rock is <0‰, of magmatic origin ≈ 0‰ and of marine origin >0‰. Hydrogen isotope ratio (δD) in H_2 leached from rock or sediments -300 - 450‰ and from magmatic sources: <-450‰. In biogenic hydrocarbons $\delta^{13}C_{CH4}$ is <-55‰ in thermogenic (wet) gas, $\delta^{13}C_{CH4}$ is higher in thermogenic (dry) gas of terrestrial origin, $\delta^{13}C_{CH4}$ but lower in such gas of marine origin. It is rather high in magmatic gas and is expected at -20 -10‰ in hydrocarbons of inorganic origin. Nitrogen is usually of atmospheric origin with $\delta^{15}N \approx 0$‰.

4. GEOTHERMOMETRY

Many reactions in geothermal systems are temperature dependent but their kinetics are not fast at lower temperatures so that their equilibrium characteristics are preserved even though the waters rise to the surface and cool down. Thus the concentrations of surface geothermal fluids may be determined and, as a result subsurface temperature may be determined as well. Reactions in the liquid phase and in the vapour phase as well as isotope exchange reactions in both phases have been used this way for geothermometry. Geothermometers may be univariant, e.g. SiO_2, CO_2, H_2S, H_2 with the disadvantage of sensitivity to secondary changes such as dilution, steam loss and condensation. They may be global involving the assumption that a number of constituents is simultaneously at equilibrium and that their present concentrations can be used to obtain the equilibrium temperature and thus depend on analytical reliability and thermodynamic data. Thirdly, equimolar and equicoulombic ratios, e.g. Na/K, CO_2/H_2 can be used for geothermometry. Such geothermometers overcome the disadvantage of univariant geothermometers but equilibrium and rate conditions limit their value. Combinations of alkali and alkaline earth metal concentrations may as well as providing subsurface temperatures be used to

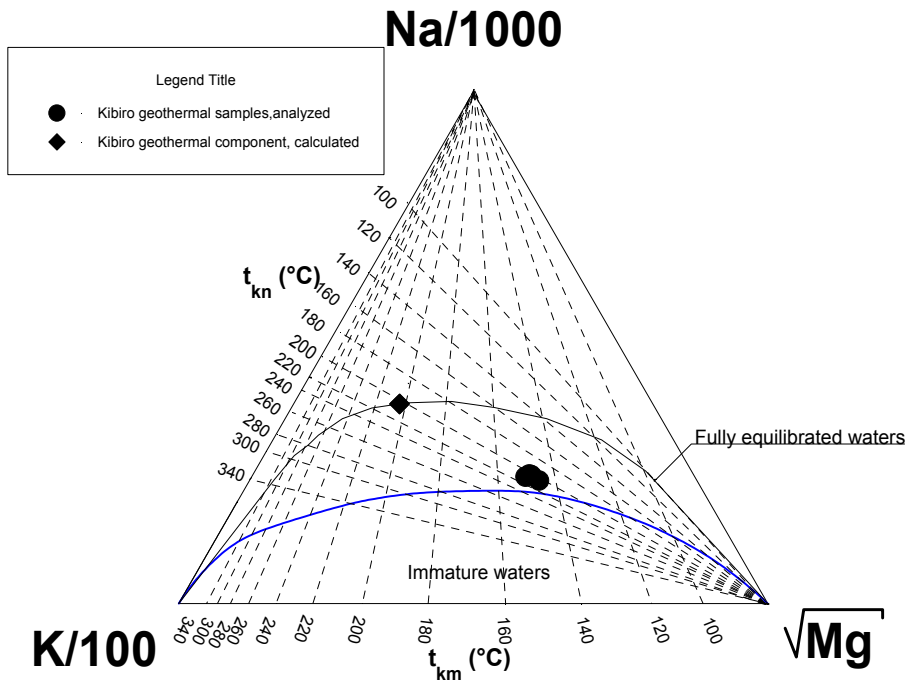

FIGURE 3: Na-K-Mg triangular diagram, showing examples from Kibiro, Uganda

evaluate whether the water is at equilibrium with the prevalent alteration minerals in the rock, e.g. by using the Na-K-Mg diagram shown in Figure 3 (Giggenbach 1991). The points in the diagram are from the Kibiro area, Uganda, and the partially equilibrated waters represent a mixture of the geothermal component and local groundwater whereas the fully equilibrated water represents the geothermal component. For equilibrium calculations which are needed to obtain temperatures from global geothermometers speciation programs such as WATCH (Bjarnason 1994) and SOLVEQ (Reed and Spycher 1989) are used. An example is shown in Figure 3 in which the temperature of well 4 in Námafjall, Iceland has been estimated by calculating log (Q/K) where Q is the activity quotient but K is the equilibrium constant over a range of temperatures. The saturation temperature and therefore the equilibrium subsurface temperature corresponds to log (Q/K) = 0 and this is found at about 160°C in the present example.

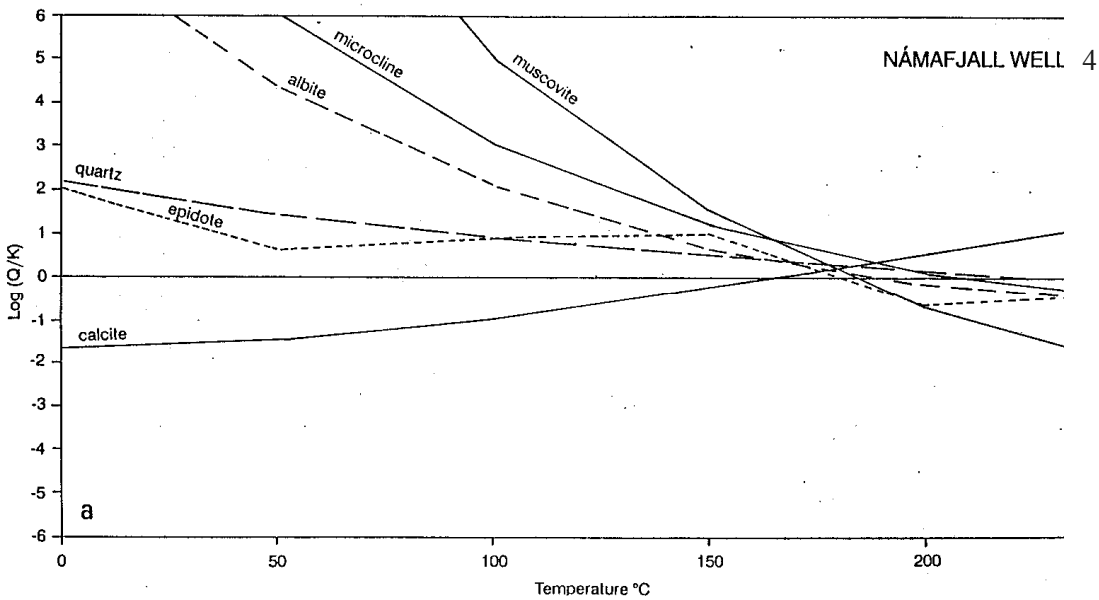

FIGURE 4: A log(Q/K) diagram for probable alteration minerals in well 4, Námafjall, Iceland (Tole et al. 1993)

5. PRODUCTION PROBLEMS

The common production problems due to the chemistry of geothermal fluids are deposition and corrosion. Pollution is usually dealt with as an environmental problem.

5.1 Deposition

The most common deposits in geothermal utilization are due to silica, iron oxides, iron silicates, sulphides, calcite and magnesium silicates. Deposits due to aluminium silicates, anhydrite, barite, apatite, borates and sulphur are also known. Studies of deposits are twofold, i.e. a theoretical thermodynamic study to find out whether deposition can take place and experimental, kinetic studies to find out whether the deposition is fast enough to cause problems.

Silica deposits are usually not formed inside wells but may form in surface equipment and reinjection wells. The saturation temperature and pressure of amorphous silica control the deposition. This can be calculated but rate experiments may be performed to find out whether it is possible to operate at a lower temperature.

Flashing causes CO_2 stripping and a pH increase, which may lead to calcite deposition according to

$$Ca^{+2} + 2HCO_3^- \Leftrightarrow CaCO_3 + CO_2 + H_2O$$

Calcite solubility is retrograde, i.e. it decreases with increasing temperature. The extent of supersaturation can be calculated and the reaction is very fast so rate experiments need not be carried out.

Magnesium silicates are formed upon heating of silica containing ground water or mixing of cold ground water and geothermal water. They have been shown to consist mainly of poorly developed antigorite (Gunnarsson et al. 2005) Their solubility decreases (deposition increases) with increased temperature and pH. The rate of deposition has been found to increase linearly with supersaturation but exponentially with temperature.

5.2 Corrosion

The term corrosion is used about the chemical destruction of materials. Steel is the most important material used in geothermal installations and its corrosion is due to the following half reactions

Anodic half reactions

$$Fe \rightarrow Fe^{+2} + 2e^-$$
$$Fe \rightarrow Fe^{+3} + 3e^-$$

Cathodic half reactions

$$H_2O + \tfrac{1}{2}O_2 + 2e^- \rightarrow 2OH^-$$
$$H_2O + 2e^- \rightarrow H_2 + 2OH^-$$
$$2H_2CO_3 + 2e^- \rightarrow 2HCO_3^- + H_2$$

The most common corrosive species in geothermal fluids are O_2 at low temperatures; H^+ (pH) but low pH favours the first two cathodic half-reactions; Cl^- which gives $Fe^{+2} + Cl^- \Leftrightarrow FeCl^+$ thus favouring the first anodic half-reaction; CO_2 which controls pH and favours the last cathodic half-reaction. H_2S attacks Cu, Ni, Zn and Pb. H_2S, CO_3^{-2} and SiO_2 may form protective films on steel.

6. CONCLUSIONS

Subsurface waters are divided into six categories but have mostly at one time or another circulated in the atmosphere. In areas of spreading the origin of geothermal waters is almost exclusively meteoric or oceanic but in subduction areas components of evolved connate and magmatic water are found. Geothermal waters have been divided into four groups according to their major ion composition, i.e. alkali chloride, acid sulphate, acid sulphate-chloride and bicarbonate waters.
Conservative constituents are used to trace origin and flow but rock-forming constituents are used to determine subsurface temperature and other conditions.

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GEOTHERMAL SAMPLING AND ANALYSIS

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ABSTRACT

Sampling and analysis provide the data for all geochemical interpretation and thus it is imperative that these tasks be performed by trained personnel with insight into possible errors. Different types of containers (glass, or plastic, amber or transparent) and different pre-treatment (filtering, freezing, addition of chemicals) is needed for the various constituents determined. Some constituents need analysis shortly after collection either on the spot or in a near-by laboratory which may be a field laboratory. The most common analytical techniques employed for geothermal fluid samples that are likely to be available in most laboratories are titrimetry, UV-Vis spectrophotometry, atomic absorption spectrophotometry (AAS), ion chromatography (IC), electrometry and gas-solid chromatography (GSC). In recent years inductively coupled plasma has become widely used both with atomic emission spectrometry (ICP/AES) and mass spectrometry (ICP/MS) but this requires expensive equipment and these instruments tend to be run by large commercial laboratories on a commercial basis and it is quite common that samples are sent there for analysis, especially for major cations and trace elements. Stable isotopes are analysed for by mass spectrometry (MS) and radioactive isotopes by radiometry. These techniques are not available to all laboratories and are frequently carried out on a commercial basis. From the returns in the inter-laboratory comparison of analytical techniques carried out by the International Atomic Energy Agency in 2002 involving 31 laboratories working with geothermal samples it is clear that AAS is the most used technique for cation analysis but titrimetry and UV-Vis spectrophotometry for anion analysis.

1. INTRODUCTION

The collection of samples for chemical analysis is the first step in a long process which eventually yields results that provide building blocks in the model of a geothermal system. It is imperative that this step is properly carried out because all subsequent steps depend on it.

There are several hidden dangers inherent in the collection of geothermal sample. The terrain may be treacherous and dangerous chemicals need to be handled. Thus there is an obvious need for well trained personnel with insight into possible errors and interferences to carry out this task. The most common mistakes made during sampling involve the use of improper containers, improper cleaning and lack of or improper treatment for the preservation of samples.

2. CONTAINERS

For lightness, ruggedness and tolerance of bumps in the field plastic bottles are the best. Most plastics are however relatively permeable and let atmospheric air easily through, possibly setting off oxidation reactions, and liquids may easily evaporate through them causing concentration of constituents and possible oversaturation. Many plastics are also rife with possible adsorption sites for sample constituents and may thus decrease their concentrations.

Glass is fragile and relatively heavy but can fairly easily be made airtight. Thus glass containers are preferable for the preservation of constituents affected by atmospheric air. Constituents that are sensitive to light are collected into amber bottles.

If containers have not been specifically pre-cleaned and prepared for a certain task they should be rinsed at least three times with the sample fluid prior to collection.

3. SAMPLE PRESERVATION

Some constituents will not survive intact from sample collection to analysis without special precautions. Common reasons for concentration changes are interaction with suspended matter, adsorption on the walls of the containers, biological activity, redox reactions, polymerization and precipitation. Different preservation methods are needed for the various processes and thus the total sample will comprise several sub-samples. Preservation methods may be physical or chemical and the more common ones are listed in Table 1.

It is desirable that samples be kept relatively cool apart from the inconvenience of handling boiling hot water and steam. Fluid that is well above ambient temperature is therefore cooled to ambient temperature using a cooling device, usually a cooling coil immersed in cold water, during collection. Steam samples collected into NaOH in double-port bottles may by-pass the cooling device and the bottle itself is cooled in cold water.

4. COLLECTION

The collection of samples of non-boiling water can be divided into two categories, samples from natural springs and samples from hot water wells. When collecting samples from hot springs it is desirable that the water be free-flowing from the sample spot. If not, a sampling pump is needed. Water temperature and discharge as well as wellhead pressure if available are reported.

The collection of representative samples from high-temperature drillholes is done either by using the separator on the wellhead separating the whole discharge or with a small Webre separator. Natural steam discharge may occur in many different forms, such as gentle discharge from a large area of hot ground or major discharge from large fumaroles. The most useful information is often obtained from steam discharged from powerful fumaroles.

It has been shown that the most representative samples are collected from the flow of a two-phase well at about 1.5 m distance from the T-joint at the well top.

The various sub-samples collected are described in detail in Table 2 but the total procedure for collection from high-temperature wells is shown in Figure 1. Samples are collected into plastic bottles unless otherwise specified.

TABLE 1: Preservation methods for geothermal samples

Type	Method	Purpose	Used for
Physical	Filtration	Prevent interaction with suspended matter	Anions, cations
	Freezing	Prevent biological activity	Nutrients
	Airtight container	Prevent interaction with atmospheric air	Volatiles
	On-site analysis	Prevent reactions of reactive constituents	Reactive constituents
Chemical	Base addition	Absorption of acid gases	CO_2, H_2S in steam, $\delta^{34}S$ in H_2S in vapour
	Acidification	Prevent adsorption on walls of containers	Cations
	Precipitation	Prevent a constituent from reaction to change the concentration of another	Sulphide to preserve sulphate
	Sterilization	Prevent biological activity, using HgCl or formaldehyde	$\delta^{34}S$ and $\delta^{18}O$ in SO_4, prevents biological oxidation of sulphide
	Dilution	Prevent polymerization and precipitation	Silica
	Redox	To change oxidation state of a volatile constituent to make it less volatile	Hg
	Ion exchange	Concentrate and further prevent adsorption on walls of container of trace constituents	Trace cations
	Extraction	Concentrate and further prevent adsorption on walls of container of trace constituents	Trace cations

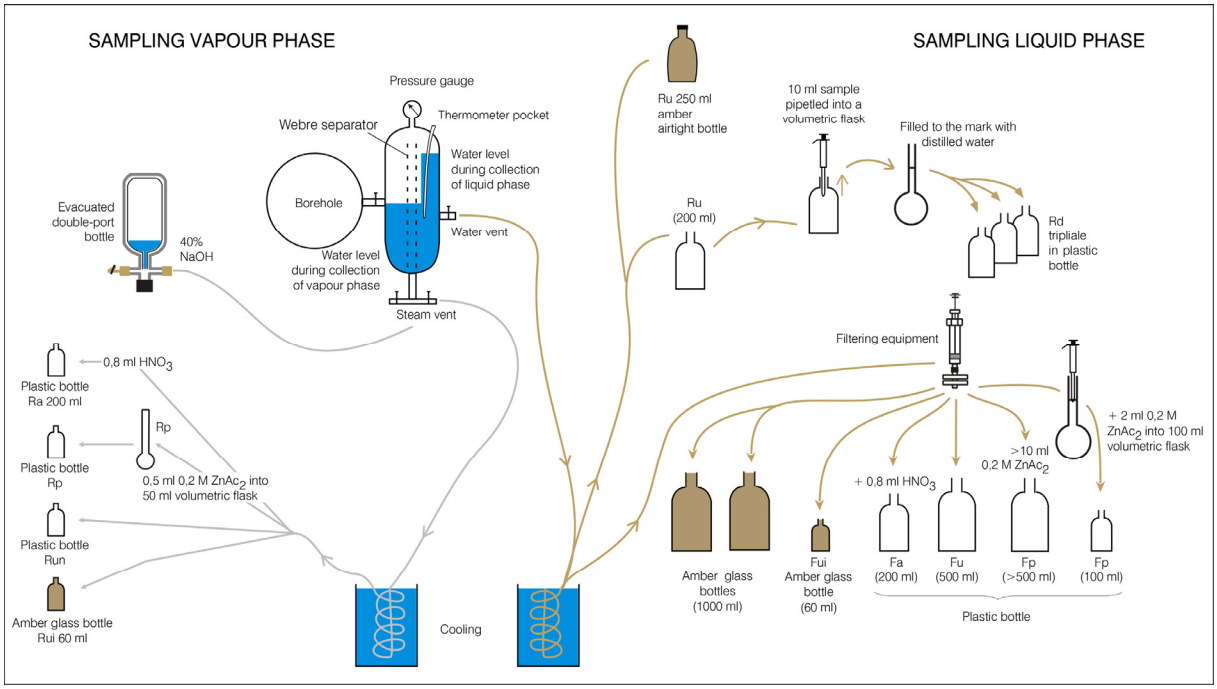

FIGURE 1: Overview of collection of a sample from a two-phase geothermal well for chemical analysis.

TABLE 2: Treatment and sub-samples from geothermal sampling

Phase	Treatment	Specification	To determine
Vapour	None; amber glass bottle	Ru	δ^2H, $\delta^{18}O$
	0.5 ml 0.2 M $ZnAc_2$ added to sample in 100 ml volumetric glass flask to precipitate sulphide	Rp	SO_4
	None	Ru	Anions
	0.8 ml conc. HNO_3 (Suprapur) added to 200 ml sample	Ra	Cations
	Added to 50 ml 40% NaOH in evacuated double port bottle	Gas sample, Ai	CO_2, H_2S in NaOH, residual gases in gas phase, $\delta^{34}S$ in H_2S in vapour
Liquid	None	Ru	Mg, SiO_2 if < 100 ppm
	Dilution; 10 to 50 ml of sample added to 90 to 50 ml of distilled, deionised water	Rd (1:10 to 1:1))	SiO_2 if > 100 ppm
	None; amber glass bottle with ground glass stopper	Ru	pH, CO_2, H_2S (if not in field)
	Filtration (0.45)	Fu	Anions
	Filtration; 2 ml 0.2 M $ZnAc_2$ added to sample in 100 ml volumetric glass flask and ≥ 10 ml to ≥ 500 ml bottle containing ≥ 25 mg SO_4 to precipitate sulphide	Fp, Fpi	SO_4, $\delta^{34}S$ and $\delta^{18}O$ in SO_4
	Filtration; 1 60 ml and 2 1000 ml amber glass bottle, with ground glass stoppers	Fui, Fuc, Fut	δ^2H, $\delta^{18}O$, ^{13}C, ^3H
	Filtration; 0.8 ml conc. HNO_3 (Suprapur) added to 200 ml sample	Fa	Cations

The vents on the Webre separator are opened and the fluid is allowed to flow from the borehole through the separator. Care is taken that the pressure in the separator does not deviate much from that of the wellhead. For the collection of the vapour phase the water level inside the separator is kept low until preferably a mixture of water and steam issues through the water vent. A blue cone should form at the steam vent showing that dry steam is being issued. To check the efficiency of the separation a small sample of condensed steam may be drawn and the concentration of a non-volatile component such as Na or Cl determined, compared with the concentration of the same component in the liquid phase and the percentage of carry-over calculated. If t<70°C it may be desirable to determine the dissolved oxygen concentration of the water to estimate its corrosion potential. This determination is carried out during sampling as described below.

When sampling fumaroles care has to be taken that a discrete, directed outflow is chosen and diffuse ones avoided at all costs. A good guide to the suitability of an outflow for sampling is sulphur deposits. A funnel is placed atop the outflow and care taken that no atmospheric air is drawn in. The funnel is connected to a titanium tube which is directed to a lower point where the sample is collected. When sampling springs care has to be taken to obtain a sample as near to the outflow as possible. An indicator such as ink may be used if it is difficult to find. Normally the water sample will be drawn with a pump into an evacuation flask. The filtering apparatus is fitted between the sample and the pump when appropriate. If a gas sample is required two evacuated flask one with taps on both ends below and a double port gas bottle containing 40% NaOH above are arranged in series. The taps are opened slowly, first on the two-ended flask and care taken that water does not enter the double port bottle (Figure 2). Sampling techniques are described in more detail by Ármannsson and Ólafsson (2006).

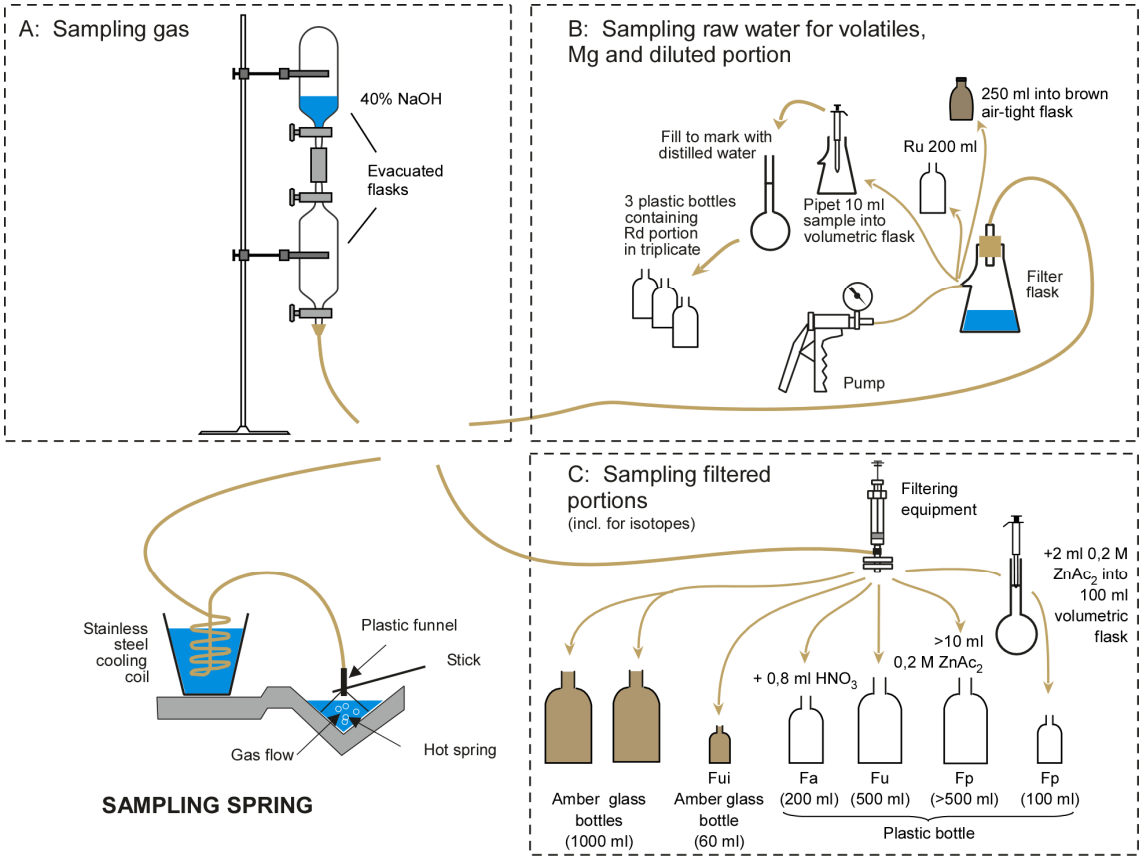

FIGURE 2: Collection of sample from a spring

5. ANALYSIS

5.1 Main laboratory

The choice of an analytical technique depends on several factors, i.e. the availability of instruments, potential servicing facilities for different types of instruments, the presence of trained personnel, and the speed, reliability and cost of the different methods.

5.2 Field laboratory

In a field laboratory facilities for the determination of volatile constituents (pH, CO_2, H_2S, NH_3, O_2), urgent constituents (e.g. SiO_2), constituent used for separation efficiency checks (Na or Cl) and apparatus for specific tests if required e.g. analytical balance, drying oven) and a supply of deionised water.

5.3 Gas analysis

The most important techniques for gas analysis are titrimetry, gas chromatography, mass spectrometry and radiometry. CO_2 and H_2S are determined titrimetrically in a solution of a strong alkali (NaOH or KOH), by an alkalinity titration with HCl, but by either iodometry or with mercuric acetate using dithizone as an indicator. Gases that are not absorbed by the strong alkali (N_2, H_2, CH_4 (higher hydrocarbons if present), O_2, Ar, He) are determined by gas chromatography. Gas chromatographs are usually designed for their specific function. The University of Iceland/Iceland GeoSurvey instrument is a Perkin-Elmer Arnel 4019 Analyser designed for the analysis of geothermal gases. It's most important features are three carrier flow sources, dual and single thermal conductivity detectors, four

valves, five analytical columns and three auxiliary carrier gas sources. It combines into three analytical channels and employs N_2 and He as carrier gases. Its special capability are the separations of H_2 and He and of O_2 and Ar. Trace noble gases (Ne, Kr, Xe) are determined by mass spectrometry and radioactive gases (e.g. Rn) by radiometry.

5.4 Determination of volatile constituents in water

It is recommended that analysis for oxygen and hydrogen sulphide be carried out in the field.

Oxygen is determined colourimetrically using ampoules from CHEMetrics, Inc., containing Rhodazine D for concentrations 0-100 ppb, but Indigo carmine for higher concentrations, but may also be determined by a Winkler iodometric titration. Hydrogen sulphide is determined titrimetrically using mercuric acetate and dithizone (Ármannsson and Ólafsson 2006). Mercury can behave as a volatile constituent. Even though it is usually present as Hg^{+2} it is easily reduced to elemental Hg which is extremely volatile. Therefore it is recommended that an oxidizing agent such as $KMnO_4$ be added upon collection to samples for mercury analysis which is carried out by reduction, gold amalgamation of elemental mercury, heating and flameless atomic absorption spectroscopy (AAS) (Ólafsson 1974).

5.5 Cation analysis

AAS (flame for major, carbon furnace for minor cations), flame emission spectrometry (FES) (major cations), ion chromatography (major cations) and inductively coupled plasma with atomic emission spectrometry (ICP/AES) or mass spectrometry (ICP/MS) (major and minor cations) are all widely used techniques for cation analysis. Specific applications include fluorimetry for Al^{+3}, spectrophotometry for field determinations of Fe^{+2} and the determination of ammonia in saline water, and ion selective electrode for the determination of ammonia in dilute water.

5.6 Anion analysis

Ion chromatography is the most convenient technique for chloride, bromide and sulphate. Sulphide has to be removed from the sample upon collection by precipitation with zinc acetate before the sulphate determination. Fluoride can also be determined by ion chromatography if care is taken to separate its peak from the chloride peak but it is more conveniently determined using an ion selective electrode. Boron and silica can both be determined easily by spectrophotometry and ICP. It is also fairly common to determine sulphate by colourimetry and turbidometry. In Table 3 the results for the three methods used by laboratories taking part in a comparative exercise are compared and for the two samples the best results are obtained by ion chromatography.

TABLE 3: Comparison of results for different methods of sulphate determination in the IAEA laboratory comparison 2001 (after Alvis-Isidro et al. 2002)

Sample No.	Method	Number of labs	Mean mg/l	RSD %
1	IC	8	22.3	10.0
	CO	16	24.2	27.0
	TU	11	26.9	38.2
	Reference		23.2	
3	IC	8	31.5	6.4
	CO	17	32.5	8.8
	TU	11	30.4	24.2
	Reference		31.8	

5.7 Isotope analysis

Stable isotope ratios are determined by mass spectrometry (MS) by comparison with a standard, but radioactive isotopes by radiometry. The most common stable isotopes determined during geothermal work are ^{2}H, ^{18}O, ^{13}C and ^{34}S but the most common radioactive isotopes ^{3}H and ^{14}C which are used for dating, and ^{222}Rn. Due to interferences such as that of water vapour in MS the compounds containing

the isotopes are converted to constituents that do not interfere. Thus H_2O is converted to H_2 for ^2H analysis and CO_2 for ^{18}O analysis. H_2S and SO_4 are converted to SO_2 for ^{34}S analysis and SO_4 to CO_2 for ^{18}O determination. The reduction of H_2O to H_2 has been problematic. Originally hot uranium was used (Friedman 1953) but that is too dangerous. Zn metal (Coleman et al. 1982) has been widely used but the general experience shows that for unexplained reasons the only reagent that seems to work is Zinc shot from BDH. Equilibration using a Pt catalyst (Horita 1988)) has given some useful results but only works for some samples. Those that give erroneous results generally contain H_2S. More recent developments involve the use of hot Cr for the reduction (Schoeller et al. 2000, Donnelly et al. 2001). Oxygen is generally equilibrated with carbon dioxide according to the method of Epstein and Mayeda (1954). Hydrogen sulphide is converted to SO_2 by precipitation as Ag_2S followed by oxidation with Cu_2O or V_2O_5 (Yanagisawa and Sakai 1983). $BaSO_4$ is precipitated either directly from high sulphate solutions or following ion exchange from low sulphate solutions, and then reduced with graphite to obtain CO which then is converted to CO_2 used for the ^{18}O determination (Nehring et al. 1977). The reduced sulphide is precipitated as Ag_2S and converted to SO_2 using the above procedure. The radioactive isotopes are determined by liquid scintillation counting.

5.8 Quality control

The precision of methods can be checked by repeated analysis of the same sample or by duplicates or triplicates of several samples. To obtain an idea of the accuracy of the determinations several approaches are possible, i.e. the use of standard additions to sample to obtain % recovery, carrying out determinations of the same constituent by different methods, using standards or reference samples that are run with each batch of samples determined, checks on ionic balance, i.e. whether the sum of anions determined is close to the sum of cations determined, or a check on mass balance, i.e. whether the sum of constituent concentrations matches that of the result of the determination of total dissolved solids.

TABLE 4: Methods used for selected constituents by laboratories in IAEA Interlaboratory Comparison 2003 (After Urbino and Pang 2004)

Method	Cl	SO_4	SiO_2	K	Mg
Co	2	16	14		
Tm	23				1
IC	5	5		2	2
Tu		9			
AA			9	24	21
ICP/MS			1		
ICP/AE			3		3
FE				1	

Co: Colorimetric; Tm: Titrimetry; IC: Ion Chromatography; Tu: Turbidometry; AA: Atomic Absorption; ICP/MS: Inductively Coupled Plasma/Mass Spectrometry; ICP /AE: ICP/Atomic Emission Spectrometry; FE: Flame Emission

One of the most useful checks is an inter-laboratory comparison in which samples whose composition is known is sent to a number of laboratories who use different methods for the determination of each sample. Thus each laboratory can measure itself against others in the same field. Examples are the inter-laboratory comparisons for the determination of major constituents of geothermal fluids organized by the International Atomic Energy Agency (Alvis Isidro 2002, Urbino and Pang 2004) from which the results presented in Table 3 are obtained. It is interesting to find out which methods were used by the various laboratories that took part in the 2003 exercise (Urbino and Pang 2004) and are presented in Table 4.

6. CONCLUSIONS

For proper sampling clean containers of appropriate material are needed. Care has to be taken that appropriate preservation techniques for particular constituents are applied. Thus each sample will be composed of several sample fractions ready for analysis. Volatile and urgent constituents are analysed for in a field laboratory or upon sampling. Analysis for most anions is usually best performed in the home laboratory but cations and most trace constituents may be advantageously analysed for in a commercial laboratory applying ICP techniques. A survey of 31 laboratories taking part in an IAEA laboratory comparison exercise showed that Atomic Absorption Spectrophotometry, UV-Vis Spectrophotometry and Titrimetry were the techniques most widely employed.

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CHEMICAL GEOTHERMOMETERS FOR GEOTHERMAL EXPLORATION

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ABSTRACT

Chemical and isotope geothermometers constitute an important geochemical tool for the exploration and development of geothermal resources. They are also important during exploitation in monitoring the response of geothermal reservoirs to production load. During the exploration phase, geothermometry is used to estimate subsurface temperatures, i.e., temperatures expected to be encountered by drilling, using the chemical and isotopic composition of the hot spring and fumarole discharges.

During the later phases in geothermal development and monitoring, geothermometry has been successfully applied to interpret the composition of well discharges with respect to locating the levels of producing horizons in the wells. Geothermometry is also useful in elucidating chemical reactions occurring in the zone of depressurization around wells that result from boiling and or cooling by recharging cold water.

1. INTRODUCTION

Geothermal fluids have diverse chemistries, which largely reflect their geological setting. Many of these chemical differences largely depend on the source of recharge waters and the contribution of gases from magmatic or metamorphic sources. The constituents may be solutes gases or isotopes. Most geothermometers are based on specific chemical equilibrium reactions. Geothermometers can be applied to both natural spring discharges and well fluids. They provide valuable insight as to the nature of the system and "the choice and interpretation of the geothermometer data are the art of the exploration geochemist".

Geothermometers take advantage of specific mineral –solute reactions, which are slow to re-equilibrate at cooler temperatures, especially under conditions where the fluid is effectively separated from the minerals which controlled the equilibria. The result is that hot equilibrium temperature is "frozen in" to the fluid as reflected by solute concentration or solute ratios.

Care must be taken in applying geothermometers, otherwise the results and interpretations may give rise to serious errors. Therefore, the limitations of any geothermometer must be considered. The initial requirement is that samples are correctly taken, and the analyses are accurate. It is good practice to compare temperatures indicated by different geothermometers.

Note that some geothermometers are empirical (e.g. Na-K-Ca, D'Amore and Panichi (1980) gas geothermometer), whereas others are based on thermodynamic properties (e.g. Na-K, K-Mg). As the factors controlling empirical geothermometers are not completely known, theoretical geothermometers may in some cases be more reliable.

Geothermometers have been classified into three groups:

1) Water or solute geothermometers
2) Steam or gas geothermometers
3) Isotope geothermometers

2. CHEMICAL GEOTHERMOMETERS

Water and steam geothermometers are collectively termed chemical geothermometers. During the ascent of geothermal waters from a deep reservoir to the surface, they may cool by conductive heat loss as they travel through cooler rocks or by boiling because of decreasing hydrostatic head.

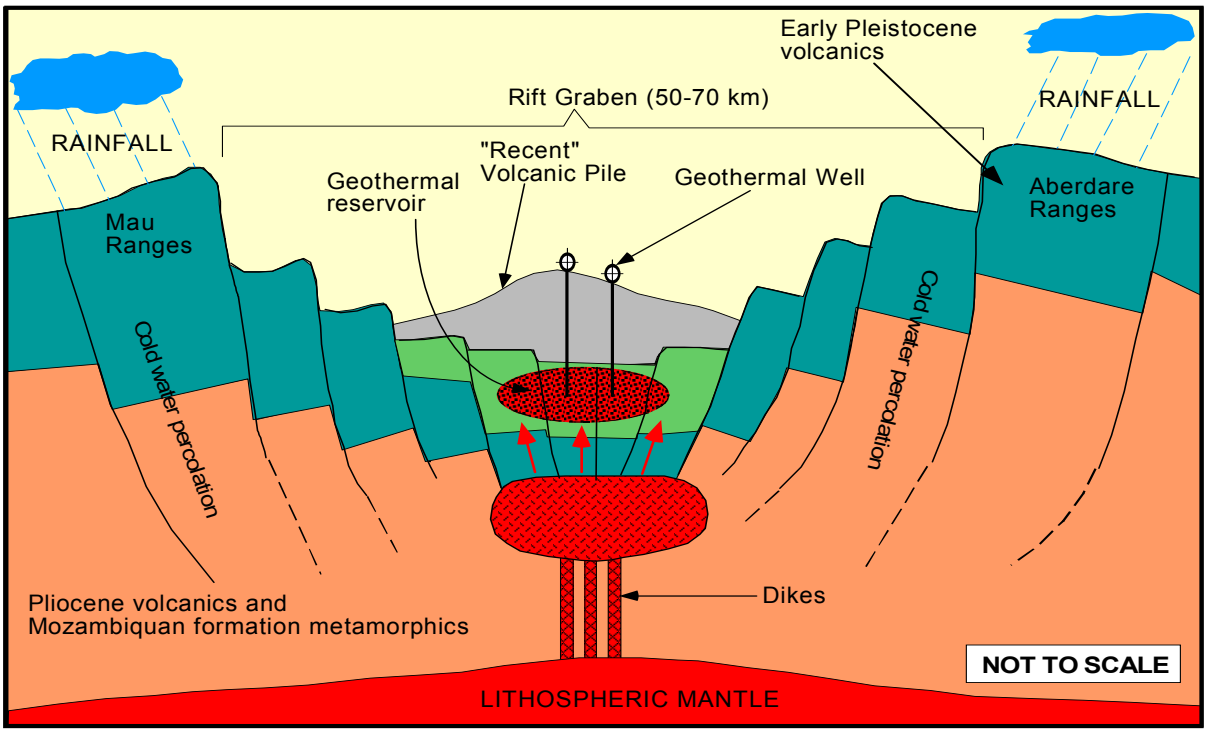

FIGURE 1: The Conceptual Model of the Rift Geothermal system

Figure 1 above shows a conceptual model of the Rift geothermal system. The geothermometers are expected to give accurate prediction of the reservoir temperatures within the production zone before drilling using the data acquired from geothermal manifestations. Cooling by conduction does not by itself cause any changes in the chemical and isotopic composition of the water. Yet, cooling may change its degree of saturation with respect to both primary and secondary minerals. As a result, conductive cooling can bring about some modification in the chemical composition of the ascending water by mineral dissolution or precipitation. Boiling invariably causes changes in the composition of rising geothermal waters. These include degassing and an increase in the solute content of the water due to steam loss. The boiling mechanism affects the gas content of the steam that forms. The principle application of chemical and isotopic geothermometers during geothermal exploration involves estimation of reservoir temperatures below the zone of cooling. When applying these

geothermometers it is invariably assumed that no changes in water composition occur in conjunction with conductive cooling; boiling is taken to be adiabatic.

The amount of conductive heat loss of ascending geothermal waters is proportional to the distance travelled and inversely proportional to the flowrate. For vertical pipe flow, Truesdell et al., (1977) have calculated that temperatures are reduced by half for waters flowing at 0.4 l/s from a 1 km deep reservoir. Conductive cooling can be expected to be important for isolated springs with flow of less than 1 l/s. In the case of closely spaced springs, trying to envisage the amount of conductive cooling in the upflow, the aggregate flow should be considered.

When geothermometers are applied to estimate subsurface or aquifer temperatures, a basic assumption is that temperature dependent chemical or isotopic equilibria prevail in the source aquifer. Further, as stated above, the approximation is made that chemical and isotopic reactions do not significantly modify the composition of the fluid as it ascends from the source aquifer to the point of sampling, whether it is a thermal spring, fumarole, or wellhead.

Equilibrium between mineral-solution or solute-solute is assumed for geothermometry to be applied. Equilibrium between quartz and solution as well as between alkali feldspar and solution is invariably attained in geothermal reservoirs when temperatures exceed about 150-180°C. Accordingly, the application of the quartz and the Na/K geothermometers to high temperature geothermal reservoirs can be regarded as thoroughly established.

Experience shows that results for different chemical and isotope geothermometers sometimes compare well for a particular discharge although sometimes, large differences are seen. Good conformity between individual geothermometers is usually taken to indicate that the assumption of equilibrium is valid and that faith can be put into the results. Discrepancy in results, on the other hand, is indicative of dis-equilibrium. A discrepancy may, however, be utilized to quantify various processes in geothermal systems such as boiling and mixing with cooler water in the upflow zones. Therefore, differences in the results of individual geothermometers need not be a negative outcome for their interpretation.

3. WATER GEOTHERMOMETERS

The most important water geothermometers are silica (quartz and chalcedony), Na/K ratio and Na-K-Ca geothermometers. Others are based on cation ratio and any uncharged aqueous species as long as equilibrium prevails (Arnorsson and Svavarsson, 1985). A temperature equation for a geothermometer is a temperature equation for a specific equilibrium constant referring to a specific mineral-solution reaction.

3.1 Silica geothermometers

Silica geothermometer is based on experimentally determined variations in the solubility of different silica species in water, as a function of temperature and pressure.

The basic reaction for silica dissolution is

$$SiO_{2(qtz)} + 2H_2O = H_4SiO_4$$

In most geothermal systems, deep fluids at temperatures > 180°C are in equilibrium with quartz; it is stable up to 870°C and has the lowest solubility compared to other silica polymorphs. Quartz is common as a primary and secondary (hydrothermal) rock- forming mineral. Silica polymorphs with a less ordered crystal structure (i.e. chalcedony, opal CT, cristobalite) have higher solubilities than quartz and form at cooler temperatures of < 180°C.

Geothermometer Temperature (°C) = 1309/ (5.19-log S) – 273.15 (Fournier 1977)
(Quartz-no steam loss)

S represents silica concentration as SiO_2 in mg/kg

The quartz geothermometer is best for reservoir conditions > 150°C. Below this temperature chalcedony rather than quartz probably controls the dissolved silica content. Six main silica geothermometers exist.

1. Adiabatic (Maximum steam loss) – this equation compensates for loss of steam from boiling solutions and the resultant increase in concentration of silica, plus the cooling of the solution by adiabatic expansion due to decrease in the hydrostatic – hydrodynamic pressure head. The silica quartz adiabatic geothermometer is best used for well discharges and vigorously boiling springs, Figure 2, and pools with high discharge rates (>= 2 kg/s), especially those with silica sinter deposits.

$$t^oC = \frac{1522}{5.75 - \log(SiO2)} - 273.15 \quad \text{(Fournier 1977)}$$

FIGURE 2: Hot geysers at Lake Bogoria geothermal prospect in the Kenya Rift

2. Conductive (no steam loss) – this equation represents experimentally determined solubilities and applies to those waters that cool solely by conduction during ascent. The silica quartz conductive cooling geothermometer is best used for springs at sub-boiling temperatures (giving a maximum estimate of the reservoir temperatures based on quartz solubility), or for well data that have been calculated to reservoir conditions.

$$t^oC = \frac{1309}{5.19 - \log(SiO2)} - 273.15 \quad \text{(Fournier 1977)}$$

3. If the quartz geothermometer, other geothermometers, indicate temperature of 120-180°C it is possible that chalcedony may control silica solubility. Under these circumstances, test the chalcedony geothermometer

$$t^oC = \frac{1112}{4.91 - \log(SiO2)} - 273.15$$ (Arnorsson et al. 1983)

4. If the chalcedony geothermometer gives temperatures of 100-120°C, it may represent the true deep temperature. However, if the calculated temperature is below 100°C, the armorphous silica may control the solubility. At lower temperatures in systems with silicic host rocks, the abundance of volcanic glass may enable saturation of a fluid with respect to amorphous silica.

$$t^oC = \frac{731}{4.52 - \log(SiO2)} - 273.15$$ (Fournier 1977)

3.2 Na-K geothermometer

The response of the Sodium/Potassium (Na/K) ratio, decreasing with increasing fluid temperature, is based on temperature dependant cation exchange reaction between albite and K feldspar (adularia)

$NaAlSi_3O_8 + K^+ = KAlSi_3O_8 + Na^+$
Albite K feldspar

$$t^oC = \frac{1217}{1.438 + \log(Na/K)} - 273.15$$ (Fournier 1979)

$$t^oC = \frac{1390}{1.75 + \log(Na/K)} - 273.15$$ (Giggenbach et al. 1988)

Waters from high temperature reservoirs (180°C) of chloride waters are suitable for this geothermometer. For lower temperature reservoirs where fluids have long residence times, the Na-K geothermometer may in some cases be applicable.

The advantage of this geothermometer include that it is less affected by dilution or steam loss given that it is based on a ratio. This is if the diluting waters are low in Na, K, and Ca. Note that seawater is not a diluent but an end member fluid of distinct composition. The geothermometer is applicable to 350°C, as the re-equilibration is slower than that of the silica-quartz geothermometer. Therefore, the Na-K geothermometer may give indications regarding the deeper part of the system in comparison to the silica – quartz geothermometer, depending on the system's hydrology. A slow rising fluid can, however, re-equilibrate at shallower levels and cooler temperatures.

3.3 Limitations on the Na-K geothermometer

The Na-K geothermometer gives poor results below 100°C. It is also unsuitable if the waters contain high concentration of calcium (Ca) as is the case for springs depositing travertine. The following general rules apply;

1) Use for waters indicating reservoir temperatures >100
2) Use if the waters contain low Ca; i.e. the value of (log (Ca1/2/Na) + 2.06) is negative
3) Use for near neutral pH chloride waters.

3.4 Na-K-Ca Geothermometer

The Na-K-Ca geothermometer was developed by Fournier and Truesdell (1973), for application to waters with high concentrations of calcium. This is an empirical geothermometer and theoretical constraints include equilibrium between Na-K feldspars plus conversion of calcium alumino silicate

minerals (e.g. Plagioclase) to calcite. The main advantage of the Na-K-Ca geothermometer in comparison with the quartz geothermometer, and especially the Na/K geothermometer, is that it does not give high and misleading results for cold and slightly thermal, non-equilibrated waters.

The assumptions included in development of the empirical equation are:

1) Excess silica is present
2) Aluminium is conserved in solid phases.

The following considerations apply in application of this geothermometer:

1) Calculate $\{\log(Ca^{1/2}/Na) + 2.06\}$; if its value is positive, the use $\beta = 4/3$ in the formula in determining the temperature. If that calculated temperature is <100°C, then this temperature is appropriate.
2) If the $\beta=4/3$ calculated temperature is >100°C, or $\{\log(Ca^{1/2}/Na) + 2.06\}$ is negative, then use $\beta=1/3$ to calculate the temperature.

$$t^oC = \frac{1647}{\log(Na/K) + \beta\log(\sqrt{Ca}/Na) + 2.24} - 273.15$$

$$\beta = 4/3 \; for \; Ca^{1/2}/Na > 1 \; and \; t < 100^oC;$$

$$\beta = 1/3 \; for \; Ca^{1/2}/Na < 1 \; or \; if \; t_{4/3} > 100^oC$$

3.5 Limitations of the Na-K-Ca geothermometer

The mineralogical background of the geothermometer must not be forgotten. It is not correct to apply the Na/K or the Na-K-Ca geothermometer to acid waters, which would not be in equilibrium with feldspars, nor are they applicable to water systems in rocks with unusually high or low concentrations of a particular alkali unless direct correlations with measured temperatures are available.

Changes in concentration resulting from boiling and dilution will affect the Na-K-Ca temperature. The main effect is loss of carbon dioxide due to boiling, causing calcite to precipitate. The loss of dissolved Ca results in the Na-K-Ca temperatures, which are too high. The amount of error is proportional to the amount of carbon dioxide in the fluid.

The effect of dilution is minimal if the geothermal fluid is much more saline than the diluting fluid. For dilution >50%, Na-K-Ca temperatures are too low as the $(Ca^{1/2}/Na)$ relationship is strongly affected.

In some dilute high temperature waters containing high dissolved carbon dioxide and in waters with low Ca concentrations, the term β may become strongly negative. Under these conditions the Na-K geothermometer may be more useful.

3.6 Mg correction for the Na-K-Ca geothermometer (Fournier and Potter, 1979)

Most fluids >180°C, contain <0.2 mg/kg Mg. In more saline fluids Mg is low relative to other cations. This strong temperature dependence of Mg concentration is mainly due to the formation of chlorite. At higher temperatures, other minerals such as biotite or actinolite may also remove Mg from solution. At cooler temperatures, Mg may be incorporated into clays or carbonates. The Mg correction is applied to those geothermal waters (unaffected by mixing) that contain high dissolved Mg, because

they are saline, or because the reservoir temperature is <180°C. The presence of high Mg gives anomalously high temperature results.

The following correction was derived empirically;

1) If $T_{Na\text{-}K\text{-}Ca}$ is <70°C do not apply correction.
2) Calculate R, using equivalents (Molality/Charge) where;

$$R = \frac{Mg}{Mg + Ca + K}(100)$$

3) If R > 50 assume the water is from relatively cool equilibrium conditions with temperatures about equal to the measured water temperature irrespective of the high $T_{Na\text{-}K\text{-}Ca}$.
4) If $T_{Na\text{-}K\text{-}Ca}$ > 70°C and R<50, use R to determine ΔT_{Mg} (Fournier 1979) and subtract ΔT_{Mg} from the $T_{Na\text{-}K\text{-}Ca}$ to get the correct geothermometer temperature.

The Mg-correction is usually applied to cooler temperature systems; it is best applied to sub-boiling springs with high discharge rates.

3.7 Na-Li geothermometer

Sodium – Lithium (Na-Li) geothermometer, which is empirical and based on the Na/Li ratio. Two equations exist, one for fluids containing < 11000 mg/kg Cl and the other for fluids containing >11000 mg/kg Cl. Both require molar values.

The theory behind this geothermometer is based on the temperature dependent reaction:

$$\text{Clay-Li} + H^+ = \text{Clay-H} + Li^+$$

In reality, the controlling equilibria are probably based on cation exchange reactions with clays and zeolites rather than formation of discrete mineral phases. The ratio is thought to be constant as the fluid ascends from the reservoir to the surface. However, some Li may be lost from solution to alteration minerals during cooling.

$$t^oC = \frac{1195}{0.130 + \log(mNa / mLi)} - 273.15 \qquad \text{(Fouillac et al. 1981)}$$

(Valid for Cl concentrations of > 0.3 mol/kg)

$$t^oC = \frac{1000}{0.389 + \log(mNa / mLi)} - 273.15 \qquad \text{(Fouillac et al. 1981)}$$

(Valid for Cl concentrations of < 0.3 mol/kg)

3.8 K-Mg Geothermometer

This geothermometer is applied to situations where dissolved Na and Ca have not equilibrated between fluid and rock. This geothermometer re-equilibrates quickly at cooler temperatures related to the reaction:

$$0.8\text{K-mica} + 0.2\text{chlorite} + 5.4\text{silica} + 2K^+ = 2.8\text{K-feldspar} + 1.6H_2O + Mg^{2+}$$

$$t^oC = \frac{4410}{14.0 + \log(K^2 / Mg)} - 273.15 \qquad \text{(Giggenbach et al. 1988)}$$

4. GAS GEOTHERMOMETERS

Surface manifestations in most geothermal fields consist mainly of fumaroles, springs and hot grounds (Arnorsson, 2000). Where the shallow ground water table is deep in the subsurface, springs are not available, for example, Figure 3, in Kenya Rift. When this is the case, water geothermometers cannot be used to predict the subsurface temperatures. This motivated the early scientists to develop gas geothermometers, e.g. D'Amore and Panichi (1980). There are 3 types of gas geothermometers based on;

FIGURE 3: Fumaroles in the Kenya Rift

1) Gas- gas equilibria
2) Gas-mineral equilibria
3) Mineral – gas equilibria involving the residual gases such as, CH4, H2, H2S.

Temperature dependent gas-gas and or mineral gas equilibria are believed to control the concentrations of gases like CO_2, H_2S, H_2, N_2, NH_3 and CH_4 in geothermal reservoir fluids. Arnorsson and Gunnlaugsson (1985) proposed temperature functions for six geothermometers applicable to fumarolic steam. Three (3) were based on the concentrations of CO_2, H_2S, and H_2 respectively. Two (2) were based on the gas ratios (CO_2/H_2) and H_2/H_2S). The gas concentration is in mmol/kg of steam.

$$t^oC = 44.1 + 269.25Q - 76.88Q^2 + 9.52Q^3$$
$$Q = \log(mmol/kg)\ CO_2$$

$$t^oC = 246.7 + 44.8Q$$
$$Q = \log(mmol/kg)\ for\ H_2S$$

$$t^oC = 277.2 + 20.99Q$$
$$Q = \log(mmol/kg)\ for\ H_2$$

$$t^oC = 341.7 - 28.57Q$$
$$Q = \log(mmol/kg) \; for \; CO_2/H_2$$

$$t^oC = 304.1 - 39.48Q$$
$$Q = \log(H_2S/H_2)$$

$$t^oC = \frac{4625}{10.4 + \log(CH_4/CO_2)} - 273.15 \qquad \text{(Giggenbach 1991)}$$

5. ISOTOPE GEOTHERMOMETERS

Isotope exchange reactions, which achieve equilibrium in the natural system, are temperature dependent. Isotopes of elements are fractionated in the chemical processes operating in natural water-rock systems (Ellis & Mahon, 1977). The fractionation is largest for lighter elements found in geothermal systems, such as, Helium, hydrogen, carbon, oxygen, and sulphur. Isotope exchange reactions may be between gases and steam phase, a mineral and gas phase, water and a solute or a solute and a solute. Although there are many isotope exchange processes, few have been used because of simplicity of sample collection and preparation, ease of isotopic measurement, a suitable rate of achieving isotopic equilibrium, and knowledge of the equilibrium constants.

5.1 Oxygen Isotopes

Chemical elements with the same atomic number (protons) and different atomic mass are defined as Isotopes. Isotopes have identical chemical behaviour but different physical properties. Hydrogen has three isotopes, ^1H, ^2H and ^3H, respectively and oxygen also has three isotopes, ^{16}O, ^{17}O and ^{18}O. Isotope geothermometers involving oxygen or hydrogen exchange reactions with water assumes equilibrium. An isotopic fractionation occurs when steam separates from hot water. The isotopic compositions of both the steam and water in a well sample may be determined from the total discharge, whose steam and water fraction is known. Isotopic fractionation factors are generally symbolized by α. The general expression for fractionation between two compounds, A and B, is as follows:

$$1000 \ln {}_{AB} = \delta_A - \delta_B$$

where δ_A and δ_B designate the respective isotopic ratios in compounds A and B (Arnorsson, 2000). Four isotopic geothermometers based on exchange reactions have been developed and extensively used.

5.2 Carbon dioxide and methane isotope geothermometer

Reaction:

$$^{12}CO_2 + {}^{13}CH_4 = {}^{13}CO_2 + {}^{12}CH_4$$

Temperature equation:

$$1000 \ln \alpha = 15.25 \times 10^3/T + 2.432 \times 10^6/T^2 - 9.56$$

(Valid in the range 100 – 400°C)

and

$$t^oC = \frac{15790}{1000 \ln \alpha + 9.0} - 273.15$$

(Valid in the range 150 – 500°C)

5.3 Methane – Hydrogen gas isotope geothermometer

Reaction:

$$CH_3D + H_2 = HD + CH_4$$

Temperature equation:

$$1000\ln\alpha = 288.9\times10^3/T + 31.86\times10^6/T^2 - 238.28$$

(Valid in the range 100 – 400°C)

5.4 Water-hydrogen gas isotopic geothermometer

Reaction:

$$HD + H_2O = H_2 + HDO$$

Temperature equation:

$$1000\ln\alpha = 396.8\times10^3/T + 11.76\times10^6/T^2 - 217.3$$

(Valid in the range 100 – 400°C for equilibrium between H_2 and steam)

5.5 Sulphate-water oxygen isotope geothermometer

The isotope exchange reaction rate is temperature dependent and is inversely proportional to the aquifer pH. The limitation with this geothermometer is that mixing with sulphate bearing shallow ground waters and oxidation of H2S may modify the isotopic composition of the dissolved sulphate, such that it no longer reflects the deep geothermal sulphate. Evaporation and mixing with shallow ground water will also affect the water isotopic composition.

Reaction:

$$S16O4 + H218O = S16O318O + H216O$$

$$1000\ln\alpha = 3.25\times10^6/T^2 - 5.6$$

(Valid in the range 100 – 350°C)

5.6 Sulphate – hydrogen sulphide geothermometer

Reaction:

$$32SO4 + H234S = 34SO4 + H232S$$

$$1000\ln\alpha = 6.04\times10^6/T^2 + 2.6$$

(Valid for t > 150°C)

5.7 Carbon dioxide – water isotopic geothermometer

Reaction:

$$C16O2 + H218O = C16O18O + H216O$$

Temperature equation:

$$1000\ln\alpha = 7.849\times10^3/T + 2.941\times10^6/T^2 - 887.28$$

(Valid in the range 100 – 400°C for equilibrium between CO2 and steam)

and

$$1000\ln\alpha = -18.29\times10^3/T + 7.626\times10^6/T^2 + 19.6$$

(Valid in the range 100-400°C for equilibrium between CO2 and water)

6. CONCLUSIONS

Chemical and isotope geothermometers constitute an important geochemical tool for the exploration and management of geothermal reservoirs. They are also important during exploitation in monitoring the response of geothermal reservoirs to production load, Figure 4. During the exploration phase, geothermometry is used to estimate subsurface temperatures, i.e., temperatures expected to be encountered by drilling, using the chemical and isotopic composition of the hot spring and fumarole discharges.

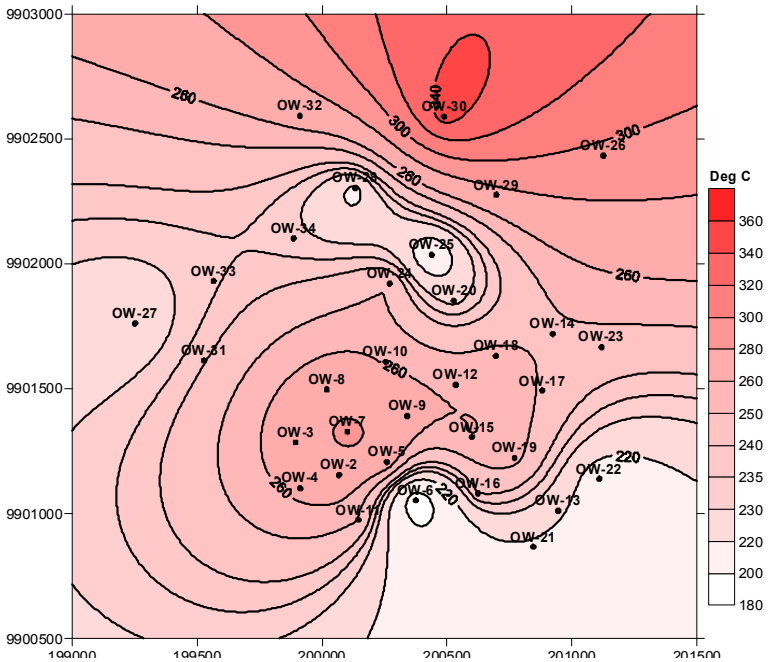

FIGURE 4: Using geothermometers as a monitoring tool in Olkaria, Kenya.

The geothermometers are based on chemical reactions, which are temperature dependent and at equilibrium. During the later phases in geothermal development and monitoring, geothermometry has been successfully applied to interpret the composition of well discharges with respect to locating the levels of producing horizons in the wells. Geothermometry is also useful in elucidating chemical reactions occurring in the zone of depressurization around wells that result from boiling and or cooling by recharging cold water.

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GEOCHEMICAL MONITORING PRACTICES

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ABSTRACT

Identifying a clear goal for any monitoring campaign will lead to selection of appropriate scientific sampling and analytical techniques. A geothermal monitoring program without a clear sense of purpose may not meet resource protection needs. Goals of geothermal monitoring efforts include determining if the production of fluid from geothermal wells will measurably affect the discharge of a hydrothermal feature. Geothermal reservoirs undergo physical and chemical changes during drilling and fluid discharge which manifest in the fluid chemistry. Overexploitation of geothermal reservoirs leads to rapid drawdown of reservoir pressure and a corresponding decline in well output and power generation. Predicting undesirable processes like scale formation and corrosion, practicing sound environmental practises are important reasons why geochemical monitoring should be carried out in a geothermal field which leads to sound formulation of management practices of the field.

1. INTRODUCTION

Geothermal systems in the Kenyan rift are located in the vicinity of volcanic centres (Figure 1) and therefore associated with gases/volatiles and fluids that need to be monitored. In these centres, there are surface manifestations indicative of the presence of a hydrothermal system that creates vital signs that can be monitored. These emit heat and discharge hydrothermal water. The water contains chemicals and gases and therefore location, area, heat, water, and chemistry become critical vital signs to monitor. Although these vital signs are observable at the surface, they also provide information about the subsurface hydrothermal system. Volatiles are an essential component in volcanic systems. Since volatiles play an important role, their behaviour can be examined to provide a better understanding of volcanic activity and therefore the geothermal system. Volatiles escape from magma bodies through manifestations like fumaroles and hot springs, often located on a volcano's flanks. Studies of volcanic gas can furnish important insights on the sources of magmas, how magmas move upward to the surface, the influence of hydrothermal systems, and the types of eruptions—for example, explosive vs. effusive—that are observed. The amount of gas dissolved in magma determines, in large part, whether an eruption will be violent or not.

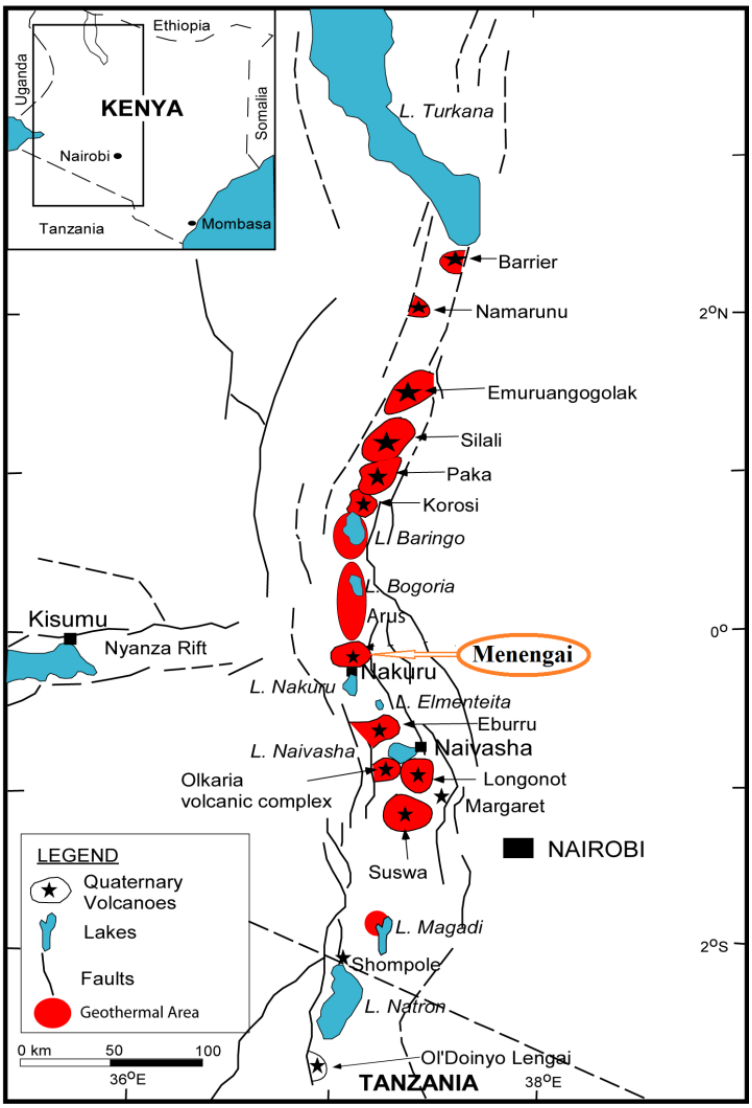

FIGURE 1: Location of Menengai geothermal field and other geothermal areas in Kenya

2. GEOCHEMICAL MONITORING

Geothermal reservoirs undergo changes during drilling and fluid discharge. The changes manifest in the chemistry of geothermal fluids. This can be monitored from the geothermal wells and other surface manifestations located in the vicinity of the geothermal field like domestic water use boreholes, fumaroles and gas vents, springs and nearby streams. The whole system of fluid quality monitoring is aimed at the generation of reliable data, i.e. data that accurately reflect the actual status of the variables which influence geothermal fluid quality. Simply generating good data is not enough to meet objectives but the data must be processed and presented in a manner that aids understanding of the spatial and temporal patterns in fluid quality, taking into consideration the natural processes and characteristics of a reservoir, and that allows the impact of geothermal drilling and fluid utilization to be understood and the consequences of management action to be predicted.

Over exploitation of geothermal reservoirs leads to rapid drawdown of reservoir pressure and a corresponding decline in well output and power generation. Information on the response of the reservoir to the production load with respect to the source of the fluids recharging producing aquifers (Arnórsson et al., 2000) can thus be evaluated and mitigation to changes in temperature or pressure made. Fluid discharged from wells penetrating rocks is a mixture of many components that have traveled different distances from their original points before the reservoir was penetrated to the wellbore. The concentrations of dissolved solids and gases in the discharge of wells penetrating such rocks, is the product of the chemical composition of each source component and its relative contribution to the well discharge. A change in the relative amounts of these components will lead to a change in the composition of the discharged fluid unless their chemical composition was the same.

Data on fluid compositions may provide useful information on the depth level of producing horizons in individual wells. These data provide information as regards recharge and enhanced boiling which in turn have proved valuable to map cold water recharge into single liquid water reservoirs. In addition, this information provides an in depth evaluation into quality of fluid including scaling and corrosion tendencies as the fluid is exploited. Gas compositions can also be used to estimate the initial steam fraction in the aquifer fluid. Some of the reasons, therefore for geochemical monitoring include:

a. ability to recognize hydrothermal processes by monitoring manifestations i.e fumaroles, springs and boreholes.
b. monitoring of the response of geothermal reservoirs to the production load.
c. monitor pressure declines in exploited geothermal reservoirs which can lead to decreased yield of wells and sometimes incursion of cold groundwater into the reservoir.
d. predicting undesirable processes like scale formation and corrosion
e. sound environmental practises
f. helping in formulate management practices of a geothermal field

2.1 Monitoring plan

Before a monitoring campaign is embarked on, a plan should be put in place to deal with management and efficiency of what the whole process will entail. The single most critical issue is the goal of the study. The factors to consider are the manifestations present in the field (fumaroles, gas vents, springs, streams, wells both domestic and high temperature), representativeness of the manifestations and their relation to what results are needed from the monitoring campaign, logistics of sampling/analysis and the data storage.

If personnel do not identify a clear goal for monitoring, then it will not be possible to select appropriate scientific techniques and analyses. A geothermal monitoring program, without a clear sense of purpose, may not meet resource protection needs. Goals of geothermal monitoring efforts include determining if the production of fluid from geothermal wells will measurably affect the discharge of a hydrothermal feature e.g. hot spring; determining if the development of known geothermal area might affect an entire hydrothermal area; and evaluating seasonal variability of hydrothermal features. Another issue in designing a geothermal monitoring plan is the budget. This will guide on how many features to sample, frequency in a given year (for example) the monitoring plan will be undertaken, and the sampling and analytical methods available.

2.2 Sampling and analysis

The rationale for selecting what elements to be monitored in a geothermal field are as listed in Table 1.

TABLE 1: Rationale for selecting different elements and gases to monitor in a geothermal field

Element / gas	Reason for its choice
Conductivity	Used as a simple general indication of bulk change in total concentration of dissolved cations and anions. High amounts of dissolved minerals and salt concentration in water yield high conductivities. Measurements of electrical conductivity can provide estimates of the hydrothermal fluid's purity and contribute to understanding its flow path.
pH	Varies with the proportion of deep to shallow components. Changes in the pH may indicate changes in the flow path of the geothermal fluid, changes in the temperature of the geothermal fluid, loss of CO_2, or anthropogenic activities.
Na^+, K^+, Ca^{2+}, SiO_2	Used as geothermometers.
Mg^{2+}	Indicates mixing with low temperature surface waters. Present in very low concentration due to solubility considerations
Cl^-	Determines dilution or contribution of deep thermal water that has high chloride content.
SO_4^{2-}	Indicates contribution of shallow steam heated waters formed by oxidation of S^{2-}
Fe, Al	Evaluate the subsurface mineralogy.
HCO_3^-	Increases with greater ground water components in samples. Helps distinguish deep steam heated and ground water components (when used together with Cl^- and SO_4^{2-}).
Hg, F^-, Fe, Al	Analysed if environmental effects of the discharge are to be considered.
Rb, Cs, Zn, Au	Host rock characterisation i.e. the elements, often when compared with other elements in various combinations of ratios (Nicholson, 1993), may provide useful information about the types of rocks that the fluids have interacted with in the subsurface.
CO_2, H_2S	Used as geothermometers and are also major geothermal gases.
O_2	Not present in deep geothermal fluids. Its presence is used to check whether a gas sample is contaminated.
CH_4	Although present in geothermal fluids, it can also indicate shallow organic decomposition.
He	Indicates a mantle component if in elevated concentrations.
Isotopes	Used for various reasons, e.g to • identify mantle input ($^3He/^4He$); • assess water source (^{15}N, $^{18}O/^{16}O$, ^2H, ^{13}C, ^{34}S) • date water (^3H, ^{14}C, ^{36}Cl)

a. Gas chemistry monitoring

i. Fumaroles

The spectacular emanations of gas (fumaroles) that are seen in the geothermal systems or fields are visible manifestations of the presence of magma at depth. However, gas observed escaping at the surface is not derived from the magma only but is a mixture from different sources that have interacted during the lifetime of the geothermal system. A certain percentage of the gas is derived from magma, which will be initially rich in components such as sulfur and carbon dioxide. Gas chemistry associated with geothermal systems gives information on the sources of magmas, movements of the magmas upward to the surface, the amount of gas dissolved in a magma that determines whether an eruption will be violent or not and also the influence of the magma on the hydrothermal system being exploited.

ii. Soil gas

Soil gas surveys for the gases that do not react with the country rock (CO_2, Rn) can give different insights into a geothermal system. The diffuse degassing of the gases are monitored by measuring their concentration in soil to provide information on the overall permeability of a volcanic edifice, the potential for lateral degassing apart from the main volcanic vent and the ability of a volcano to diffusely release large quantities of gases.

b. Fluid chemistry

Fluids emanating from springs, streams and wells (both domestic and geothermal) should be monitored as is done for the gases emanating from different manifestations in a geothermal system. These fluids give more information in addition to the gases monitored. Some of the information that can be monitored includes dilutions in the reservoir, physical and chemical effects of exploitation of a field (e.g. the changes in temperature, pressure), cold water inflows as seen when there are lower Cl and higher SO_4 measured, boiling in the wells and equilibration of the fluid in the reservoir.

2.3 Reservoir monitoring

Arnórsson et al., (2000) states that the chemical data on fluids and steam sunk into a boiling reservoir provide useful information on the response of the reservoir to the production load as regards recharge and enhanced boiling. These data has proved valuable to map cold water recharge into single liquid water reservoirs and provides information on the quality of the fluid including scaling and corrosion tendencies. Geothermal reservoirs undergo changes resulting from steam exploitation during production that could be physical and/or chemical. Reservoir monitoring should start with power plant commissioning to obtain the information through a carefully planned monitoring program on the effects of water / steam extraction.

As the steam is converted to electricity for use, different areas on the flow diagram of the steam extraction need to be monitored (see Figure 2). This enables monitoring of the quality of the fluid extracted, the separated steam and the re-injected fluid. Overexploitation of geothermal reservoirs leads to rapid drawdown of reservoir pressure and a corresponding decline in well output and power generation. When production is more than the reservoir recharge, pressure drop is experienced and vice versa. Pressure drop can be large, small, and fast or slow depending on the nature of the system. This pressure decline manifests in further changes like decrease in well discharge, changes in surface activity, lowered water level in wells, increased boiling (in high enthalpy systems), increased recharge into the system (usually cold water) and in the worst of cases, surface subsidence that may result in damage to surface installations and equipment.

Cold water recharge leads to changes in chemical composition of the reservoir fluid, usually dilutions, and changes in temperature/enthalpy of reservoir fluid. Temperature changes are measured using various types of sensors or by monitoring the geothermometers. Monitoring of measured and calculated temperatures can give a good insight into the reservoir. Truesdell and Fournier (1977) made comparisons of the measured and calculated temperatures and concluded that equilibrium is only observed in the well if all the

temperatures are closely related or equal e.g. $T_{meas.} = T_{quartz}$. Other conclusions they brought forward are as given in Table 2.

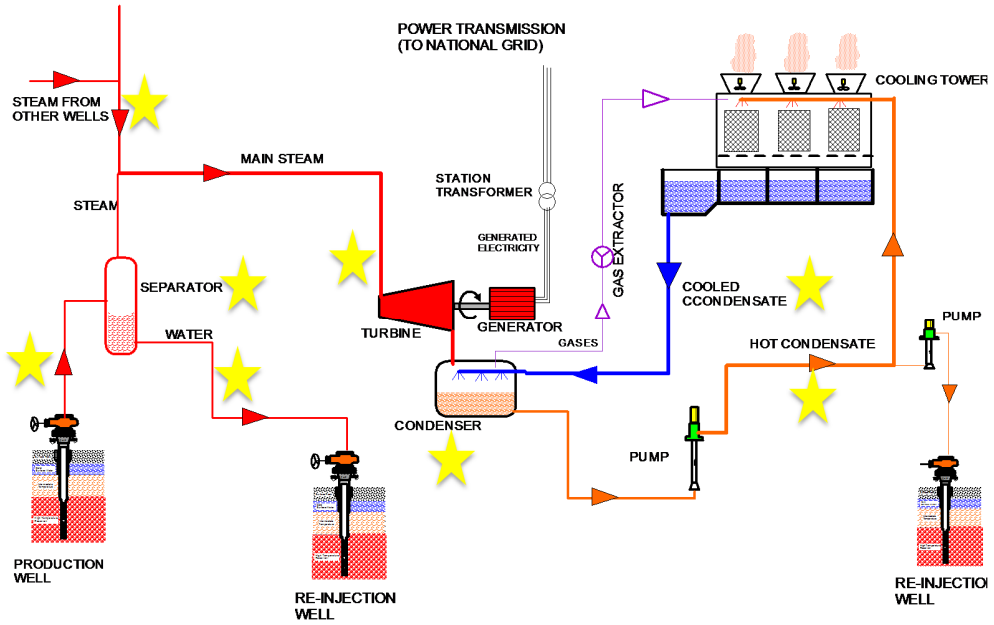

FIGURE 2: Flow diagram of a geothermal power generating station. The yellow stars represent the places where chemical monitoring should take place to ensure good quality steam is extracted and fluids re-injected back into the reservoir

TABLE 2: Temperatures relations to geothermal reservoir processes

Temperature comparison	Conclusion
$T_{NKC} > T_{Qtz} = T_{Meas.}$	Boiling in the flowing well
$T_{Qtz} > T_{NKC} > T_{Meas.}$	
$T_{NKC} > T_{Meas.} = T_{Qtz}$	Mixing of hot geothermal fluids with cooler waters near the well bore.
$T_{NKC} = T_{Qtz} > T_{Meas.}$	Mixture of equilibrated liquid with steam cap
$T_{NKC} > T_{Qtz} > T_{Meas.}$	Cooler more dilute fluid mixing with equilibrated brine

Where T_{NKC} refers to temperature calculated from the Na, K and Ca geothermometer, T_{Qtz} from the quartz geothermometer and $T_{Meas.}$ is the measured temperature from well logging.

Steam purity should be checked at moisture separators before it enters the turbine house. The samples are tested for moisture carry-overs in steam as can be indicated by elemental concentrations of Cl, TDS, SiO_2 and Na. Solid scales may deposit in steam flow pipes as the fluid is extracted and moves on towards the separators or towards the re-injection point. In the cases where the deposition occurs in the line from the well onto the steam separators, steam delivery is drastically reduced. Scale formation can be predicted from monitoring chemistry data as the fluid moves from the reservoir towards the wellhead. In addition to the reservoir monitoring of producing fields, environmental monitoring of potentially harmful elements in waste water e.g. Pb, Zn, As, B, Li, Hg; and gases, mostly H_2S, CO_2 needs to be put in place. Other environmental concerns apart from chemical pollution include surface disturbances, noise, thermal pollution, protection of sites and social and economic effects in the areas where the geothermal exploitation is taking place.

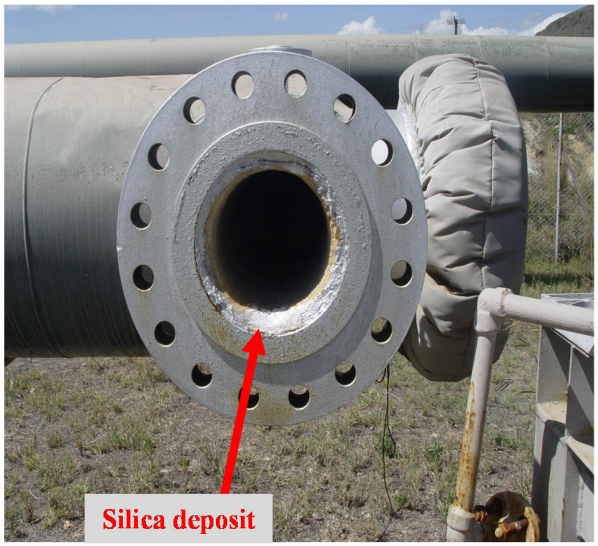

FIGURE 3: Silica scale forming in a steam delivery line. (*Photo courtesy James Wambugu*)

From the study gathered from the reservoir monitoring plan, the management gets information that they use for planning a geothermal field. This can be helpful in decisions concerning:

a. brine re-injection – should the brine re-injected be hot or cold
b. location of the wells used to re-inject and for how long the injection will take place
c. the need to drill more replacement wells, retire some wells
d. the need to increase installed capacity by installing additional generating units

3. CASE STUDY

3.1 Geohazard monitoring in the Menengai Geothermal Field

The main objectives for this study were to create a baseline for fluid chemistry in the regions surrounding the Menengai geothermal field (Figure 1) in view of the ongoing drilling for geothermal steam and future exploitation of the Menengai geothermal field, characterize the fluids that are feeding or are peripheral to the geothermal system, and monitor any changes that might arise due to exploitation of the geothermal resource in the Menengai field. Borehole sampling in the area was divided into five regions namely northern, southern, eastern and western with an addition of the GDC water boreholes located in the caldera (Figure 4).

Water samples were collected from the boreholes in the aforementioned regions in three major sampling campaigns: March-July 2011, September – November 2011 and February – July 2012. The samples were analyzed for various parameters including TDS, pH, CO_2, H_2S, SiO_2, Na, K, Ca, Cl, SO_4, F, and NH_3 using different methods suitable for each parameter. Borehole temperatures were also recorded.

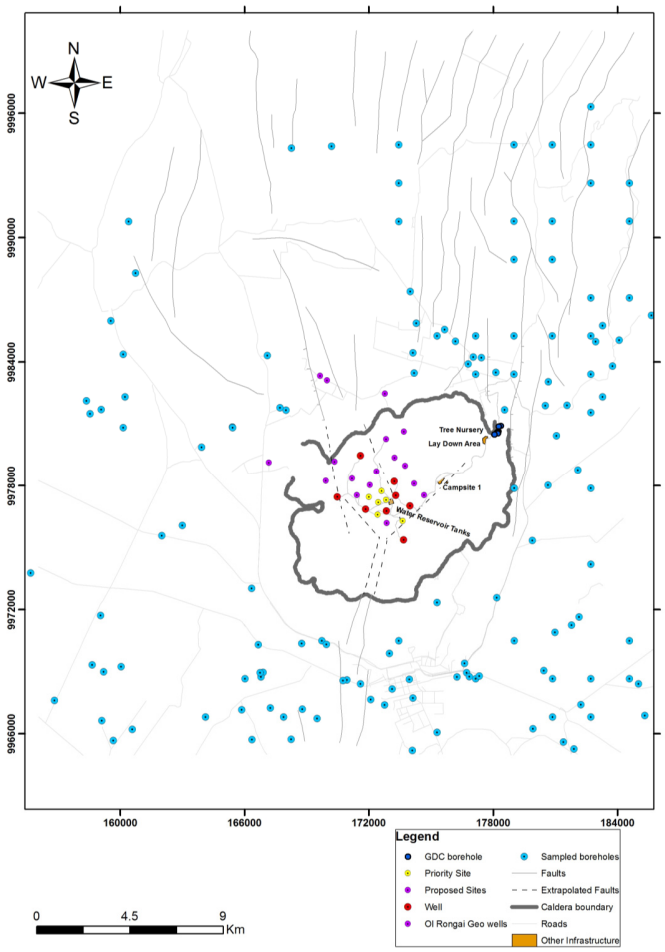

FIGURE 4: Location of boreholes considered for the geohazard monitoring study in the Menengai geothermal field

3.2 Chemical characteristics of the borehole water

This sampling program was carried out to monitor the changes that may have occurred in the borehole waters due to the drilling program being undertaken in the Menengai caldera. Figure 5 shows the contour maps depicting the distribution of various major parameters like borehole temperature, SiO_2, Na, CO_2, H_2S, Cl, SO_4, F and Ca) measured from the waters of boreholes in the Menengai region.

There seems to emerge a clear trend (NW-SE) for most of the parameters and the correlation of the measured temperatures to the silica concentrations suggest elevated temperatures in the region west of the caldera.

The waters from the boreholes were also classified based on the relative concentrations of the three major anions Cl, SO_4 and HCO_3 by use of ternary/piper diagrams. The Cl-SO_4-HCO_3 ternary diagram is one diagram for classifying natural waters (Giggenbach, 1991). Using it, several types of thermal water can be distinguished: mature waters, peripheral waters, steam-heated waters and volcanic waters. Figure 6 provides an indication of the relative concentrations of the major anions.

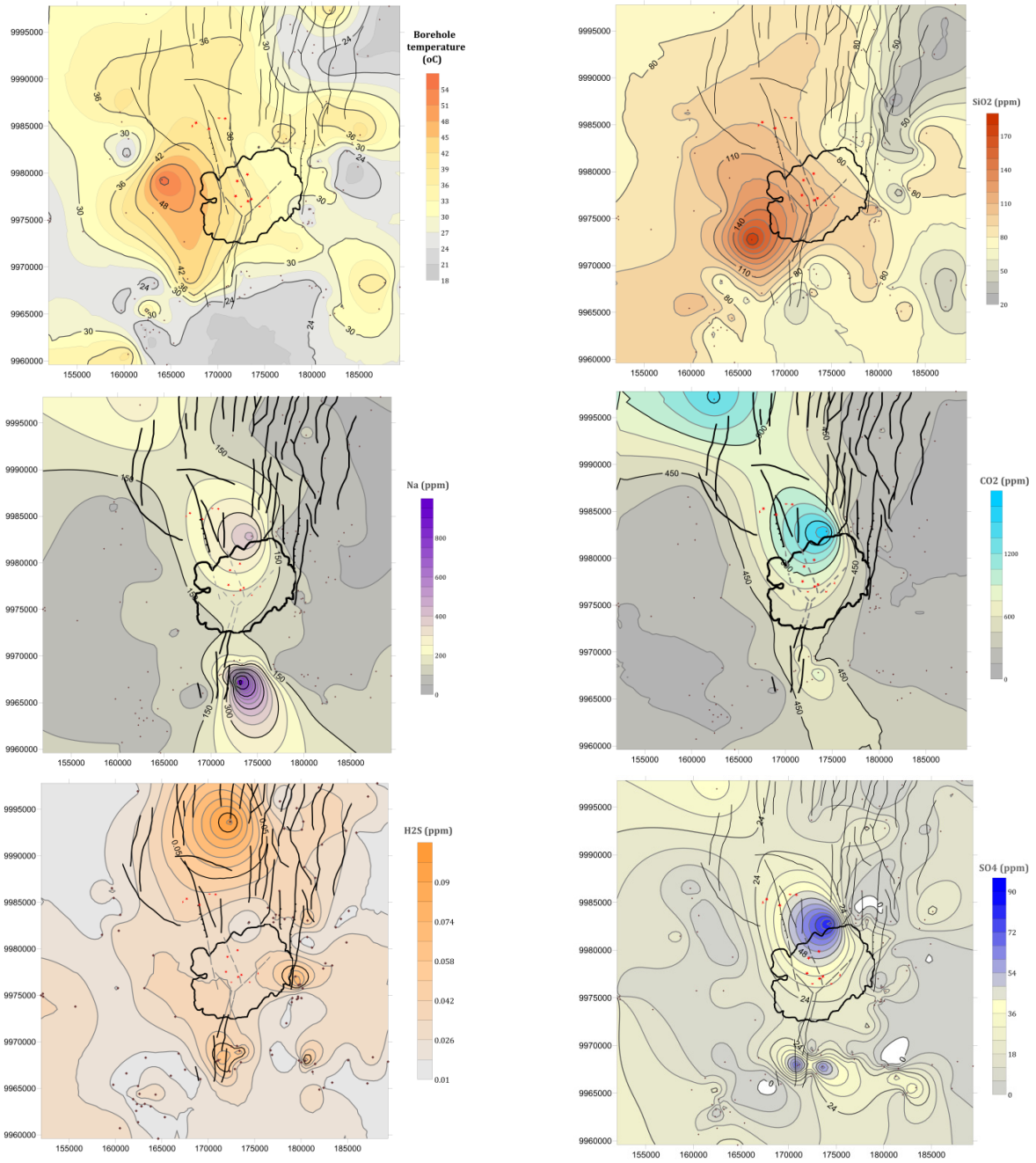

FIGURE 5: Contour maps depicting distribution of some of the various parameters of borehole waters in the region surrounding the Menengai geothermal field

The borehole waters surrounding the Menengai geothermal field plot in the region of high HCO_3-peripheral waters and low chloride (Figure 6) illustrating that the fluids in these borehole reservoirs are bicarbonate waters and correspond to peripheral waters. It should thus be noted that bicarbonate-rich waters originate through either dissolution of CO_2-bearing gases or condensation of geothermal steam in relatively deep, oxygen-poor ground waters.

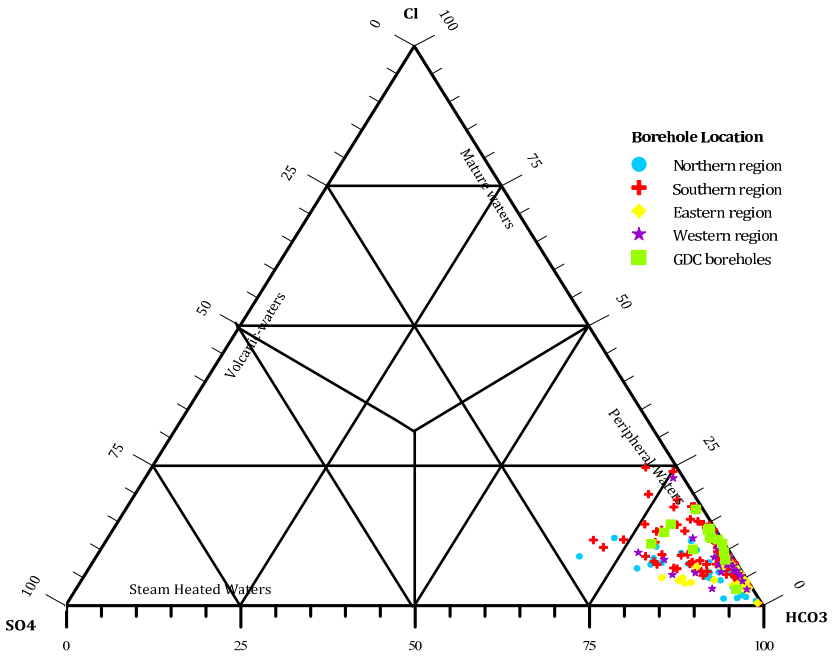

FIGURE 6: Relative Cl-SO_4-HCO_3 contents from the boreholes considered for geohazard monitoring surrounding the Menengai geothermal field

3.3 Conclusions

From the initial geohazard study of boreholes in the area surrounding the Menengai geothermal field, no major chemical changes were observed during the monitoring period. This case study being the baseline creation of the geohazard monitoring program, there was need to establish a continuous sampling campaign (which is in place) in case any changes in the chemical and physical parameters of the borehole waters occur due to the drilling ongoing in the Menengai geothermal field. A majority of the boreholes sampled discharged above ambient temperature waters with most having TDS less than 1,000 ppm. There seems to emerge a clear trend (NW-SE) for most of the parameters suggesting correlation to the Molo TVA.

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THE GEOCHEMICAL RESERVOIR MONITORING - A CASE STUDY OF OLKARIA NORTHEAST FIELD IN KENYA

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ABSTRACT

The results of the geochemical bi-annual reservoir-monitoring program, of the Olkaria Northeast Field (ONEF) for the second half of 2007 are presented. The chemical changes in the reservoir have been evaluated in terms of the changes in the concentration of total discharge chloride, silica, sulphate, discharge enthalpy, calculated geo-thermometer temperatures and the variations in the gas composition of the discharge fluids.

The regions of high chloride concentration are around wells OW-714 and OW-716 to the east, OW-709 and OW-727 to the west and OW-726 at the center of the Olkaria Northeast field. The three regions indicate upflow zones within the field. The area in the vicinity of wells OW-R2, OW-710, OW-711 and OW-724 are recharge areas with low mineralized fluids. The Olkaria fault zone contributes significantly to the reservoir fluid movement in the Olkaria Northeast field. Recharge from the Ol Olbutot fault may be encroaching the reservoir around well OW-711. This will be confirmed in the next monitoring periods.

The Na/K geothermometer temperature distribution in 2nd half of 2007, indicate three low temperature (less than 250°C) centers around wells OW-708, OW-720 and OW-724. The rest of the area lies between 270 and 340°C. The probable cause of heating around the wells to the southwest is boiling while the increase around well OW-727 may in addition, be due to incursion of separated re-injection fluids. The CO_2 geothermometer temperature mark out wells that have received the separated reinjected fluid from wells OW-720 through OW-728 to well OW-714 & OW-716 in a NE-SW elongated structure.

1. INTRODUCTION

The Olkaria Northeast Field (ONEF) has been under steam exploitation since October 2003. Thirty-two (32) wells have been drilled and twenty (20) of them connected to the steam gathering system in this field (Figure 1). Six (6) wells (OW-709, OW-710, OW-712, OW-713, OW-718, and OW-721), have individual separators, while the other fourteen wells have combined separators (OW-701 & OW-727, OW-705 & OW-725, OW-706 & OW-711, OW-707 & OW-715, OW-714 & OW-716, OW-719 & OW726, OW-720 & OW-728). Six are re-injection wells (OW-R2, OW-R3, OW-703, OW-708, OW-201 and OW-204) while the other six, (OW-702D, OW-704, OW-717, OW-722, OW-723, and OW-724) are non-producers. Hot brine from the separator stations is re-injected in wells OW-R2, OW-R3, OW-703, and OW-708. Cooling tower blowdown is injected in either OW-201 or OW-204 (currently in OW-201).

Monitoring is done in wells that are delivering steam to the power plant. At any one time, some productive wells may be shut-in or may not be monitored due to various reasons e.g. low steam demand due to machine outage. During this monitoring period the wells monitored were OW-701, OW-705, OW-706, OW-709, OW-713, OW-714, OW-715, OW-716, OW-720, OW-721, OW-725, OW-726, and OW-728.

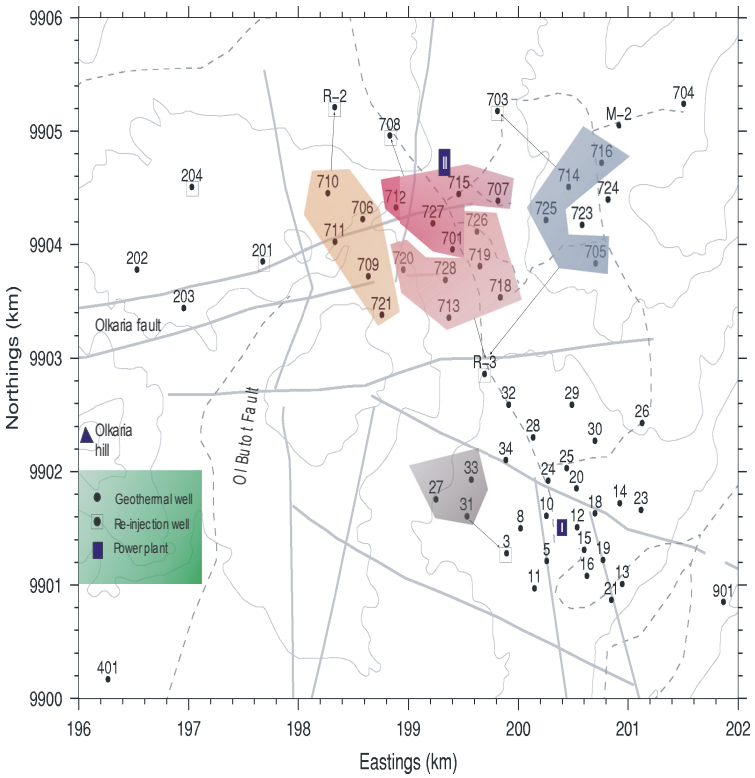

Figure 1: Well locations in Olkaria East and Northeast fields. The shaded areas show wells connected to the same re-injection well

The main objective of the steam field monitoring is to observe important changes that take place in the reservoir, which could lead to future development shortfalls. Such conditions are easily observed in advance by use of careful chemical, thermodynamic and output monitoring program. Undesirable conditions include, decrease in reservoir temperature and pressure by incursion of cold water from the periphery, which could lead to reduction in well discharge enthalpy and output resulting in decline in generating capacity. Positive changes can suggest enhanced field development and these include increase in well output as a result of wells clearing up as well as incursion of hotter fluids as a result of pressure drawdown and positive effects of re-injection which may finally lead to generation expansion.

Chemical changes in a geothermal fluid like changes in solute and gases concentration will manifest way ahead of any physical change and would give a suitable time interval for remedial action to be taken. The concentrations of various chemical constituents in both water and steam discharged from geothermal wells provide valuable quantitative information about reservoir condition and changes in response to steam exploitation. Field monitoring is therefore important in order to follow the changes and processes that influence fluid composition and thermodynamics during exploitation of the field. It also assists with calibration of the reservoir model as trends in physical and chemical parameters change.

This report presents the status on steam production and field chemistry in Olkaria Northeast Field (ONEF) for the second half of 2007.

2. GEOCHEMICAL CHANGES IN WELL CHARACTERISTICS

2.1 Monitoring Procedures

During the current monitoring period, water and steam chemical data were collected from the well discharge. Water samples were collected from the weir box except for wells that share a common separator station whose water was collected using a Webre separator. Gas samples were collected from the steam line after the well cyclone separator.

The water samples were analysed for pH, silica, boron, sodium, potassium lithium, calcium, magnesium, carbon dioxide, sulphate, hydrogen sulphide, chloride, fluoride, total dissolved solids, and electrical conductivity. The steam samples were analysed for carbon dioxide, hydrogen sulphide, hydrogen, methane, nitrogen and oxygen gases. Some wells were not monitored, as they were not connected to the production system during the second half of 2007 due to various reasons.

2.2 Chemical Analytical Results

Results of chemical analysis for well discharge fluids for the wells monitored during this period and the previous period are presented in Table 2. Calculated solute geothermometry temperatures used here are from Fournier and Potter (1982) for quartz and Arnorssson et al. (2000) for sodium-potassium. The gas geothermometry temperatures used here are those derived from the functions of Arnórsson and Gunnlaugson (1985). The analysed data have been re-calculated to 10 bar absolute vapour pressure to remove the effects of "excess" enthalpy due to phase separation on the initiation of boiling and aid in interpretation of fluid patterns and processes that prevail in the reservoir. Solute concentration is expressed in ppm while the concentration of gases is expressed in mmol/100 moles of steam.

3. WELL MONITORING RESULTS AND DISCUSSIONS

3.1 Geochemical monitoring

The monitoring of the wells in the producing field of Olkaria Northeast was done in the months of July to December 2007. The parameters used in the assessment of changes in the reservoir are those thought to provide significant indication of processes such as boiling, mixing and phase separation that influence fluid composition as fluids are discharged to the surface from the wells. These parameters include derived solute and gas geothermometry temperatures, gaseous concentrations of carbon dioxide, hydrogen sulphide, hydrogen and nitrogen in the steam. Others include solute concentrations of silica, sulphate, chloride and the enthalpy of the well discharge.

Water and steam samples were collected at different pressures. The water samples were collected from the weir-box and the steam samples at elevated pressures. For the purposes of interpretation of the chemical analytical data all the component concentrations were recalculated to the same pressure (10 bars absolute vapour pressure) with the assistance of WATCH, a chemical speciation programme developed by Arnorsson et al, 1983; Bjarnason, 1994). Table 2 compares derived chemical analysis results of the two most recent monitoring periods.

3.1.1 Well OW-701

Well OW-701 (Figure 1) shares a common separator station with well OW-727. Sulphate levels for well OW-701 increased from 11.2 ppm 15.9 ppm, whereas the chloride levels increased from 842 ppm to 875 ppm. Minor increase in chloride concentration during this monitoring period would indicate a possible mild mixing of reservoir fluids with reinjected separated brine from well OW-708. The solute and gas geothermometers have been erratic but generally constant. In the last monitoring period, the solute geothermometer temperatures were 233°C and 279°C for quartz and Na/K geothermometers respectively. These temperatures are comparable to the computed gases geothermometer values of 260°C, 278°C, and 286°C from T CO_2, T H_2S, and T H_2 respectively. The temperature values are close to the previous monitoring values. This implies that the well discharges fluid from one dominant feeder zone whose fluid has attained equilibrium.

TABLE 2: Derived Chemical analytical results for wells monitored in first half 2007 and second half 2007

Well no.	Cl (ppm)		T Na/K		T H_2		Remarks
	Second half 2007	First-half 2007	Second half 2007	First half 2007	Second half 2007	First half 2007	
OW-701	875	842	279	273	286	279	
OW-705	579	634	253	253	285	280	
OW-706	639	760	289	312	285	282	
OW-707	492	492	264	264	264	264	Assumed
OW-709	971	950	315	342	291	294	
OW-710	368	368	300	300	269	269	Assumed
OW-711	391	391	294	294	279	279	Assumed
OW-712	970	970	291	291	276	276	Assumed
OW-713	642	587	282	289	270	290	
OW-714	929	720	277	314	291	290	
OW-715	759	854	298	344	275	282	
OW-716	1091	737	288	309	293	285	
OW-718	381	381	256	256	277	277	Assumed
OW-719	357	357	273	273	271	271	Assumed
OW-720	485	630	239	257	296	292	
OW-721	546	433	268	288	285	281	
OW-725	663	615	257	270	287	280	
OW-726	877	883	288	302	276	263	
OW-727	837	890	292	303	291	291	Assumed
OW-728	780	808	285	297	291	290	

Note: In the remarks column, the well with the remark "Assumed" implies that the well was not monitored in the last monitoring period and therefore the respective values have been assumed constant.

3.1.2 Well OW-705

Well OW-705 was drilled to a depth of 2006 meters as an exploration well. The well shares a steam separator with well OW-725. The chloride concentration moderately reduced from 634 ppm to 579 ppm while sulphate concentration reduced from 27.5 ppm to 10.1 ppm. The K-Na geothermometer increased by 11°C from 253°C to 264°C, which corresponds to a similar increase in T H_2S and T H_2 gas geothermometers. This implies that the well was discharging fluid from a deeper part of the reservoir as shown by the huge reduction of Total Discharge carbon dioxide from 3294 ppm to 2002 ppm.

3.1.3 Well OW-706

This well is located to the western sector of Olkaria Northeast borefield (Figure 1). It was drilled to 2099 m depth. The total discharge chloride reduced in the 2nd half of 2007 from 760 ppm to 639 ppm while the total discharge carbon dioxide reduced from 2672 ppm to 1994 ppm, which is close to the 1988 values. This implies that the well has not stabilized since it was opened in 2003. This will be confirmed in the next monitoring period. The chloride concentration reduced to the 2nd half of 2005 values of 669 ppm. The alternative explanation is that the well is receiving less mineralized recharge fluid.

The Na/K geothermometer, indicate a decrease in reservoir temperature from 312°C to 289°C, a decrease of 23°C. The gas geothermometry temperature functions of TCO_2 and T H_2S are comparable

to the T H_2 over the monitoring period. The temperatures values are 259°C, 284°C, and 285°C for T CO_2, T H_2S, and T H_2 respectively. The inconsistent temperature values indicate that the reservoir fluid is mixing with re-injected fluid at depth, and hence creating a state of in-situ re-equilibration.

3.1.4 Well OW-707

Wells OW-707 is located in the eastern part of the field (Figure 1), it was drilled to 1802 m. Well OW-707 share a common cyclone separator station with well OW-715. During the 2nd half of 2007 monitoring period the well was shut-in.

3.1.5 Well OW-709

Well OW-709 is located in the western sector of the well field (Figure1). The well has an individual separator station. Total Discharge Chloride, silica, sulphate and enthalpy have been cyclic and erratic over time. The cyclic nature of the well discharge is mainly due to the well discharging from multiple feeder zones.

The Na/K ratio geothermometer decreased from 342°C, to 315°C, during the 2nd half of 2007 monitoring period. This could suggest that the well was drawing fluids from an aquifer, which is undergoing cooling. The gas geothermometers exhibit a similar pattern, with temperature values of 259°C, 281°C, and 291°C for T CO_2, T H_2S, and TH_2 respectively.

3.1.6 Well OW-710

Well OW-710 lies on the edge of the Olkaria Northeast field to the Northwest. The well was drilled to 1801 m deep. This well has an individual separator due to the cyclic nature of the well discharge. The well was shut-in during the last five monitoring periods.

3.1.7 Well OW-711

Well OW-711 lies to the western part of the Olkaria Northeast Field. The well was drilled to 1807 m and shares a common separator with well OW-706. The flow pattern in this well showed cyclic behavior and thence the fluids sampled may not be representative of the deep fluid. The well was shut-in during the monitoring period of 2nd half 2007.

3.1.8 Well OW-712

Well OW-712 is located to the West of Olkaria II power plant. The well has been stable in its production. The well was shut-in during the last monitoring period.

3.1.9 Well OW-713

Well OW-713 is located to the south of Olkaria Northeast borefield. The well has an individual cyclone separator and has been fitted with a motorized valve for steam regulation in the field hence it is mostly throttled (Mwawongo, 2005).

Chloride concentration in this well increased from 587 ppm to 642 ppm. The chloride concentration variation is erratic just like the well discharge. This implies the well has multiple feeder zones flowing into the well bore.

The gas concentrations show erratic changes over most of the production period. In the period between 1st half 2007 and 2nd half 2007, there was a increase in the total discharge carbon dioxide gas concentration from 1277 ppm to 7799 ppm. Hydrogen sulphide reduced from 46 ppm to 36 ppm implying that the well is discharging fluid that is mixed from multiple feeder zones.

Both solute and gas geothermometry temperatures could be used to infer other processes that could be at play in the reservoir near this well. Over most of the production period, the quartz equilibrium temperatures have been lower than the Na/K temperature. In 2nd half of 2007 the Na/K temperature reduced from 289°C to 282°C. This implies dilution of aquifer fluid by less mineralized fluid. The gas equilibrium geothermometers indicate variable temperature values of 263°C, 236°C, and 270°C for T CO_2, T H_2S, and T H_2 respectively. This is a reduction of upto 20°C when compared with 1st half values for T H_2S, and T H_2 of 274°C and 290°C respectively.

3.1.10 Well OW-714

Well OW-714 is located in the eastern part of the Olkaria Northeast field and it has the largest output. The well was drilled to 2502 m and shares a common separator with well OW-716. The total discharge chloride concentration increased from 720 ppm in the 1st half of 2007, to 929 ppm in the 2nd half of 2007. The erratic variation of the chemical constituents is a reflection of the reservoir processes that occur in the aquifers feeding the well.

Geothermometry temperatures show erratic values and stable values from solute and gas geothermometers respectively. Quartz temperatures could give the best indication of reservoir temperatures but are mostly affected by condensation and mixing. The quartz temperatures over most of the production period show lower temperatures than those of Na/K. Quartz also responds more quickly to re-equilibration than the Na/K temperatures. The Na/K geothermometer values decreased from 314°C to 277°C for the 2nd half of 2007. During the 2nd half monitoring period of 2007 the gas temperature geothermometers gave higher or lower values of 255°C, 299°C and 291°C for T CO_2, T H_2S and T H_2 respectively. The geothermometer temperatures showed almost similar temperatures, which would suggest a probable attainment of mineral equilibria. Increase in geothermometer temperature may indicate boiling in the aquifer.

3.1.11 Well OW-715

Well OW-715 is located to the south of the power plant (Figure 1). The well was drilled to 2003 m depth and shares a common separator with well OW-707. The chloride concentration decreased from 854 ppm in the 1st half of 2007 to 759 ppm in 2nd half of 2007. This implies that the well is discharging from one dominant aquifer, which is also receiving less mineralized fluid and hence the decrease in chloride concentration. The gas concentration of the well discharge during the monitoring period, show mild decrease in total discharge carbon dioxide gas from 1519 ppm to 1403 ppm.

The Na/K geothermometer temperature decreased from 344°C to 298°C over the same monitoring period. The gas equilibrium geothermometers indicate highly variant values, with temperature values of 260°C, 278°C and 275°C for T CO_2, T H_2S, and T H_2 respectively. This is a reflection of the multiple feeders flowing into the well and hence the hybrid discharge obtained during sampling.

3.1.12 Well OW-716

Well OW-716 is located in the eastern sector of the Olkaria Northeast field. This well shares a cyclone separator with well OW-714. The well produces at a fairly stable steam and water flow rates. The chloride contents generally remained almost constant during the discharge tests. However, the concentration increased drastically in 2nd half of 2007 to 1091 ppm from 737 ppm obtained in 1st half of 2007. This implies that the aquifer around the well may be experiencing a recharge from a deeper more mineralized aquifer.

The solute geothermometers have decreased in this monitoring period from 309°C in 1st half of 2007 to 288°C in 2nd half of 2007 for the Na/K geothermometer. This is consistent with recharge of reservoir by deep aquifer fluid. The gas geothermometers TCO_2, T H_2S, T H_2 value are 256°C, 292°C, and 293°C respectively.

3.1.13 Well OW-718

Well OW-718 is located on the southeastern edge of the Olkaria Northeast field (Figure 1). The well has a cyclic pattern of flow and the samples taken from this well may not reflect the true composition of reservoir fluids. The well was shut-in during this monitoring period.

3.1.14 Well OW-719

Well OW-719 is located to the south of Olkaria II power plant along the same alignment as wells OW-718 and OW-717 as well as wells OW-713 and OW-728. This well shares the same separator with well OW-726 and has fairly steady output. The well was shut-in during this monitoring period.

3.1.15 Well OW-720

Well OW-720 is located in the western sector of Olkaria Northeast field. The well shares a common separator with well OW-728. The total discharge chloride concentration decreased from 630 ppm to 485 ppm while the total discharge Carbon dioxide concentration increased from 698 ppm to 699 ppm in the 2nd half of 2007. However, hydrogen sulphide decreased from 118 ppm to 106 ppm. The increase or decrease from various chemical constituents, imply that the well is discharging fluid that is a hybrid of fluid from multiple feeders.

The Na/K geothermometer temperature decreased from 257°C to 239°C in the 2nd half of 2007. This is consistent with a well discharging fluid from multiple feeder zones. The gas geothermometers TCO_2, T H_2S, T H_2 value are 254°C, 299°C, and 296°C respectively.

3.1.16 Well OW-721

Well OW-721 is located in the southwestern part of the Olkaria Northeast production field. The well was drilled to 2201 m. The total discharge chloride concentration show, an increase from 433 ppm in 1st half of 2007 to 546 ppm in 2nd half of 2007. The total discharge carbon dioxide increased from 406 ppm to 763 ppm during the monitoring period. The solute geothermometry temperatures of quartz and Na/K show an erratic variation in the last four monitoring periods. The Na/K geothermometer temperatures decreased from 288°C to 268°C, a reservoir temperature decline of 20°C. This implies that recharge fluid from the Ol Olbutot fault zone has started mixing with reservoir fluid flowing into the well. The gas geothermometers show higher or equal temperatures with T CO_2, T H_2S, and T H_2 giving 258°C, 296°C and 285°C respectively.

3.1.17 Well OW-725

Well OW-725 is located in the eastern sector of Olkaria Northeast field and shares a common separator with well OW-705. The total discharge chloride concentration increased from 615 ppm to 663 ppm in the 2nd half of 2007. Total discharge carbon dioxide concentration shows an increase from 437 ppm to 1000 ppm. The other chemical species variation has been erratic. This implies that the well is drawing a more mineralized fluid, from another aquifer, which was not feeding the well before. This observation will be confirmed in the next monitoring period.

The solute geothermometry temperatures of Na/K show a reduction trend between 2nd half of 2006 and 2nd half of 2007. The temperature decreased from 276°C to 257°C between the three monitoring periods. The decrease in these geothermometry temperatures with corresponding chloride increase implies that mixing of reservoir fluids with cooler (150°C) re-injection fluid in taking place. Gas equilibration temperatures in the 2nd half of 2007 were erratic at 256°C for T CO_2, and 297°C for T H_2S, however, T H_2 increased from 280°C to 287°C. This implies moderate phase segregation within the aquifer close to the well.

3.1.18 Well OW-726

Well OW-726 is located in the center of the Northeast production Field (Figure 1) and shares a cyclone separator with well OW-719. The total discharge chloride concentration reduced from 883 ppm to 877 ppm in the 2nd half of 2007. This has been the trend since 2nd half of 2005 with a total discharge chloride concentration of 1005 ppm. However, total discharge carbon dioxide increased from 359 ppm in the 1st half of 2007 to 2290 ppm in the 2nd half of 2007. This implies that the well has been discharging from different feed zones whose chemistry is diverse. This fact is reflected in the erratic variation in the discharge enthalpy in addition to the solute geothermometers. The Na/K geothermometer decreased from 302°C to 288°C while the quartz geothermometer remained increased from 254°C to 271°C. The temperature shift between the two geothermometers is evidence to the hybrid nature of the fluids discharged by the well. The increase in quartz geothermometer may be due to boiling in the immediate area around the well such that the Na/K ratio still remained constant. The gas geothermometers show variable temperatures with T CO_2, T H_2S, and T H_2 giving 262°C, 267°C and 276°C respectively for 2nd half of 2007 monitoring period. This implies that the well discharges fluid from different feeder zones, which have undergone diverse reservoir processes.

3.1.19 Well OW-727

Well OW-727 is located in the western sector of the Olkaria Northeast production field and shares a common separator with well OW-701. The chloride concentration has increased from 837 ppm to 890 ppm in 1st half of 2007. However, silica has declined from 543 ppm to 523 ppm. The quartz geothermometer reduced from 268°C to 263°C while the Na/K geothermometer increased from 292°C to 303°C. This implies that the well is discharging from more than one dominant feeder zone. The gas geothermometers show variable temperatures with T CO_2, T H_2S, and T H_2 giving 257°C, 291°C and 291°C respectively for 1st half of 2007 monitoring period. The well was not available for monitoring during the 2nd half of 2007.

3.1.20 Well OW-728

Well OW-728 is located in the western sector of the Olkaria Northeast production field. It shares a common separator with well OW-720. The chloride concentration decreased from 808 ppm to 780.5 ppm in the 2nd half of 2007. The total discharge concentration of hydrogen sulphide increased from 76.4 ppm to 113.5 ppm while carbon dioxide concentration decreased from 944 ppm to 821 ppm. However, other chemical constituents have erratic variation. This may suggest that the well discharges from multiple feeders in the aquifer. A similar behavior is observed in the case of the solute geothermometers, they reduced from 297°C to 285°C for Na/K geothermometer. The gas chemistry is erratic and no specific trends have been observed. The gas geothermometers (T CO_2 = 255°C, T H_2S = 298°C) are lower or higher than the solute geothermometers including T H_2 whose temperature value of 291°C during the 2nd half of 2007.

3.2 Overall chemical changes

To evaluate the chemical changes that have occurred in the reservoir over a period of the last six months during geochemical monitoring, reservoir distribution plots of chemical constituents and geothermometry temperatures over the monitoring period of 2nd half of 2007 were made and compared with distribution plots of the previous monitoring period 1st half of 2007. These distribution plots are used to infer processes that influence fluid composition in the reservoir in response to production load. Overall total discharge chloride concentration distribution plot is illustrated in Figure 2 and Figure 3. The regions of high chloride concentration are around wells OW-714 and OW-726 to the east and OW-709, OW-727, to the west and OW-726 in the center. The three regions indicate upflow zones within the Olkaria Northeast field (Ofwona, 2002). The area in the vicinity of wells OW-R2, OW-710, OW-711, OW-718, and OW-724 are recharge areas with low mineralized fluids. The Olkaria fault zone contributes significantly to the reservoir fluid movement in the Olkaria Northeast field.

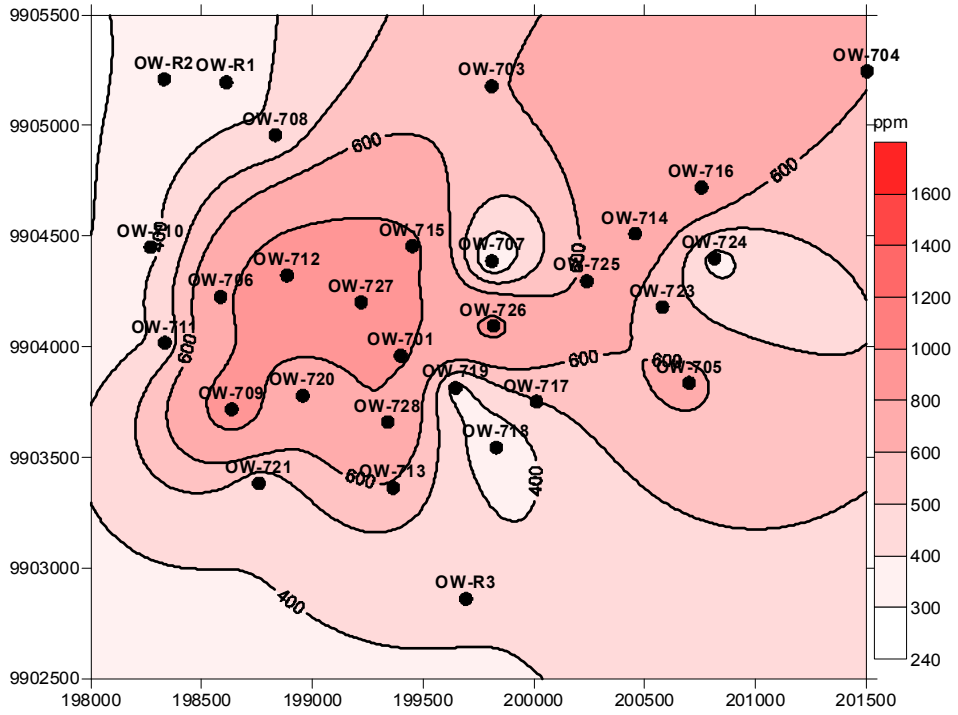

FIGURE 2: TD Chloride conc 1st half 2007 distribution plot

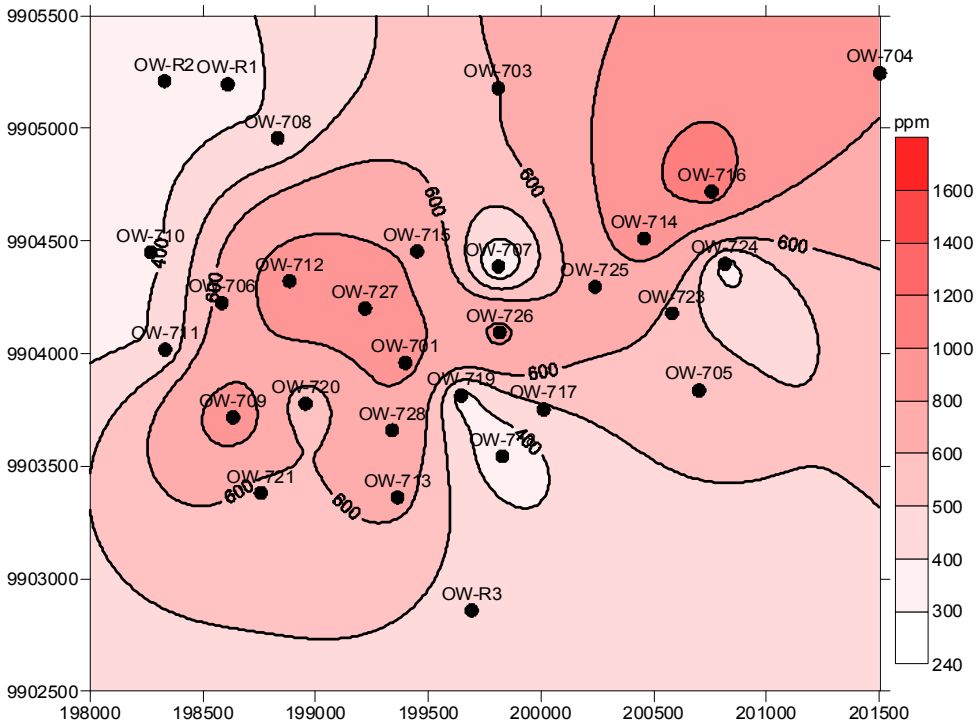

FIGURE 3: TD Chloride conc 2nd half 2007 distribution plot

Figure 4, 1st half 2007 total discharge carbon dioxide distribution plot indicate three high concentration centers around wells OW-706, OW-707, and the south east part of the field enclosed by the contour passing through wells OW-719, OW-717, OW-723, OW-724, OW-718 and OW-705 whose concentration is in excess of 1600 ppm. In the 2nd half of 2007, the distribution of the total discharge carbon dioxide changed significantly (Figure 5). The high concentration centers around wells OW-706 and OW-707 have reduced and the large southern front has shifted from the east around well OW-

705 to the west around well OW-713. These centers are areas where re-injection fluid has mixed with the reservoir fluid and then discharged by the wells in the vicinity.

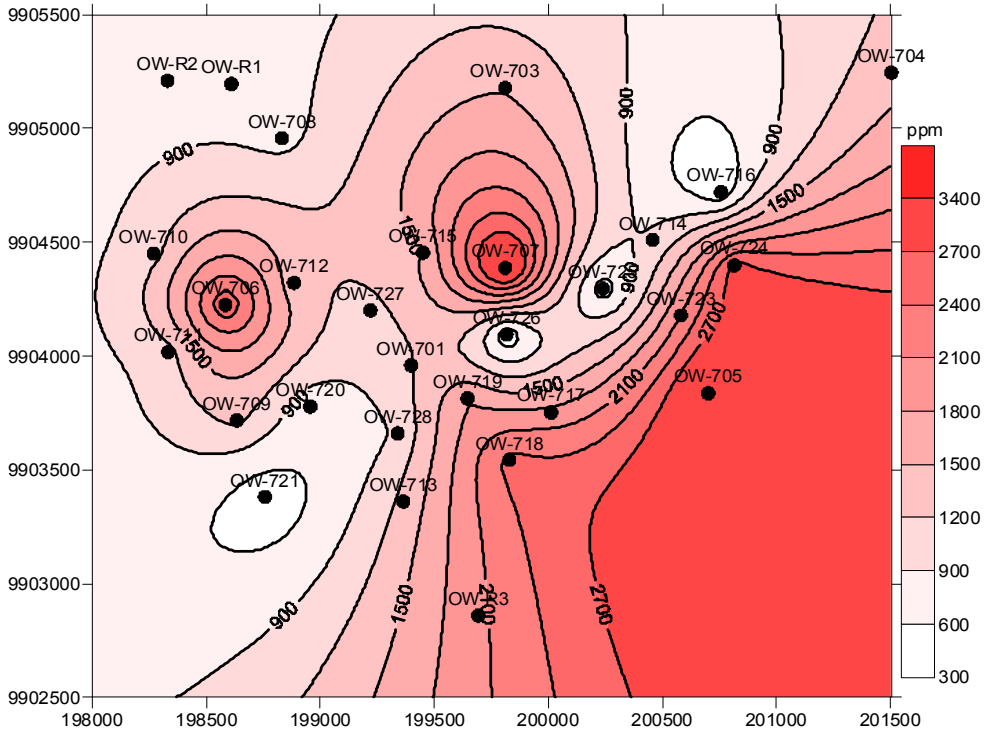

FIGURE 4: TD Carbon Dioxide conc 1st half 2007 distribution plot

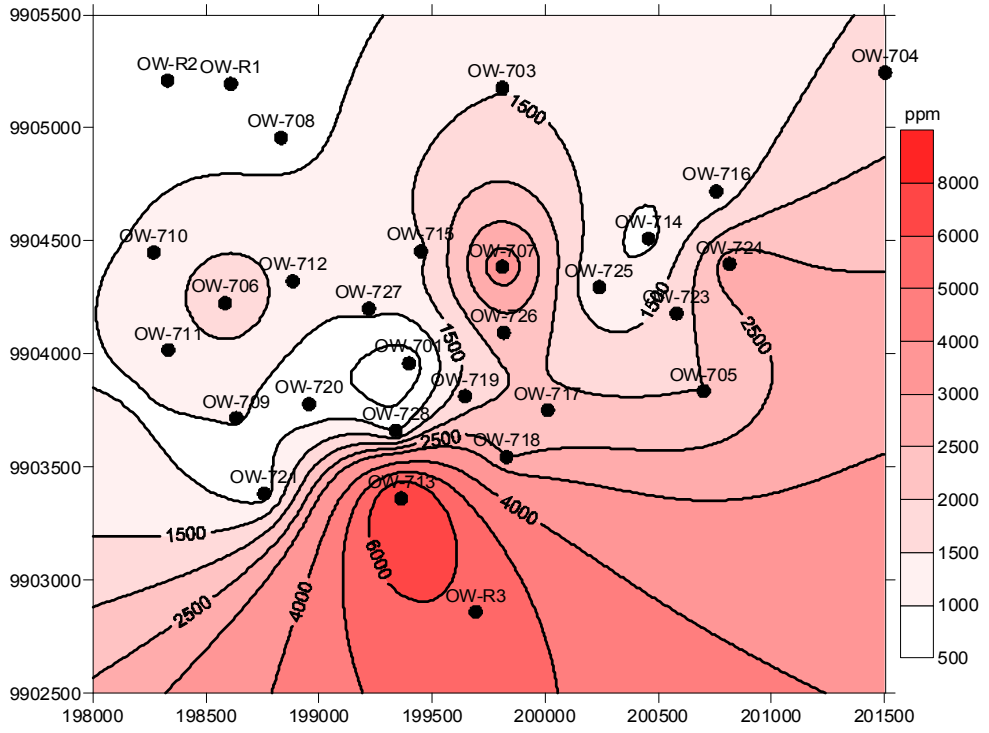

FIGURE 5: TD Carbon Dioxide conc 2nd half 2007 distribution plot

Figure 6, T Na/K temperature distribution plot 1st half of 2007, indicate two large high temperature zones; to the west around wells OW-709 & OW-706 and to the east around wells OW-714, OW-715,

& OW-716. The plot in addition shows two low temperature (less than 265°C) centers, one around well OW-708, and the other near wells OW-705, OW-723 and OW-724. The rest of the area lies between 270 and 340°C. In the 2nd half of 2007 monitoring period, the cold center around well OW-708 has persisted and enjoined the region around well OW-720 (Figure 7). The other cold center around wells OW-723 and OW-724, has maintained the status quo. The area covered by the 280°C, contour line has increased, which implies that the reservoir has cooled by about 20°C. The high temperature peaks around OW-701 and OW-713 have been eliminated. The probable cause of cooling around the wells may be due to the re-injected fluid entering the reservoir around wells OW-708 through OW-712 to well OW-720 zone. On the other hand the other wells within the Olkaria fault zone may be receiving cooler recharge fluids. This will be confirmed in the next monitoring period.

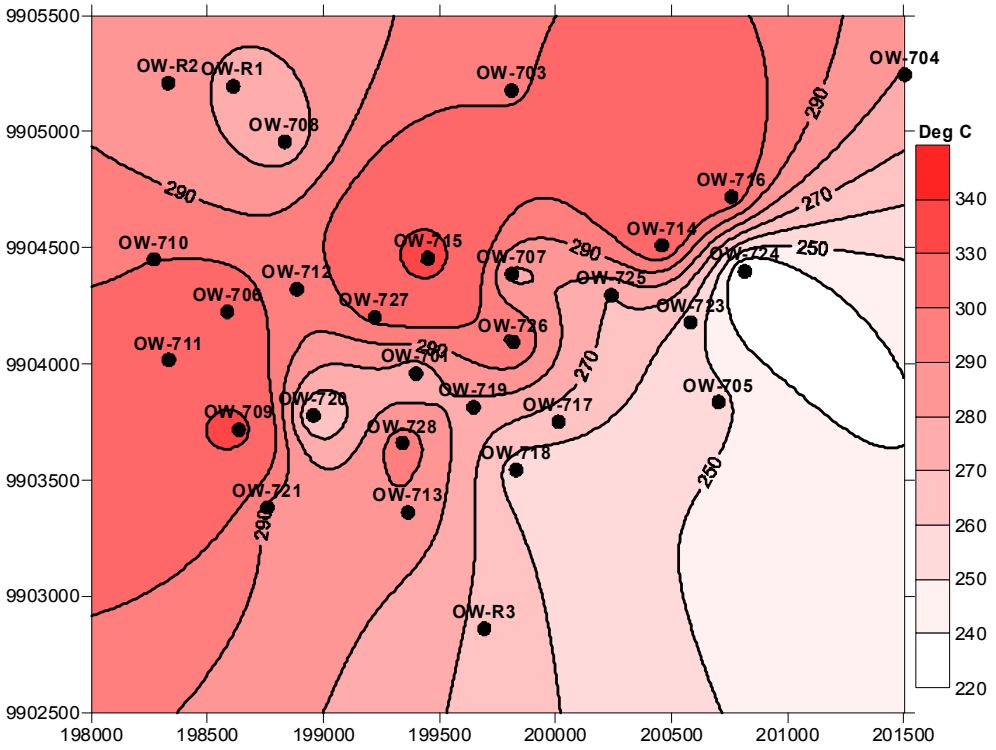

FIGURE 6: Na/K geothermometer temperature 1st half 2007 distribution plot

In the 1st half of 2007 monitoring period, the hydrogen geothermometer temperatures Figure 8, are lower compared to the solute Na/K geothermometer values, Figure 6. In sharp contrast, the lowest temperature zone from the hydrogen geothermometer is around wells OW-707 and OW-726. Other low temperature centres can be observed around wells OW-710 and OW-R2. Two high temperature centres can be observed around wells OW-709 & OW-720 to the west and wells OW-714 & OW-716 to the east. Figure 9, hydrogen geothermometer 2nd half of 2007 temperature distribution plot, the area under the 280°C contour has reduced and a central zone of 270°C running from OW-R2 through OW-707 to OW-718 has emerged as distinct. The area under the 280°C contour indicates reservoir cooling to account for the reduction in temperatures possibly from the re-injection fluid.

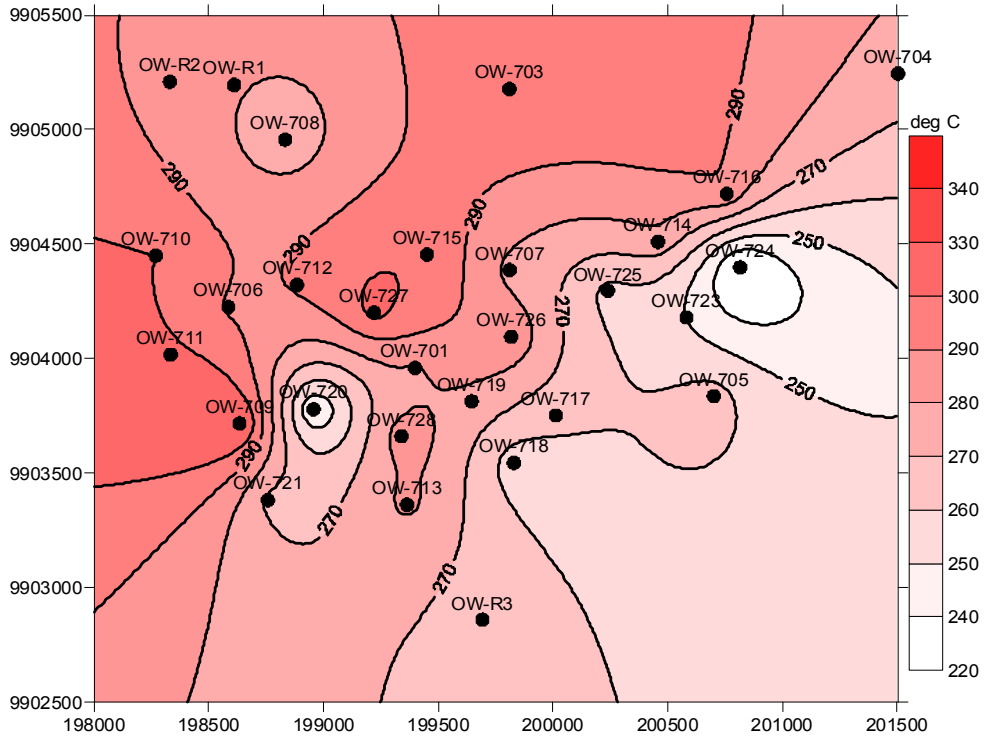

FIGURE 7: Na/K geothermometer temperature 2nd half 2007 distribution plot

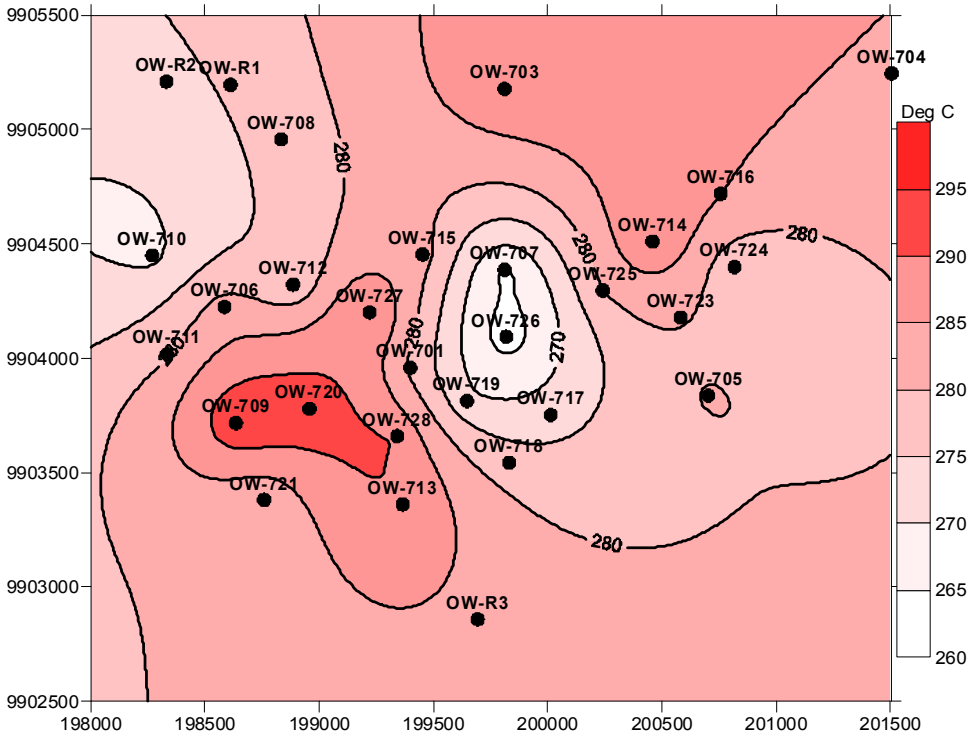

FIGURE 8: Hydrogen geothermometer temperature 1st half of 2007 distribution plot

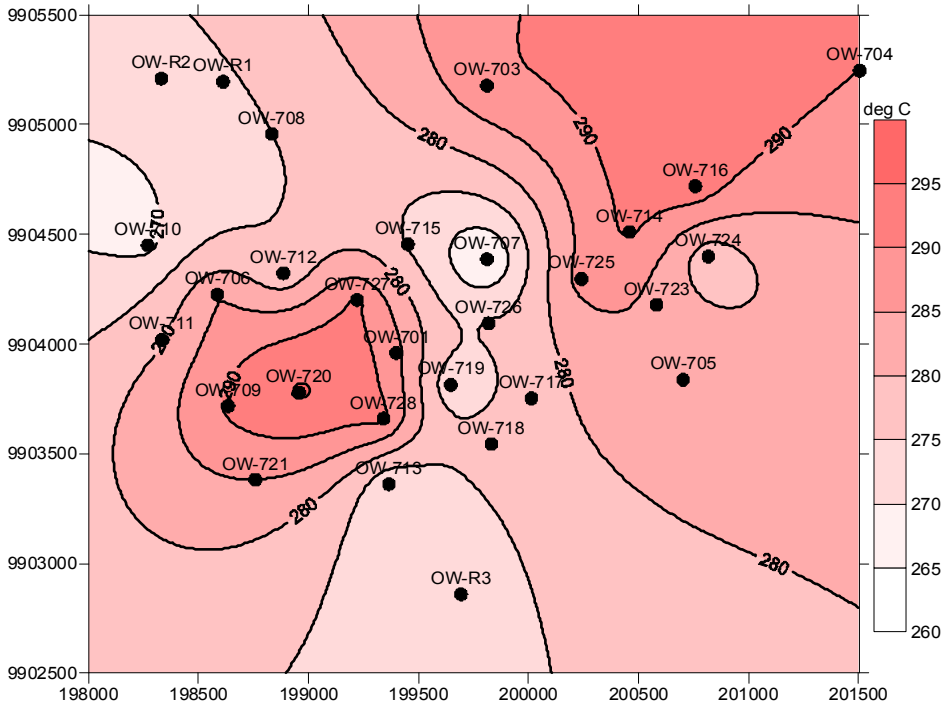

FIGURE 9: Hydrogen geothermometer temperature 2nd half of 2007 distribution plot

Figure 10, CO_2 geothermometer temperature 1st half of 2007 distribution plot, highlights a unique NE - SW temperature regime, with a cooler front of less than 260°C, entering the production field in the area near wells OW-712, OW-720 and OW-721. In the 2nd half of 2007 monitoring period, the CO_2 geothermometer temperature distribution. Figure 11, shows that temperatures have decreased across the entire field with two low temperature centers near wells OW-716, OW-720 and OW-727. This implies that the aquifer feeding these wells has received reinjected fluid, which has low gas content and hence reduces the concentration of carbon dioxide in the discharged fluid. This is confirmed in Figure 3 (total discharge chloride concentration 2nd half 2007 distribution plot), which shows corresponding regions of high concentration in the total discharge chloride. Separated brine will have high concentration of solutes, which when mixed with the aquifer fluid will result in a fluid enriched with residual chemical species.

The best indicator of incursion of atmospherically contaminated fluid in the reservoir is N_2 gas and O_2 in the steam. Figure 12 and Figure 13 present the N_2 gas concentration distribution during the 1st half of 2007 and 2nd half of 2007 monitoring periods. Generally, high concentration is observed around wells OW-708, OW-715, and OW-724. Similarly, during the 2nd half of 2007 monitoring period the high nitrogen concentration centers have remained intact. This implies, fluid that has had atmospheric contamination is being discharged through these wells. The high nitrogen gas concentration may be as a result of mixing the reservoir fluid with natural shallow recharge and re-injected separated brine in wells OW-R2, OW-R3 and OW-708 with the reservoir fluid being discharged by the wells monitored.

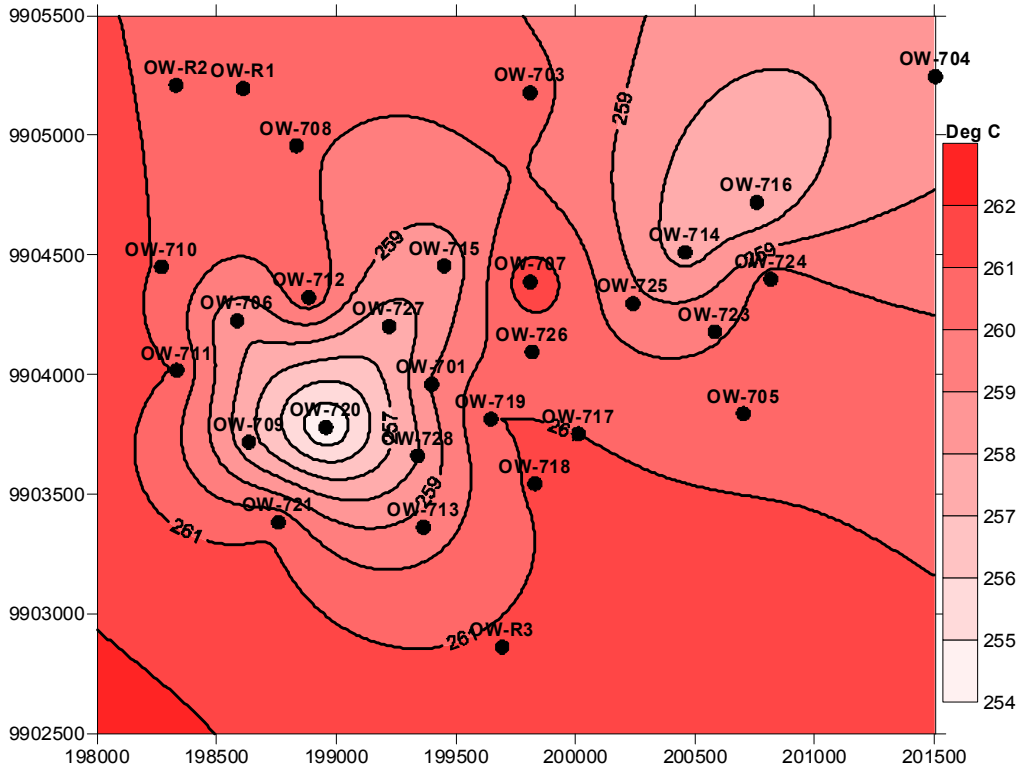

FIGURE 10: CO_2 geothermometer temperature 1st half of 2007 distribution plot

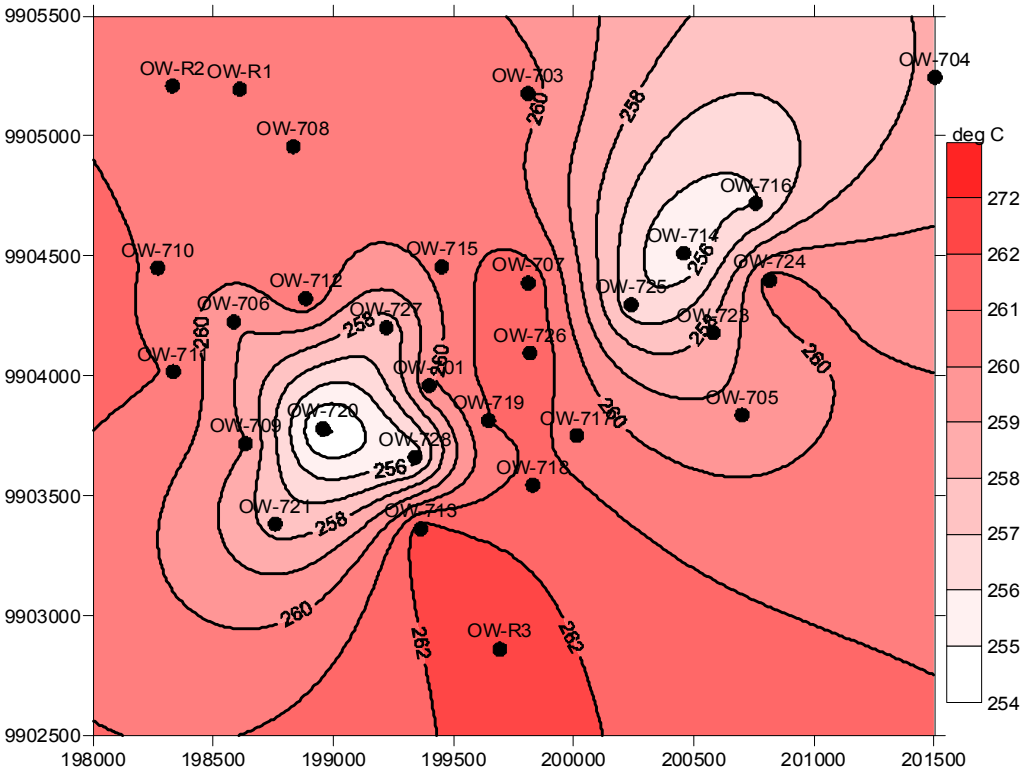

FIGURE 11: CO_2 geothermometer temperature 2nd half of 2007 distribution plot

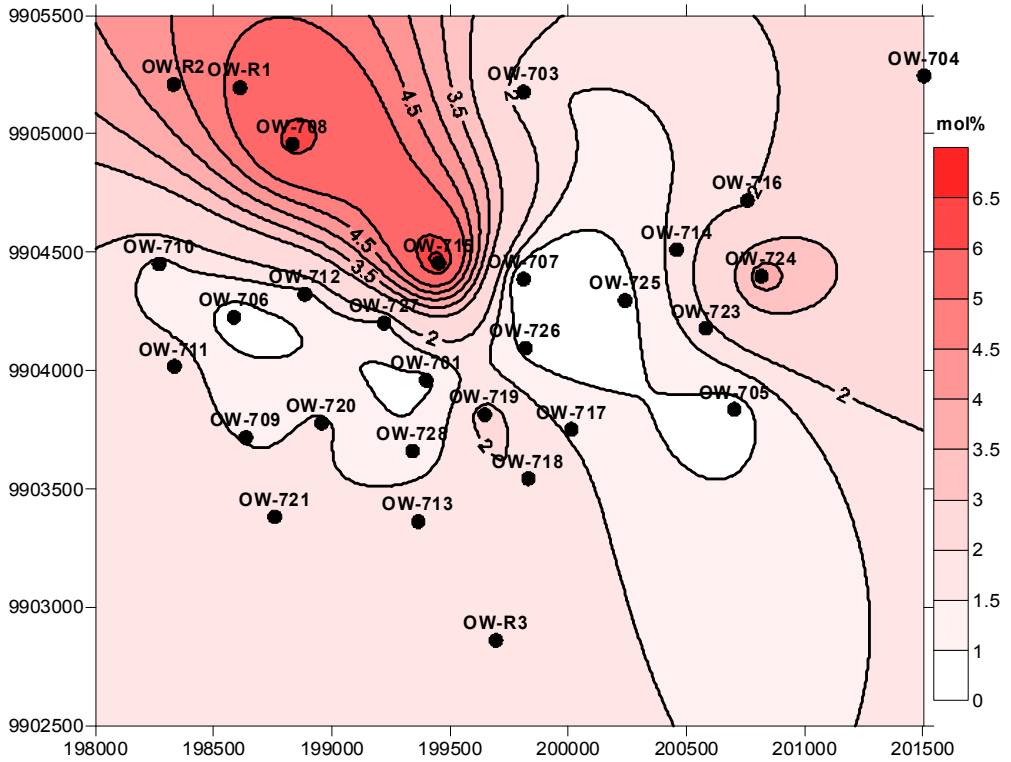

FIGURE 12: Nitrogen gas concentration 1st half of 2007 distribution plot

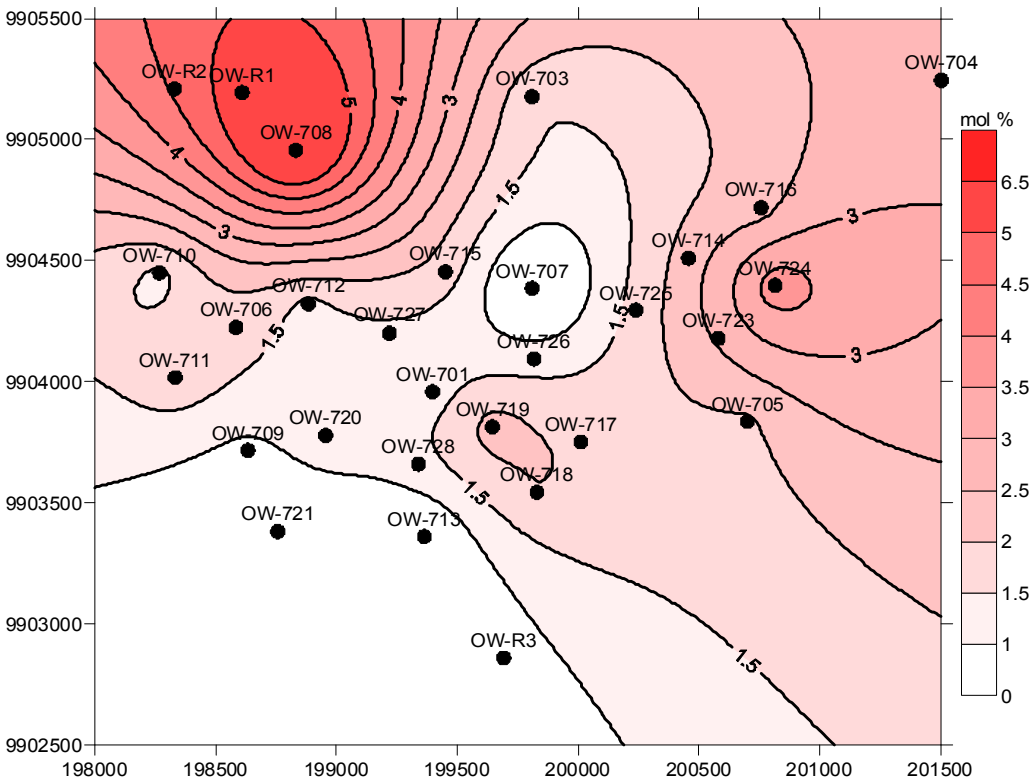

FIGURE 13: Nitrogen gas concentration 2nd half of 2007 distribution plot

4. CONCLUSIONS

The regions of high chloride concentration are around wells OW-714 and OW-716 to the east, OW-709 and OW-727 to the west and OW-726 at the center of the Olkaria Northeast field. The three regions indicate upflow zones within the field. The area in the vicinity of wells OW-R2, OW-710, OW-711 and OW-724 are recharge areas with low mineralized fluids. The Olkaria fault zone contributes significantly to the reservoir fluid movement in the Olkaria Northeast field. Recharge from the Ol Olbutot fault may be encroaching the reservoir around well OW-711. This will be confirmed in the next monitoring periods.

The Na/K geothermometer temperature distribution in 2nd half of 2007, indicate three low temperature (less than 250°C) centers around wells OW-708, OW-720 and OW-724. The rest of the area lies between 270 and 340°C. The probable cause of heating around the wells to the southwest is boiling while the increase around well OW-727 may in addition, be due to incursion of separated re-injection fluids. The CO_2 geothermometer temperature mark out wells that have received the separated reinjected fluid from wells OW-720 through OW-728 to well OW-714 & OW-716 in a NE-SW elongated structure, Figure 11. When steam separates from a liquid during boiling or flashing, gases like CO_2, H_2S, H_2, N_2, and CH_4 move preferentially into the vapor phase. Therefore, the wells that have received separated reinjected fluid may possibly show elevated CO_2 geothermometer temperatures.

High Nitrogen gas concentration is observed around wells OW-708, OW-712, OW-719, OW-724, and OW-716. During the 2nd half of 2007 monitoring period the nitrogen concentration has increased across the entire field. However, the high concentration centers have remained intact. This implies, fluid that has had atmospheric contamination is being discharged through these wells. The high nitrogen gas concentration may be as a result of mixing the re-injected fluid in wells OW-R2, OW-R3 and OW-708 with the reservoir fluid being discharged by the wells monitored.

The bi-annual monitoring is adequate as a reservoir management tool. The re-injection fluid appears to move rather fast into the production field aquifer and the re-injection wells should be moved further away from the production field.

5. RECOMMENDATIONS

Further work need to be done in order to determine the optimum re-injection flow rate into well OW-708 so as to minimize negative effects on well OW-712.

Well OW-711 and OW-712, need to be online to enable monitoring of their output as well as any possible effects of cold re-injection at OW-201 and OW-204 since the wells are closest to the re-injection wells.

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THE THEISTAREYKIR GEOTHERMAL SYSTEM, NORTH EAST ICELAND: CASE HISTORY

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ABSTRACT

Surface exploration was carried out in the Theistareykir high-temperature geothermal area, NE-Iceland in 1972-1974 and 1981-1984, and the area monitored intermittently from 1991-2000. The results of surface exploration suggested that the temperature of the fluid was at least 280°C and that it was drawn from a single reservoir with good permeability. The recharge is from the southeast, and the origin of the fluid probably far to the south. The fluid may be 100 years old or more. The geothermal area has been divided into five sub-areas, three of which are expected to be productive. Wells have been drilled in all and the results of drilling do not contradict the results of the surface exploration. A conceptual model based on all the results has been established and a volumetric assessment of the geothermal suggests that the most likely value for production potential over 30 years is 348 MW_e.

1. INTRODUCTION

Theistareykir is a high-temperature geothermal area in NE-Iceland (Figure 1). For centuries it hosted the main sulphur mine in Iceland, providing the Danish king with raw material for gun powder. Early records tell of prospecting for sulphur, Bemmele nand Rutten (1955) mapped interglacial lavas and palagonite, and Kjartansson (1972) reported on exploration for clay. The first geothermal exploration was carried out in 1972-1974 (Grönvold and Karlsdóttir 1975), and a major geothermal assessment was made in 1981-1984 (Layugan 1981, Gíslason et al. 1984, Ármannsson et al. 1986, Darling and Ármannsson 1989). The area was monitored intermittently from 1991-2000 (Ármannsson et al. 2000), and Ármannsson (2001) reviewed research in the area up to the year 2000.

Gautason et al. (2000) suggested drill sites based on available knowledge. The first well was drilled in 2002, the second in 2003, the third in 2006, the fourth and fifth in 2007, 1 more drilled and another redrilled in 2008. The purpose of this paper is to reflect on the results of drilling with reference to information gained from surface exploration.

2. RESULTS OF SURFACE EXPLORATION

The main features in the geology of the area are an E-W trending heat source astride a N-S tectonic structure connected to an active central volcano. A N-S fissure swarm, 4-5 km wide stretches from Lake Mývatn in the south and to the sea in Öxarfjördur in the north. The area is covered in lavas all of

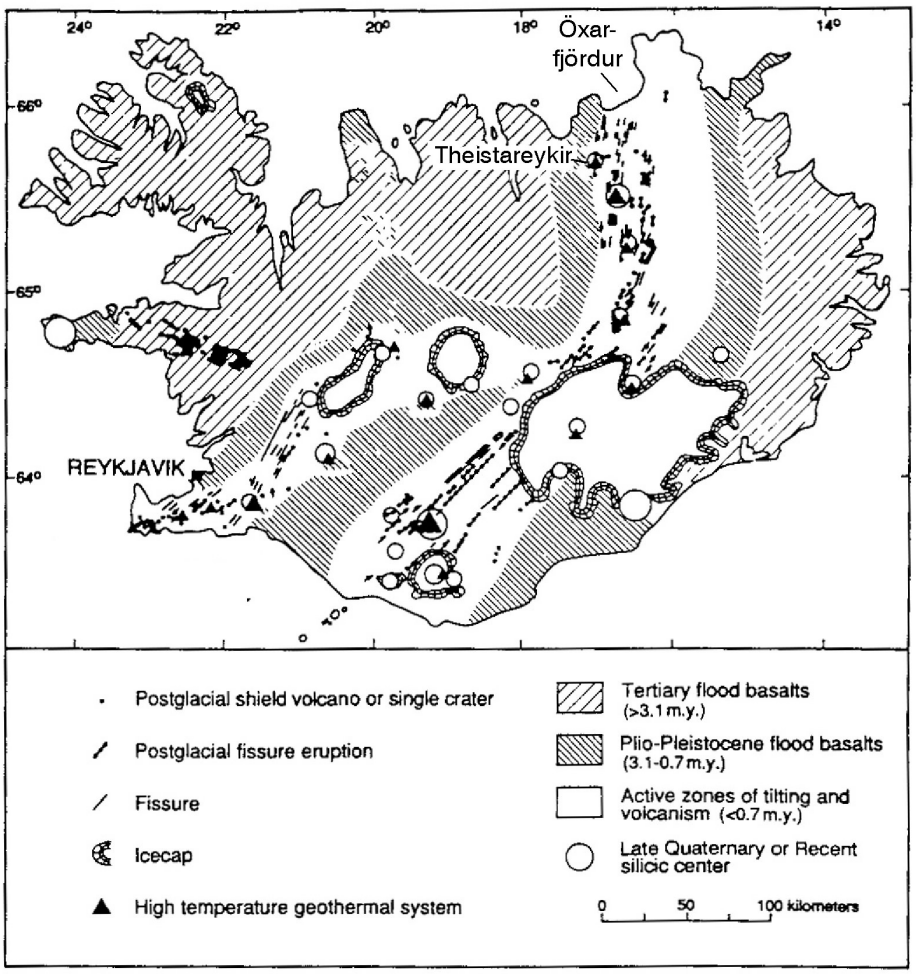

FIGURE 1: Iceland. Tectonic map (Saemundsson 1986).
Location of Theistareykir

which except for one being erupted in the last stages of the Ice Age or shortly afterwards. The youngest lava is about 2700 year old.

Surface manifestations have been estimated to cover about 11 km^2 (Gíslason et al. 1985) as is shown on the geothermal map (Figure 2) (Saemundsson 2007) but recent TEM and MT soundings suggest that the extent of the actual geothermal area be up to 45 km^2. (Karlsdóttir et al. 2006, Yu et al. 2008 a,b) (Figure 3).

Ármannsson et al. (1986) divided the active surface area into five sub-areas (Figure 4), three of which (A, C and D) appeared promising for drilling. Gas geothermometers gave the temperature ranges shown in Table 1. Darling and Ármannsson (1989) concluded from isotope values for fumarole steam that, in area D (Tjarnarás), the steam had been condensed to a fraction of 0.15 to 0.25 of the original steam at temperatures in the range 130-200°C, and that gas geothermometer temperatures were probably too high. Their interpretation of isotope values for area C (Theistareykjagrundir) was that the steam was mostly secondary steam and that the geothermometer temperatures were probably too low.

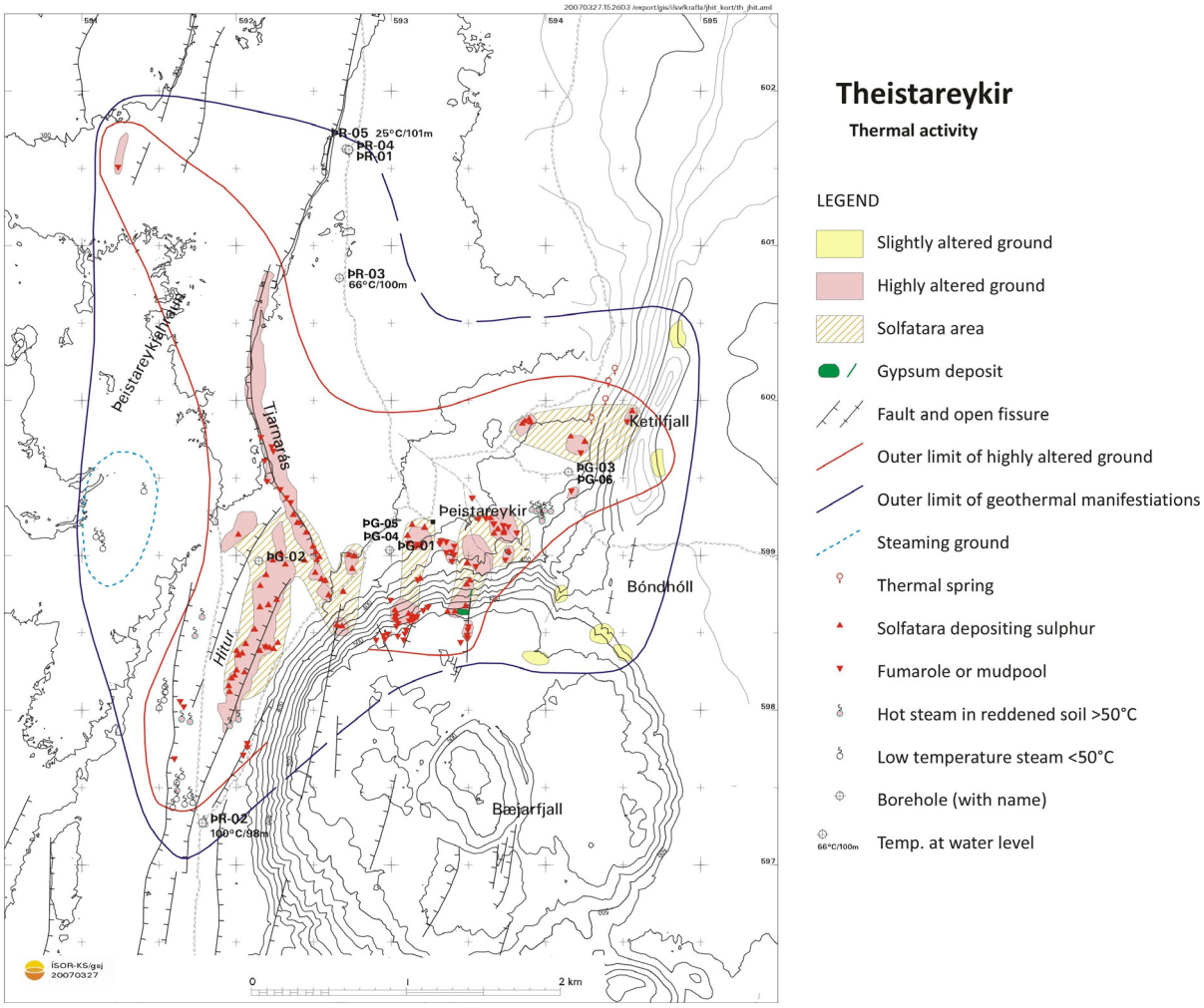

FIGURE 2: A geothermal map of the Theistareykir geothermal system

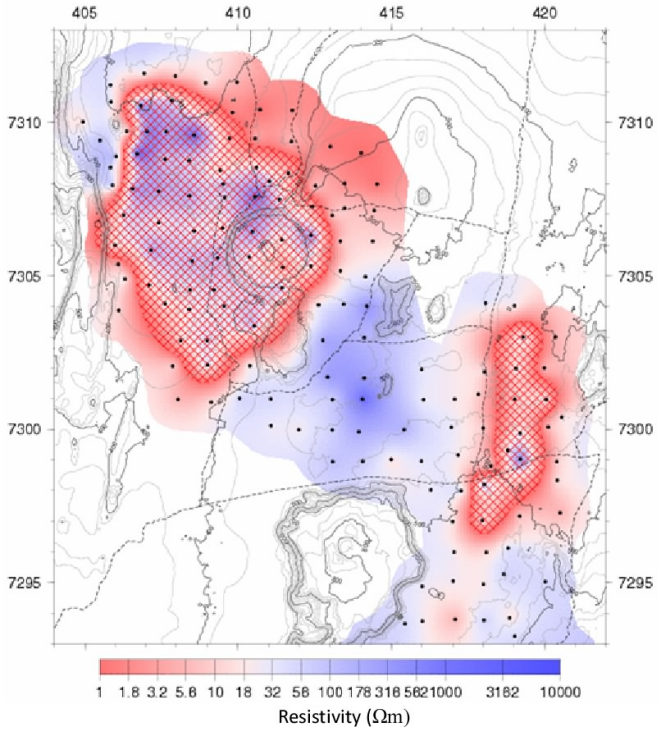

FIGURE 3: Resistivity at 500 m.b.sl. at Theistareykir.(top left) and Gjástykki (bottom right) (Karlsdóttir et al. 2006). High resistivity cores are surrounded by low resistivity

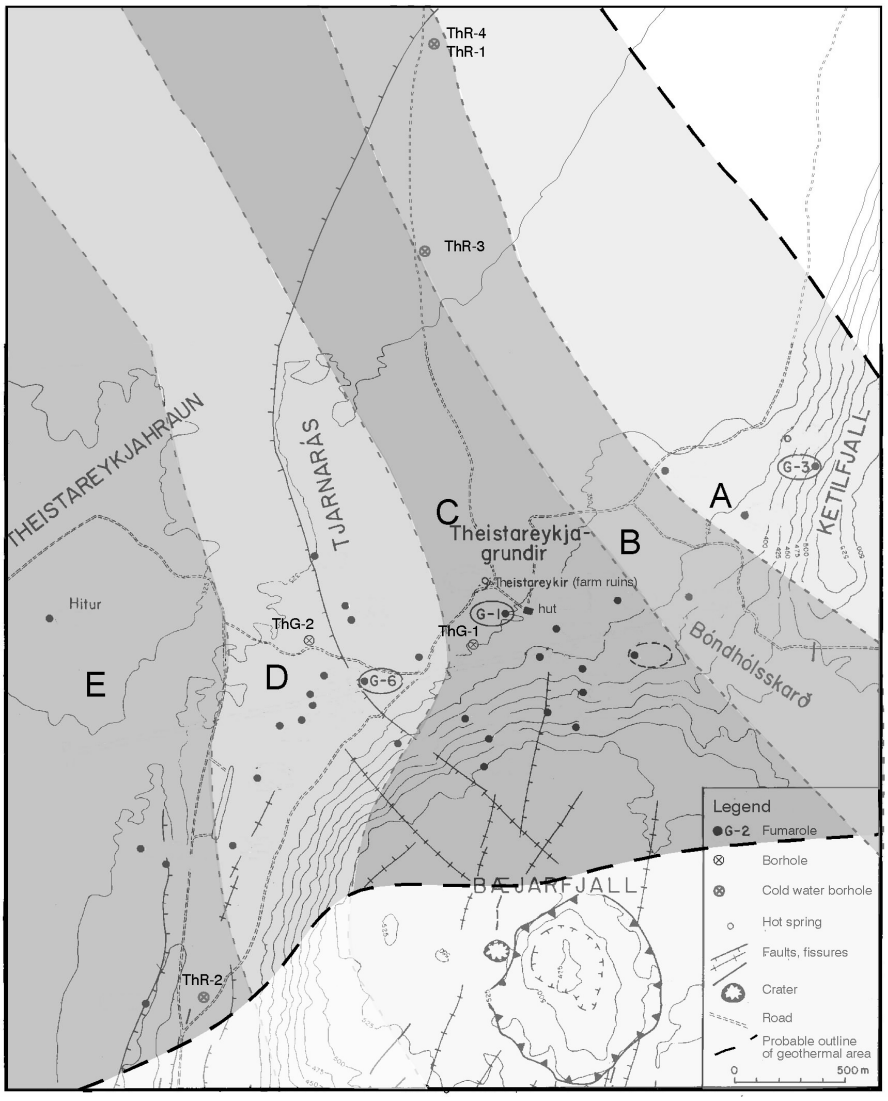

FIGURE 4: Theistareykir. Division into five subareas (Ármannsson et al. 1986). Geothermal and cold water boreholes in and north of the geothermal area are shown as well as three fumaroles sampled during monitoring 1991-2000

They concluded, however, that the steam rising from area A (Ketilfjall) was undisturbed and that the geothermometer temperatures were close to true values. Ármannsson et al. (1986) proposed a deep inflow to the area from the southeast with area C closest to the source. Thus area C was considered promising even though the gas geothermometer values seemed rather low. A relatively large, cool, shallow flow was predicted through Bóndhólsskard (Figure 4), preventing primary steam from rising to the surface in area B. Areas C and D are more accessible than area A, and therefore the suggestion was that the first drillholes be situated in these two subareas. The dissolved solids content of the steam was very low suggesting that the reservoir fluid was dilute. Low radon concentrations were interpreted to suggest good permeability especially in area D.

TABLE 1: Gas geothermometer temperatures in A, C and D (°C)

Subarea	**1980´s (°C)**	**Fumarole**	**1991 (°C)**
A	272-315	G-3	289
C	232-271	G-1	284
D	274-309	G-6	263

3. MONITORING AND HEAT LOSS

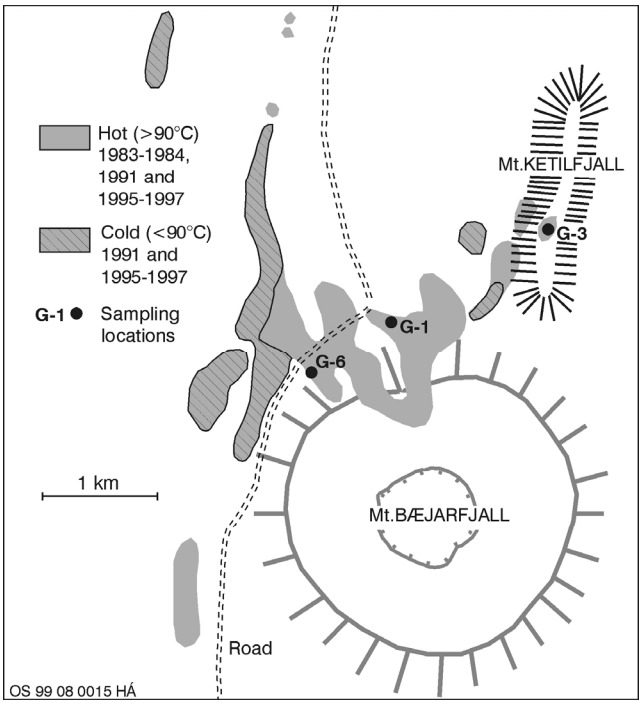

FIGURE 5: Theistareykir. Changes in surface manifestations from 1983-4 to 1991 (Ármannsson et al. 2000); fumarole sampling locations used during monitoring shown

The area was visited again in 1991 at the beginning of a monitoring program in which some unexploited high-temperature areas were to be monitored to establish the extent of natural changes in geothermal areas as opposed to changes due to production (Ármannsson et al. 2000). Changes in surface manifestations were mapped and steam samples collected from 3 fumaroles, one from each of areas A, C and D. At that time considerable changes in surface manifestations were observed, mainly cooling in area D (Figure 5). There was information from local people that following earthquakes in 1958 the surface activity in the area had increased drastically but had been declining since. The gas geothermometer temperature for the fumarole from area D (G-6, Figures 4 and 5) had decreased drastically, but little change or a slight increase were recorded for gas geothermometer temperatures for fumarole steam from areas A (G-3, Figures 4 and 5) and C (G-1, Figures 4and 5; Table 1). It is possible that the secondary effects suggested by Darling and Ármannsson (1989), condensation and formation of secondary steam, were less pronounced this time. The area has been visited a few more times, but it has remained relatively unchanged after 1991.

Using information from Hafstad (1989, and personal communication) about the Lón estuary in Öxarfjördur, 20 km to the north of the Theistareykir area, Ármannsson (2001) calculated the heat loss from the Theistareykir area (Table 2). This estuary is believed to receive solely subsurface water from the Theistareykir area. The values are minimum values but they suggest a total output of 300 MW. Therefore a powerful geothermal system with a temperature of about 280°C recharged with dilute, probably relatively old, water from far south and with an isotope signature of $\delta D = -100‰$ and $\delta^{18}O = -12‰$ was predicted prior to drilling.

TABLE 2: Heat loss from the Theistareykir area

Inflow to Lón, Öxarfjördur	20 m^3/s
Local groundwater ambient temperature	3.7°C
Inflow to Lón, mean temperature	7.2°C
Excess temperature	3.5°C
Heat power of area	3.5×20×42≈300 MW
Areal extent of Theistareykir	15 km^2
Heat loss from area	300/15=20 MW/km^2= W/m2

4. RESULTS OF DRILLING

Prior to deep drilling, four shallow "cold water" wells, ThR-1-4 (Figure 3) were drilled to obtain drilling fluid. Well ThR-2, which is 102 m deep, just reached the groundwater table, and the temperature of the water proved close to boiling. In ThR-3 the groundwater table is also close to 100 m depth. The temperature was 66°C there, but 90°C at 140 m depth. The groundwater table was at

about 100 m depth in wells ThR-1 and ThR-4, the former is 128 m deep and the temperature of the water was 26-28°C, but the latter is 150 m deep, with water temperature 26-35°C (Hafstad 2000). Water from these two wells was used as drilling fluid for the deep geothermal wells.

Well ThG-1 was drilled in area C (Theistareykjagrundir; Figure 3) in autumn 2002 to a depth of 1953 m, with a casing to 614 m depth. The major inflows are at 620-640 m depth and 1620-1640 m depth. Other inflows are observed at 710, 860-880, 1050, 1230-1240, and 1350 m depths and possibly at 1780-1800 and 1900-1910 m depths. An overpressured aquifer was observed at 212 m depth (Gudmundsson et al. 2002). The well started discharging in late October 2002.

The results of chemical analysis suggest that in November 2002 the fluid was still contaminated by drilling fluid and thus the results from July 2003 (Table 3) are used for the purpose of interpretation. The measured enthalpy at the surface was 2180 kJ/kg and the total flow from the well 16-17 kg/s. The calculated steam fraction at depth at 280°C was 0.611.

The stable isotope composition for the total fluid was δD = -108‰ and $\delta^{18}O$ = -12.7‰, or a little lower than predicted. Thus the fluid probably originated as precipitation far to the south of the area, probably as far south as Vatnajökull, and it may also be 100 years old or more.

Geothermometer temperatures were calculated in six ways with the results reported in Table 4. As is apparent, the results come in pairs, and there is a significant difference between the pairs. It had been suggested that, in this part of the area, some secondary steam was formed in fumaroles. Using the calibrations of Arnórsson et al (1998) for the CO_2, H_2S and H_2 geothermometers, the same kind of pattern emerges from the results as for the fumaroles, i.e. CO_2 and H_2S temperatures around 240°C, but H_2 temperatures of about 300°C or higher. As H_2 and Ar are relatively insoluble at these conditions they may not be affected by the secondary steam formation whereas CO_2 and H_2S will dissolve in the water phase and be released again at a lower temperature.

One model that explains these geothermometer temperatures assumes that the main inflows are at 620-640 m and 1620-1640 m, that the upper inflow is essentially liquid phase at 280°C but the deeper one essentially vapour phase at 300°C or higher. The logged temperatures of well ThG-1 are 270-280°C at 6-700 m and 300-305°C at 1600-1700 m. The temperature of the liquid phase at 280°C is reflected in the results for the solute geothermometers, whereas the temperature of the steam phase is approximated by the H_2 and H_2/Ar temperatures. CO_2 and H_2S travel some way after being dissolved in the water phase and before the fluid flashes at a lower temperature.

Well ThG-2 was drilled October to December 2003. After some circulation losses suggesting aquifers in the top layers, the well was cased to a depth of about 260 m. Shortly after drilling started again, a total loss of circulation was encountered and persisted. Logging revealed a well diameter in excess of 30” over a 10 m interval. An attempt to seal off this interval by gradually pouring 120 m^3 of gravel and sand into the well and cementing with 140-150 m^3 of concrete failed to stop the circulation loss. Drilling was resumed, a total loss of circulation was encountered again at 327 m depth, but drilling was still continued with total loss to 617 m depth where it was cased again. The final depth was 1720 m, drilled again with a total loss of circulation (>50-55 l/s) from 657 m depth. It was finished with a slotted liner. Pumping tests suggested very high permeability.

Extremely strong flows are inferred from 260 m depth and considerably below this. There is a possibility that this constitutes a large cave or some such feature whose temperature has been estimated at a little over 200°C, and that this large flow might cause cooling of the rock over some distance from the cave, possibly sufficient to cause partial condensation of steam rising to the surface in the vicinity. It is suggested that this may be the mechanism responsible for the condensation of steam in area D suggested by Darling and Ármannsson (1989).

Using information from wells ThG-1 and ThG-2 a model of the flow in the system was constructed

(Figure 6) showing the large relatively cool flow in area D, the intermediate aquifers at 600-800 m depth and the deep hot aquifer at about 1600-1800 m depth.

Well ThG-3 was drilled in area A in 2006 to a depth of 2659 meters and the maximum temperature recorded was 380°C. Its flow oscillated with enthalpy varying from about 1600 to 2600 kJ/kg but has approached the higher value with time and eventually settled as a high enthalpy well giving 10-12 kg/s of high temperature steam. The total dissolved solids in the fluid are low and so is the gas concentration.

Wells ThG-4 and ThG-5 were both drilled directionally from the same well pad as ThG-1; ThG-4 to the SE beneath Mount Baejarfjall and well ThG-5 towards well ThG-2. Well ThG-4 is a high enthalpy well with a steam flow of 30 kg/s of high temperature steam but well ThG-5 is a low enthalpy well similar to well ThG-2 with a large liquid water flow. The concentration of dissolved solids and gas are low in these wells two and the results for the wells drilled after ThG-2 do not conflict with the model suggested in Figure 6.

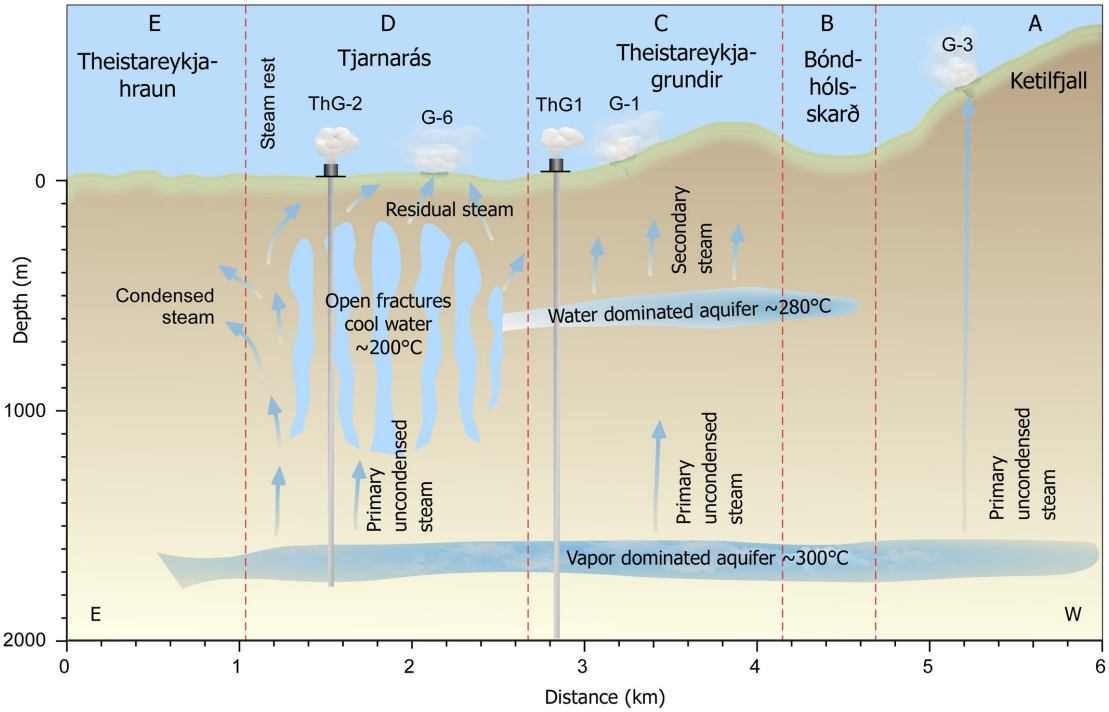

FIGURE 6: The most important aspects of fluid flow in the Theistareykir geothermal system based on surface exploration and results of drilling wells ThG-1 and ThG-2

Finally Well Th-G-5 was redrilled under a sharper angle in 2008 (ThG-5b) and well ThG-6 was drilled directionally from the well pad of well ThG-3 to the west. These wells have started discharging in early November. In late October the maximum temperature in ThG-5B was 300°C but ThG-06 312°C. In early December the enthalpy of ThG-5b flow was 1485 kJ/kg and the amount of high temperature steam 20.8 kg/s, but the enthalpy of the ThG-6 flow was 2663 kJ/kg and high temperature steam 13.2 kg/s.

The strata observed in the wells show thick palagonite strata (tuff, breccias and pillow lavas) in the top part. The number of intrusions increases with depth. At a depth of about 1150-1300 m a change occurs and lava layers with intermediate layers become prominent. The alteration pattern suggests a steadily increasing temperature with depth.

The results of temperature and pressure logging show wells ThG-2 and ThG-5 to be cooler than the others presumably reflecting cooling from the surface of the fissure system shown in Figure 2.

TABLE 3: Chemical composition of deep water and deep steam in fluid from well ThG-1, Theistareykir at 280°C

Constituent	Water phase	Steam phase
pH	7.96	
CO_2 mg/l	37.53	1463
H_2S mg/l	30.65	265
B mg/l	1.29	
SiO_2 mg/l	574.3	
Na mg/l	89.44	
K mg/l	18.36	
Mg mg/l	0.003	
Ca mg/l	0.38	
F mg/l	0.79	
Cl mg/l	80.81	
SO_4 mg/l	7.06	
Al mg/l	1.57	
Fe mg/l	0.0055	
Mo mg/l	0.0144	
Mn mg/l	0.0014	
Zn mg/l	0.0050	
As mg/l	0.0057	
H_2 mg/l		25.3
N_2 mg/l	0.10	33.8

TABLE 4: Chemical geothermometer results for fluid from well ThG-1, Theistareykir

Type	Quartz[1]	Na/K[2]	CO_2[3]	H_2S[3]	H_2[3]	H_2/Ar[4]
T(°C)	276	279	244	237	295	302

[1]Arnórsson et al. 1983, [2]Fournier 1977, [3]Arnórsson et al. 1998, [4]Giggenbach 1991.

5. CONCEPTUAL MODEL AND VOLUMETRIC ESTIMATE

The A conceptual model (Figure 7) has been presented on the lines of Figure 6 showing a strong upflow in area C, a weaker one in area A and a possible one in area E but a possible downflow in area D. The possible potential of the system has been estimated using the so-called Monte Carlo method and the most probable values are 348 MW_e (90% probability 191-622 MW_e) for 30 years, 209 MWe (90% probability 115-373 MWe) for 50 years and 104 MWe (90% probability 57-187 MW_e) for 100 years (Gudmundsson et al. 2008).

6. CONCLUSIONS

The results of surface exploration in the Theistareykir area suggested that it encompassed 3 distinct subareas (A, C and D, Figure 4) suitable for drilling, drawing fluid from a single base reservoir with a temperature of at least 280°C. The fluid originates far to the south of the area, and is probably more than 100 years old. Results for stable isotopes in fumarole steam suggested that in area D, there was condensation of fumarole steam during its passage from the reservoir to the surface, but that in area C the fumarole steam was in some cases secondary steam.

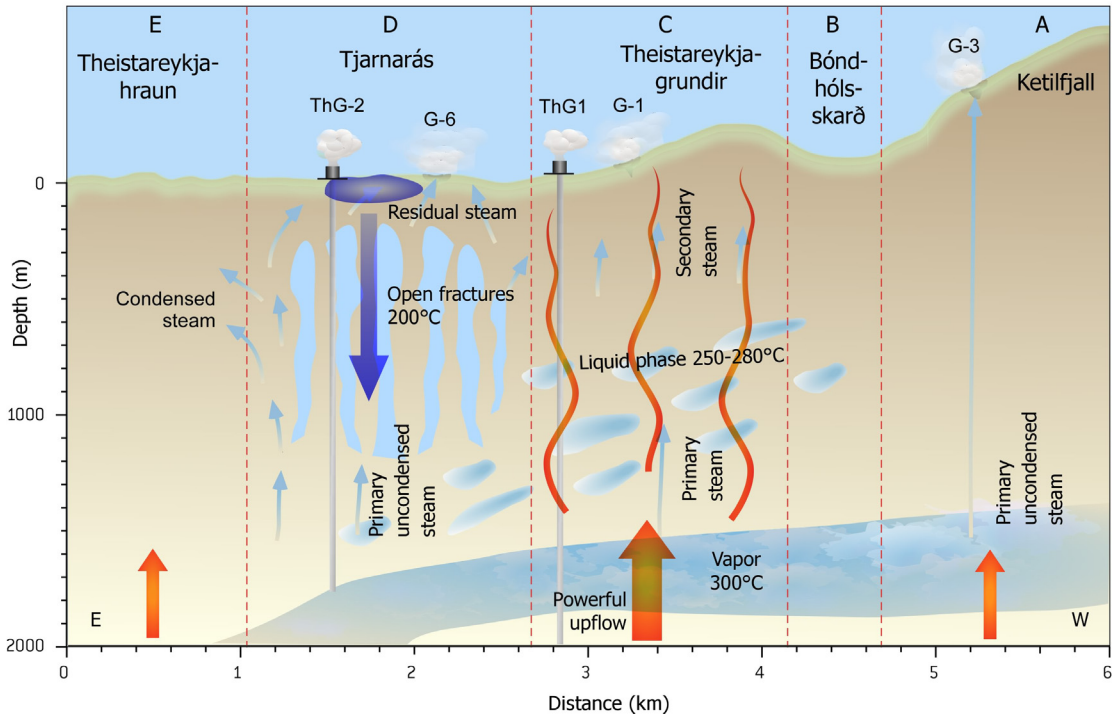

FIGURE 7: A conceptual model of the Theistareykir geothermal system (Gudmundsson et al. 2008)

During drilling of wells ThG-1 and 2 large inflows of relatively shallow cool water, which can explain condensation and secondary steam formation in area C and D, were encountered. Good permeability was predicted for area D from results of surface exploration. Thus the preliminary results of drilling do not contradict those of surface exploration.

The results for wells ThG-3 to ThG-6 confirm these results and show area C to be powerful probably above the main upflow although a smaller upflow is predicted for area A.

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GEOTHERMAL WELL DRILLING

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ABSTRACT

The drilling process complex as it may be rotate about breaking the ground and lifting the rock cuttings from the resulting hole. The ultimate geothermal drilling objective is to access the resource for exploitation. However, during resource development and exploitation, drilling is used to confirm existence of the resource, obtain data for resource assessment, provide adequate steam fuel for the power plant and resolve well production complications. Tri-cone tungsten carbide insert bits are very often used in geothermal drilling. Mobile and conventional land rigs are predominantly used in the geothermal drilling industry. The rigs are selected to technically fit the job at the lowest cost possible. The wells are made useful by casing them. Several casing string are used for each well. They are cemented to bond them to formation. Large production casing of 13 3/8" casing is increasing becoming common where large well outputs are encountered and directional drilling is being employed to target major faults that transmit fluids.

1. OVERVIEW OF THE DRILLING PROCESS

Actual breaking of ground is achieved by use of a rock bit. The bit is rotated under weight. The bit both crashes and gouges the rock as it rotates. The broken rock pieces arising from the drilling are lifted from the bore by floating them in a circulating drilling fluid. This process continues until the well is completed.

2. REASONS FOR DRILLING

The ultimate goal for drilling is to access the resource for exploitation. However, during the resource development and exploitation drilling serves various purposes.

2.1 Exploration

The very first evaluation of a prospect is achieved through detailed surface reconnaissance. It is aimed at defining the resource by its key system characteristic namely: existence of a heat source in the form of hot magmatic body near earth surface, existence of hydrological system, characteristic of the geological setting and areal extent of the prospect (Figure 1). However, while the surface measurement and mapping and evaluation of the surface manifestations provide great insight as regards the resource characteristics and potential, results of the reconnaissance remain inferences and are inconclusive. The initial employment of drilling in geothermal prospecting is aimed at providing proof of exploitable steam and data required for further refining of the conceptual model.

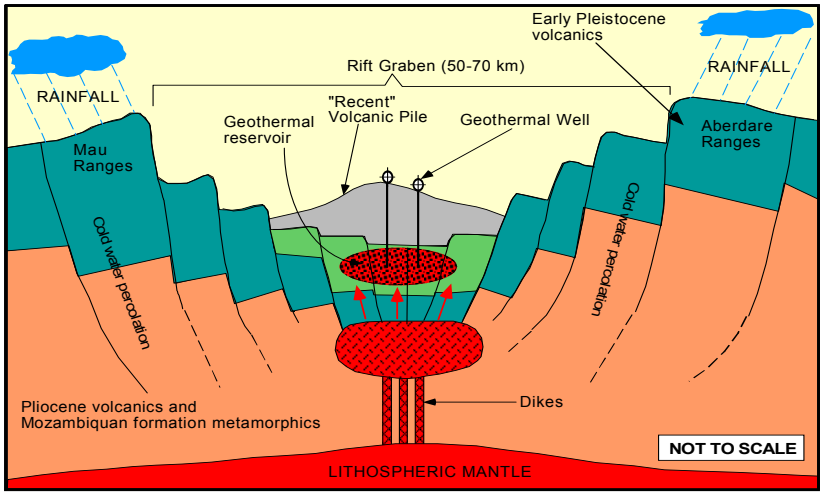

FIGURE 1: Typical conceptual model of a geothermal system in Kenya

2.2 Appraisal

Striking steam with the first well while is exciting opens up doors for more questions. Having confirmed existence of the resource, the next question is its technical, economic and financial viability. Further drilling (appraisal) is therefore carried out to delineate the resource and establish production well and reservoir fluids characteristics.

2.3 Production and re-injection

At this stage of development, a decision to construct a plant is already made. The drilling is therefore to provide sufficient steam to run the plant. Additional wells are drilled for reinjection purpose. One reinjection well is required for every 4 to 5 production wells.

2.4 Make-up

After commissioning of the power plant, with time the reservoir surfers pressure decline which affects well productivity. In addition, deposition may occur within the formation around the wells further reducing wells productivity. With time, therefore further drilling is carried out to replenish the reduced steam delivery.

2.5 Work-over

Two types of problem may arise during exploitation. Steam depletion in the shallow reservoir may necessitate deepening of the initial wells or deposition of scales within the well bore may necessitate a mechanical removal of the scales. These two cases require some form of drilling to accomplish.

3. BITS

3.1 Types of bits

3.1.1 Drag bits

Drag bits is the oldest rotary tool still in use (Figure 2). The cutting blades are integrally made with the bit body. They are fixed to it and rotate as a unit with the drill string. The bit is used primarily in soft and gummy formations.

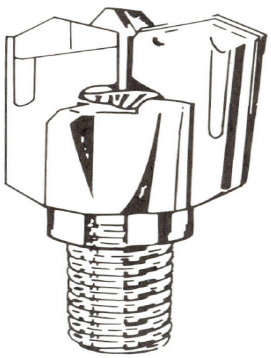

FIGURE 2: Drag bit

3.1.2 Polycrystalline diamond compacts (PDC) bits

The PDC bits use diamonds inserts embedded on the bit body (Figure 3). They operate by the diamonds embedding into the formation and dragged across the face of the rock in a ploughing action. The diamond bits drills according to the shear failure mechanism. They are of higher cost but their

long life make them cost economic in certain circumstances. The PDC bits are used in 5% of the drilling cases in the oil industry. (Moore 1986). The bits are however hardly used in geothermal drilling.

FIGURE 3: PDC bits

3.1.3 Roller cutting bit

More than 95% of the oilfield footage is drilled today with tri-cone roller bits (Figure 4). This will form the basis of our discussions.

3.2 Description-working mechanism

Rotary bits drill the formation using primarily two principles; 1) rock removal by exceeding its shear strength and; 2) removal by exceeding the compressive strength (Adams 1985). The broken rock chips are removed by scraping or hydraulic cleaning.

FIGURE 4: Tri-cone roller bits

Shear failure involves the use of the bit tooth shearing, or cutting, the rock into small pieces so it can be removed from the area below the rock bit. The simple action of forcing the tooth into the formation creates some shearing and results in cuttings development. In addition, if the tooth is dragged across the rock after its insertion, the effectiveness of the shearing action will increase. Shear failure mechanism requires that the formation exhibit low compressive strength that will allow the insertion of the tooth. The mechanism is employed while drilling softer formations (Adams 1985).

As the compressive strength or abrasiveness of the formation increases, the shearing – twisting is reduced. The rock with high compressive strengths generally prevents the insertion of the tooth that would have initiated the shearing action. In addition, rocks with a high abrasiveness wear the bit tooth if it is twisted or dragged across the formation face. These types of rocks generally require that a compressive failure mechanism to be used.

Compressive failure of a rock segment requires that a load be placed on the rock that exceed the compressive strength for that given rock type. The load must remain, or dwell on the surface long enough for rock failure to occur. This is the basis for hard–rock drilling characteristics of high bit weight and low rotary speeds.

3.3 Key design features of the tri-cone bits

Roller cones bits have three components groups; the rolling cones, the bearings and the bit body (Figures 5, 6 and 7). The body is a forged and welded structure, initially having three pieces, called the legs, with bearings pins on the lower end of each leg. Each leg also has a nozzle boss and a one third circular arc-shaped piece at the top. After welding and turning, these three arc-shaped pieces form the API thread pin connection.

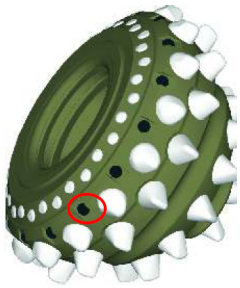

FIGURE 5: Bit cone

FIGURE 6: Bit bearing

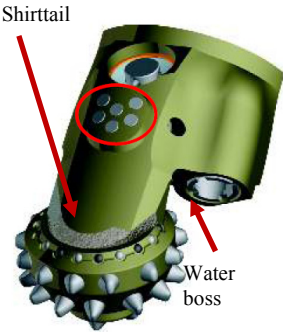

FIGURE 7: Bit body (single leg) with cone and bearing in place

3.3.1 Cones

Cones bearing axis are designed with an offset from the bit geometric centre (Figure 8). Ordinarily one would imagine that the bits roll on the hole bottom surface as the bit is turned. However, due to the offset, the cones tend to drag across the surface of the formation resulting in sliding, tearing or shearing, gouging and ripping action by the teeth on the bottom which help remove chips faster and more efficiently. For softer-formation, the offset is increased and therefore increase the ripping action. This means faster drilling with softer formations. As harder rocks are drilled, the degree of offset for various bits decreases since compressive failure becomes the primary drilling mechanism instead of shearing. Too much offset would cause the bit to wear quickly in hard formations.

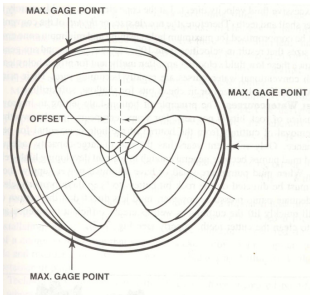

FIGURE 8: Cone offset (Adams 1985)

3.3.2 Teeth

Two types of teeth exist namely the "mill steel tooth" bit and the tungsten carbide insert bits (TCI). Under hard, abrasive rocks environment, the milled steel tooth bits are not recommended as they would wear more rapidly. Tungsten carbide insert bits are more appropriate as they are made of more wear-resistant materials.

The type of failure mechanism influences bit and tooth design and bit selection. Soft formations drilled with shearing actions are drilled most effectively with long tooth, while harder formations require more numerous, shorter teeth (Figure 9). Insert bits use tungsten carbide buttons pressed into the cone rather than milled, steel teeth.

FIGURE 9: Typical tungsten inserts profiles

3.3.3 Bearings

Roller bits bearings are manufactured in one of three configurations and usually use ball bearing retainers; unsealed roller bearing, sealed roller bearing and sealed journal bearing

Unsealed bearing, initially grease filled, is exposed to drilling fluids. Failure rate is high due to increase wear as a results cuttings etc. contacting with the bearing surfaces. Sealed and self lubricating journal bearing are the premium design both for the steel tooth and TCI bits.

3.3.4 Gauge protections

The lower exterior section of the bit leg is the "shirttail". This area is an important part of the bit because it is the only part of the body section that contacts the formation and therefore is subject to abrasive wear. The shirttail is often protected from wear by inserting tungsten carbide inserts (Figure 7 and 9) or applying sintered tungsten carbide. Wear in the shirttail area often indicates an under gauge hole that will give future problems when running a new, full gauge bit

3.3.5 Water ways

An important part of the rock bit is the watercourse, without which the rest of the rock bit could not function as intended. Watercourses are passageways for the circulating fluid (Figure 7), which primarily brings cuttings to the surface and cleans the formation below the bit. The watercourse are either designed to direct the force of the drilling fluid to the cuttings to clean them from adhering materials and thus enhance drilling rate or directed at the hole bottom to quickly remove cuttings as hole bottom as soon as they are cut to improve bit drilling performance.

3.4 Roller cone bits classification

The drilling industry has adopted the international Association of Drilling Contractors classification as the standard in the industry (Appendix A). The System uses a three-digit code for classification which appears as follows:

A,B,C

where,

A= a number between 1 to 8, known as the major class

B= a number between 1 to 4, known as the subgroup

C= a number between 1 to 9, known as the specialty features

When A is between 1and 3, the code denotes a milled steel tooth bit (Figure 10).

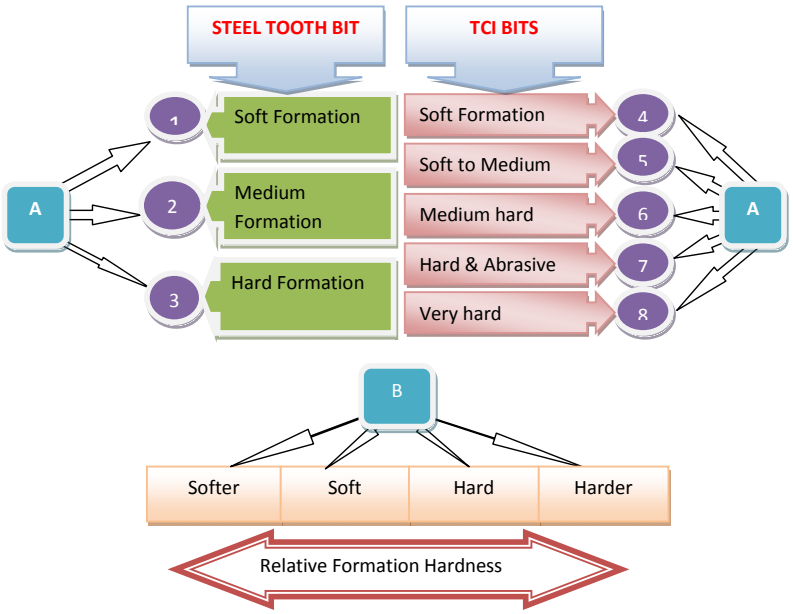

FIGURE 10: Bit Classification

3.5 Bit selection

Bit selection can be a very complex procedure if all the factors quoted by manufacturers were to be evaluated. The following is a simple guide to bit selection:

- Determine the likely formation hardness and abrasiveness
- Determine the bit size. Note that though the classification chart may show existence of a bit in a certain class, the size of bit you require may not be a common off self bit. Note also that the selected bit must easily go through the previous casing string.
- Bit economics. There exists a formula for use to determine most economical bit in an area.
- Classification chart is a good starting point (Appendix A)

3.6 Failure pattern

Bits failure mainly arises from the key design features discussed above.

- The cones could dislodge and be left in the hole. Good drillers would notice this by increased torque. In addition, the cones could also lock again generating high torque.
- The teeth could wear out or break rendering the bit performance poor
- The bearings could burn out resulting to very loose cones
- The bit shirttail could wear down resulting in under gauge hole

3.7 Bit records

Performance of various bits within a certain region is captured through proper bit records. Analysis of the bit records (Appendix B) would give bits that give long life under the drilling conditions prevalent in that region

4. DRILL STRING

For the bit to perform as noted above, it requires the rotary motion, water for cleaning the bit and hole bottom and the force (weight) to crash the rocks. The drill string (Figure 11) serves to provide essential requirement for the bit to perform. The drill string is therefore an essential part of the rotary process. It is the connection between the rig and the bit.

4.1 Purpose

The drill string serves several general purposes including the following:

- Provide the fluid conduits to the drill bit
- Impart rotary motion to the drill bit
- Provide and allow weight (force) to be set on the bit
- Lower and raise the bit

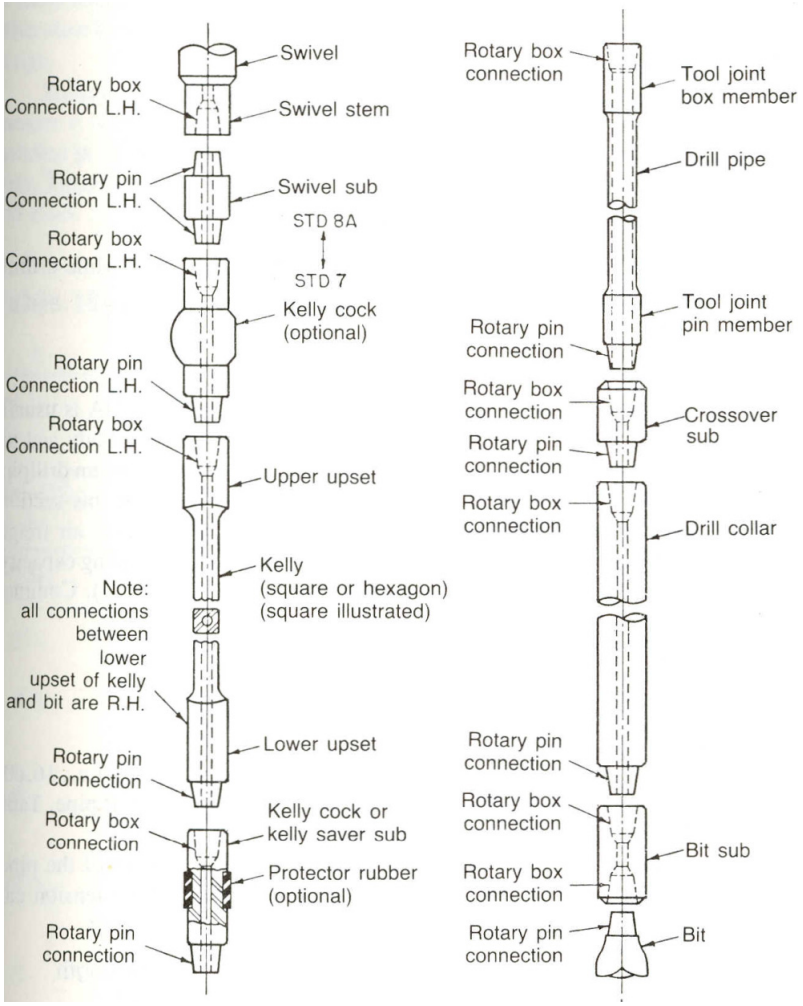

FIGURE 11: Components of the drill string

4.2 Components and descriptions

4.2.1 Bit sub / NRV sub

Immediately above the bit is fitted a bit sub and may double as non-return valve (NRV) sub. The sub is a piece of metal with a hole having female (box) thread on both sides which is about a 0.3 m (foot) to 1 m (three feet) long. It is used to connect the bit and the first collar. In addition, it could have a recess to accommodate a non-return valve. The non return valve ensures that fluid do not flow back through the string to the rig floor. This especially is very important in geothermal because the fluids could be dangerously hot for staff work at the rig floor.

4.2.2 Drill collar

Drill collars (Figure 12) are fitted immediately above the bit sub. They are stiff steel components of about 10 m long weighing 2 to 3.5 ton. The most common sizes of collars are 6" to 10" diameter. Their functions are:

- Provide weight for the bit
- Provide strength needed to run in compression
- Minimize bit stability problems from vibrations, wobbling, and jumping
- Minimize directional control problems by providing stiffness to the bottom hole assembly (BHA)

Drill collars are available in sizes and shapes such as round, square, triangular and spiral grooved. The most common are round (slick) and spiral grooved.

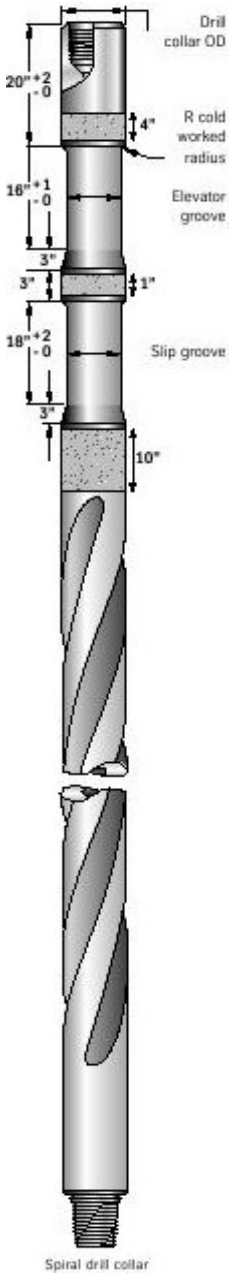

FIGURE 12: Drill collar

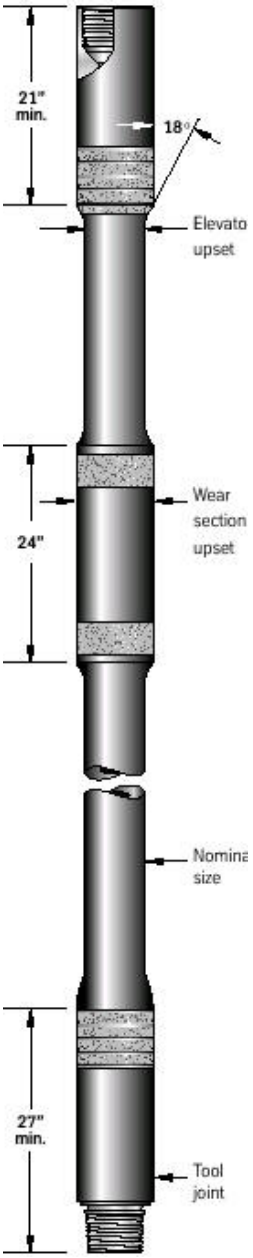

FIGURE 13: Heavy weight drill pipe

FIGURE 14: Drill pipe

4.2.3 Heavyweight

On problem faced by running stiff collars in the hole is that as the string rotates, the more flexible drillpipes above if fitted directly above the collar will suffer bending stresses resulting to pipe failure. The heavy weight drillpipe (Figure 13) having 2-3 times the weight of drillpipe offer a safer transition and minimize drillpipe failure.

4.2.4 Drillpipes

The drillpipes (Figure 14) are the longest section of the drillstring. They consist of a tube body welded to two tools joints with male (pin) and female (box) threads. The most common sizes are 3 ½, 4 ½ and 5" diameter drill pipes.

4.2.5 Kelly saver sub

In general the Kelly saver sub is fitted between the Kelly and drillpipe. It is a sacrificial tool to save the Kelly from wear arising from frequent connections.

4.2.6 Kelly

Kelly (figure 15) is a very important component of the drill string. It designed in a square or hexagonal shape. It is fitted into a Kelly drive bushing (Figure 16). The drive bushing has pins that slot into the rotary table. As the rotary table rotates, the drive bushing rotating with it imparting the rotary motion to the string which is then transmitted by the string to the bit. Note for top drive the Kelly is not required.

4.3 Key Design consideration

- The string must withstand the pull (tension) of its own weight. Well have been drilled to about 5000m. The total string weight may go to over 150 tons inclusive of drag.
- Besides it own weight, the design must have a safety reserve margin of about 50 tons (over pull) above the string weight which becomes necessary to free the string if stuck in the hole
- The string must withstand the force of pressure arising from the formation or drilling fluid i.e. should not collapse due to external pressure or burst due internal fluid pressure.

4.4 Common string failure

The most common downhole failure is fatigue failure. As the pipe rotates in the hole it subjected to cyclic stress in crooked hole. Over time part of the string develops cracks which propagate to twist offs. The weakest point in the strings is the drill collar and drillpipe tool joints. Other failures are tool joint washouts, belling and thread and tool joint shoulder damage.

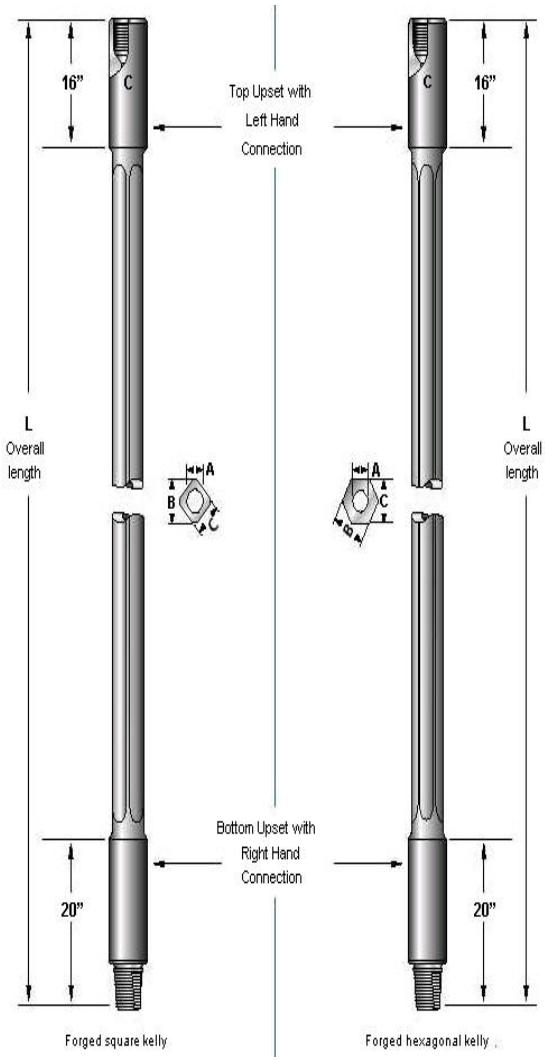

FIGURE 15: Square and hexagonal Kellies

FIGURE 16: Kelly fitted into a drive bushing

4.5 Drill string management

Most of the failures can be prevented or be avoided with proper care of the string. The care includes:

- Frequent string inspection. In Kenya, the string is inspected at least once every three wells drilled. In some other countries inspection is carried out after drilling every well.
- Use of thread protectors will eliminate thread and shoulder damage
- Proper torquing will eliminate over torquing, belling, and washouts
- Proper use of the right lubricants with eliminate thread galling (abnormal wear)
- Proper storage and transportation will eliminate bending

5. DRILLING FLUIDS

5.1 Purpose of drilling fluids

Primarily, the drilling fluid function is to remove the cuttings from the bottom of the hole as fast as they are created to facilitate further and efficient hole making process. In addition, the fluid transports the cuttings to surface. The two functions constitute what is normally referred as hole cleaning. The drilling fluid in real drilling situation is a complex subject with consideration ranging from the basic hole cleaning, economics, availability, logistics, chemistry, safety, fluid dynamics and reservoir management. As such the drilling fluids serve many functions.

The major functions include;

- Cleaning of the hole bottom,
- Carry cuttings to the surface
- Cool and lubricate the bit and drillstring
- Remove cuttings from muds at the surface
- Minimize formation damage
- Control formation pressure
- Maintain hole integrity
- Assist in well logging operations
- Minimize corrosion of drillstring and casing
- Minimize contamination problems
- Minimize torque, drag and pipe sticking
- Improve drilling rate
- Cooling of the formation – unique for geothermal

5.2 Types of drilling fluids

The drilling fluids vary widely. The following table gives a classification of drilling fluids (Chilingarian, 1983)

I. Water based drilling fluid.
    a. Fresh water muds with little or no treatment. This include spud mud, inhibited muds and natural clays
    b. Chemical treated muds without calcium compounds added. This includes phosphate muds, organic treated muds (lignite, chrome-lignosulfonate etc.)
    c. Calcium treated muds which include lime, calcium chloride and gypsum
    d. Salt-water muds which include sea water muds, saturated salt water muds
    e. Oil emulsion muds i.e. oil in water
    f. Special muds
II. Oil based drilling muds

a. Oil based muds
b. Inverted emulsion muds – water in oil

III. Gaseous drilling fluids
a. Air or natural gas
b. Aerated muds
c. Foams

5.3 Key drilling fluid properties

The three basic properties of drilling fluids that are mostly important for successful completion of a well are:

a) Density as related to hydrostatic pressure.
b) Viscosity which affects the efficiency of the cutting lifting capacity of the drilling fluid
c) Filtrate loss – the loss of water component of the drilling fluid into formation

5.4 KenGen drilling fluid practice

5.4.1 26" Surface hole

The first section of the well is commenced with spud mud consisting of bentonite – lime with marsh funnel viscosity of 60-80 sec marsh funnel viscosity and is drilled to 60 m.

If return circulation is lost and cannot be regained with loss control materials (LCM), drilling continues blind (without circulation to surface) with water and high viscosity gel sweeps at every connection or more frequently depending on the hole problems.

5.4.2 17 ½" intermediate hole

This section of well is drilled to a depth of about 250 to 300m with a bentonite –lime mud. If loss of circulation returns occurs, attempts are made to regain it using LCM. If the loss cannot be healed, drilling continues blind with water and frequently mud slug of high viscosity mud. The section is drilled with high pumping rates on the hole to clean the hole. In extreme circumstance of poor cleaning stiff foam is used.

5.4.3 12 ¼" production hole

This section that is drilled to between 500 to 1200 m is drilled with mud and when mud circulation cannot be sustained, aerated water with foam is used.

5.4.4 8 ½" main hole

This section that is drilled normally to 2200 m to 3000 m is entirely drilled with water and when the first signs of lost circulation appear, partial or total, aerated water with foam is used. No mud is ever introduced to this section for protection of the formation. However, in one of our field, Olkaria West, we have used aerated mud for this section due to severe sloughing problems. The in-going fluid is maintained at a maximum temperature of 40°C, which is the maximum recommended operating temperature for the pumps. Control of temperature is also critical for extending the bit life.

6. DRILLING RIGS

6.1 Basic functions

From a basic and simplistic view, the rig can be seen as that equipment that provides the motive power to rotate the bit, allow weight on the bit to crash the rock beneath and circulate the drilling fluid and hence achieve the drilling action. Achievement of these basic rig functions requires systems and processes where various individual pieces of equipment serve only as part of the function in the whole process and system. Operational requirements and economics dictate the sophistication of drilling rigs.

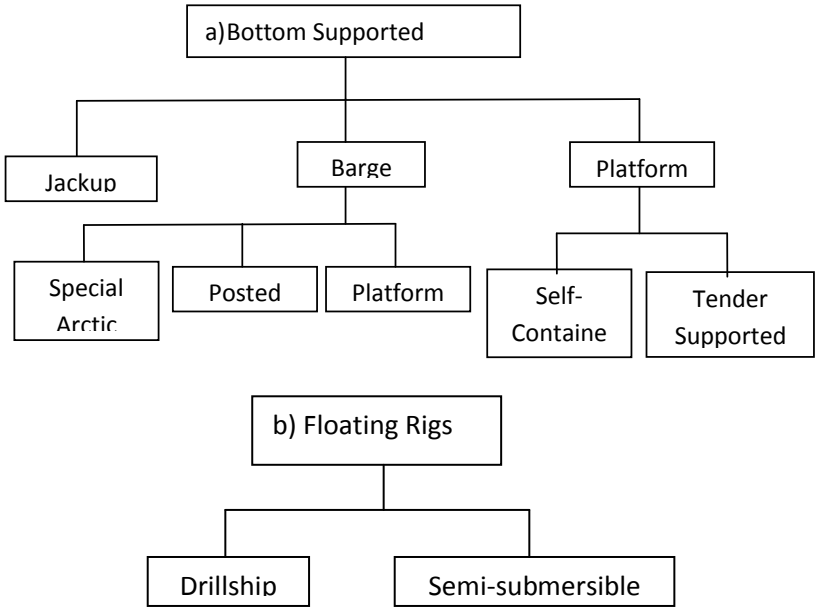

FIGURE 17: Classification of Marine rigs

6.2 Types of rigs

All rigs are categorized as either land or marine. Each of these categories, comprise various types of drilling rigs.

6.2.1 Marine rigs

Drilling rigs used offshore (in water) are termed marine rigs. They fall under two categories; those supported on water bottom and floating vessels (Figure 17). Figure 18 shows one type of marine rig.

The marine rigs are not employed in drilling of the geothermal wells.

FIGURE 18: Jack-up marine rig

6.2.2 Land rigs

The land rigs fall under two main categories; the cable tools and the rotary rigs. The cable tools accomplish the drilling action by raising a special drill bit and dropping it. The cable tools are the predecessor of the modern rotary rigs and are hardly used anymore.

The rotary rigs fall under three categories:

a) The standard derrick where the mast/derrick was built on location and dismantled after the drilling process.

FIGURE 19: Mobile land rig

These were the very early rotary rigs

b) Portable rig mostly truck-mounted for low rig up time (Figure 19).
c) Conventional rig where key components are so large that they cannot be transported on a single truck bed (Figure 20).

FIGURE 20: Typical conventional rig

6.3 Rig equipment systems

The rig (Appendix C) has six distinct systems:

- Power system
- Hoisting System
- Circulating System
- Rotary system
- BOP System
- Auxiliary Rig equipments

6.3.1 Power system

The power system consists of a prime mover, primarily diesel engines, and some means of transmitting the power to the auxiliary equipment. Transmission may be in the form of mechanical drives like chains, DC generators and motors or AC generators, SCR (Silicon control rectifiers), Dc motors

6.3.2 Hoisting system

The hoisting system is one of the major components of the rig. Its primary function is to support, lift and lower rotating drillstring while drilling is in progress. It consists of:

i) Supporting structure: The support structure includes the mast or derrick, the substructure and the rig floor
ii) The hoisting equipment: This includes the drawworks, crownblock, travelling block, hook, links, elevators and the drilling wire-line

6.3.3 Circulation system

The circulation system (Figure 21) is another major component of the rig affecting its overall success. Its main purposes are stated under the drilling fluid section above. It consists of pumps, standpipe, rotary hose, swivel, Kelly, drillstring, shale shakers, tanks and mud pits.

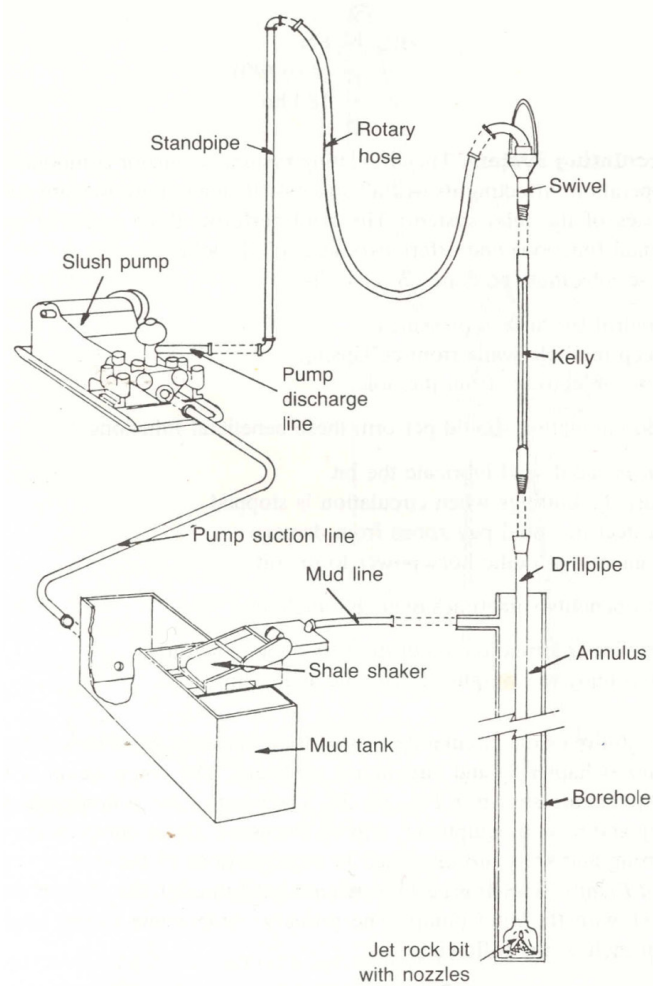

FIGURE 21: Typical fluid circulation system

6.3.4 Rotary system

The rotary system is responsible for imparting a rotating action to the drillstring and bit. The principle components are the Kelly, rotary table and drive bushing, swivel rotary hose and drillstring.

6.3.5 BOP system

The blowout preventer (BOP) are primarily used to seal the well to prevent uncontrolled flow, or blowout, of formation fluids. Typically it consists of annular BOP (Figure 22), drillpipe or casing ram BOP, blind ram BOP and accumulator system

FIGURE 22: Two BOP stack

6.3.6 Auxiliary rig equipment

The auxiliary rig equipments are those items of the equipment that added to the drawworks, rotary, Kelly, swivel, blocks, drilling line, bits and prime movers, make it possible for the rig to function more efficiently. The can be broadly be groups as:

- Drillstring handling tools; spinning wrenches, power tongs, hydraulic torque wrenches, power slips, automatic drilling, Kelly spinner, automatic cathead
- Instrumentation; weight indicators, mud pumps pressure gauge, rotary tachometer, rotary torque gauge indicator, pump stroke indicator, tong torque indicator, rate of penetration recorder
- Air hoist
- Rig floor tools

6.4 Rig selection

Rig Selection comes as the last activity after the complete well design i.e. after setting the drilling depth, casing sizes, weights and casing depths, the drilling fluid and hydraulic power requirements. The key considerations are to select a rig that will be technically adequate for job and at minimum cost. In addition, qualifications of the rig's manpower and its performance track records, logistics of servicing the rigs and rig-site requirements are also considered. Table 1 shows typical rig sizes.

TABLE 1: Typical Rig Sizes (Composite catalog, 1998-1999)

Drawworks Hoisting Power rating		**Typical Depth Rating**		**Maximum Hoist Capacity (Hook Load)**									
				6 lines		**8 lines**		**10 lines**		**12 lines**		**14 lines**	
hp	kw	ft	m	lb	ton	lb	ton	lb	ton	lb	ton	lb	ton
550	410	3,000 to 8,500	914 to 2,591	236,000	107	302,800	137	364,500	165				
750	559	7,000 to 12,000	2,134 to 3,658	314,200	143	403,100	183	485,300	220				
1000	746	10,000 to 14,500	3,048 to 4,420			437,300	198	526,700	239	609,500	277		
1500	1,119	12,000 to 18,000	3,658 to 5,486					708,100	321	819,300	372	922,900	419
2,000	1,864	13,000 to 25,000	3,962 to 7,620					919,200	417	1,064,100	483	1,198,600	544
3,000	2,237	16,000 to 30,000	4,877 to 9,144							1,484,360	673	1,671,960	756

7. WELL PLANNING & CASING DESIGN

7.1 Objective of well plan

The main objective of planning a well is to drill safely, minimize costs and drill usable well.

7.2 Classification of wells

Wells can be categorized as follows:

- Exploration/discovery wells — No geological data or previous drilling records exist
- Appraisal wells — Delineates the reservoir's boundary; drilled after the exploration wells
- Production wells — Drill the known productive portions of the reservoir
- Work-over wells — Re-entry of already drilled wells to deepen, clean etc.

Planning for the drilling of exploration wells takes more effort than appraisal wells and production drilling. This is because the discovery wells are drilled in unknown area thus the unexpected can happen.

7.3 Purpose of casing

The target resource is found for Kenya from around 500m to as deep as 3000m. The wells are cased for the following reasons:

- Isolate fresh underground water to prevent contamination
- Maintain the hole integrity by preventing caving in to enable drilling further below
- Minimize lost circulation into shallow permeable zone
- Cover weak zones that are incompetent to control kick-imposed pressure (prevent blowouts)

- Provide a means for attaching and anchoring BOP and wellheads and thereby contain resultant pressures.
- Provide safe conduit for the reservoir fluids to the surface
- To prevent cooling of the reservoir fluids by shallow cooler fluids
- Prevent well collapse

7.4 Categories of casing strings

Before the well is drilled to completion, several strings of casing are run and cemented in place. The actual number used is depended on the drilling safety and operational problems anticipated or encountered. The types of casing strings are:

- Surface casing: Mainly used to isolate the shallow loose formation to enable further trouble free drilling below.
- Intermediate casing: This may be more than one string. They primarily isolate the shallow potable water from contamination, provide anchorage for the wellhead and seal off zones of loss of drilling fluid. They also protect the shallow formation from high downhole pressure thus prevent blowouts.
- Production casing: This primarily act as the safe conduit for the reservoir fluid to surface, protect shallow formation from deep reservoir pressure thus prevent blowouts and isolate cooler shall water from degrading the reservoir fluids
- Slotted liner: This is primarily run to prevent the reservoir wellbore from collapsing and blocking the well flow path.

7.5 Selecting casing depths

The first design task in preparing the well plan is selecting the depths to which the casing will be run and cement. The considerations made are the geological conditions such as formation pressures and formation fracture gradient. Other considerations are policy and government regulations. Wells have been drilled and cased too shallow or too deep.

7.6 Hole geometry (well casing profile)

Having decided on the casing depth, the next design aspect is to decide on the casing string sizes to be run in the hole. Figure 23 shows the typical casing profile within KenGen. The key consideration at this point is well productivity versus costs. Small well bore may choke the well thus rendering it unproductive while on the other side large wellbore cost much more. The drilling industry has developed several commonly used geometries (Appendix D). These programs are based on bit and casings availability as well as the expected drilling conditions. The most common casing geometry employed in geothermal is:

- 20” Diameter casing for 26” diameter surface hole

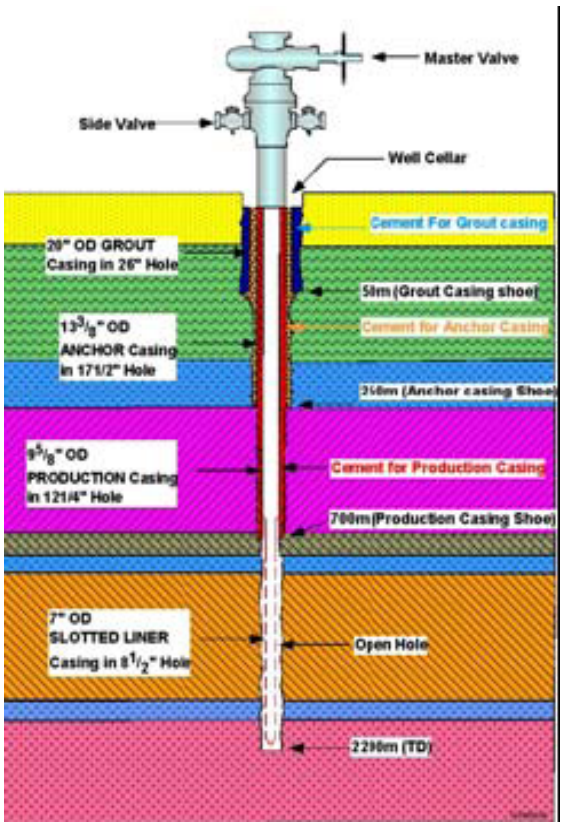

FIGURE 23: Typical well in Kenya

- 13 3/8"diameter casing for 17 ½" diameter intermediate hole
- 9 5/8" casing for the 12 ¼" production hole
- 7" slotted liner for the 8 1/2" main hole

The considerations made are casing inner and outer diameter, coupling (collar) diameter and bit sizes.

Sufficient allowance is made to allow flow area between the casing and wellbore to reduce washouts while provide sufficient velocity for drilling fluid to lift cuttings.

7.7 Casing design

The casing is used for protection during the entire life of the well and therefore it is designed to withstand many severe operating conditions.

Common problems often considered for casing design when drilling are kicks, lost circulation, stuck pipe, wear, hydrogen sulphide environment and salt. Just like the drilling string, the casing is designed to with stand burst, collapse, tension forces and biaxial effects (combined effects).

In General the thicker the casing the more resistance it is to the above factors. However, the more the well cost.

8. CEMENTING

8.1 Purpose

Cementing of casings is one of the critical operations during the drilling of a well that affects the producing life of a well. Casing strings are usually cemented in the hole to:

- Bond the casing to the formation
- Protect deeper hot producing zones from being cooled by cooler water emanating shallow bearing zones
- Minimize the danger of blowouts from deeper high pressure zones by isolating weaker shallow zones
- To isolate shallow troublesome formation to enable deeper drilling

8.2 Surface and subsurface casing equipment

Figure 24 (Smith, 1976) shows the key equipment used in casing cementing. Their basic functions are summarized as follows:

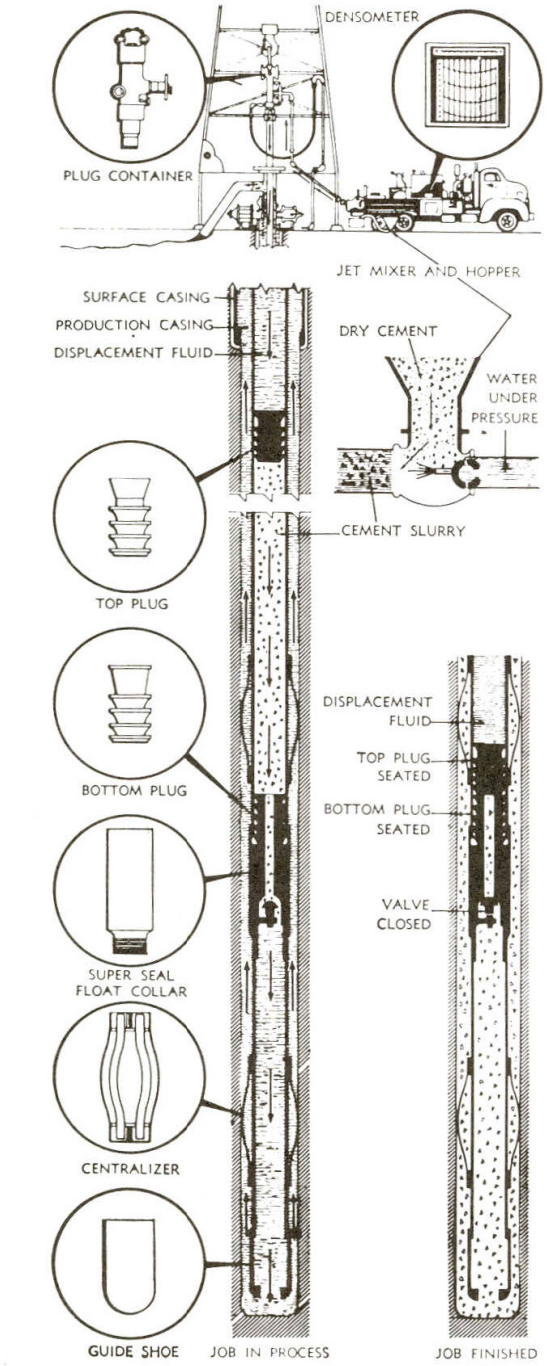

FIGURE 24: Typical primary cementing job

8.2.1 Guide shoe

A casing shoe joint is a short pipe run on the casing bottom. Inside of the pipe is packed with drillable but hard material shaped in a rounded nose provided with a hole which is used to guide the casing into the hole through crooked sections. The shoe is screwed on the casing and is glued with a thread locking compound to avoid inadvertent loosening while being run in the hole.

8.2.2 Float collar

The float collar is placed one or two casing joints above the guide shoe. The collar serves as a stop for the cement wiper plug such that all the cement is not inadvertently pumped out of the casing and diluting the cement at the shoe a situation that would result to a poor cementing job. It is fitted with a ball or spring-loaded backpressure valve. The valve prevents well bore fluid entering the casing while allowing pumped fluid through the casing to pass through.

8.2.3 Casing centralizers

The uniformity of the cement sheath around the pipe determines to a great extent the effectiveness of the seal between the wellbore and the casing. Centralizers are placed on the exterior of the casing string to centralize the casings within the wellbore in an effort to attain cement around the casing in the whole string. There are several types of centralizers with the bow spring type being the most common. The centralizers are normally hinged to aid in fitting them round the casing.

8.2.4 Cementing plugs

Drillable Plugs are used to separate cement and water/mud while displacing cement within the casing.

8.2.5 Cementing head

Cementing heads are containers for the cement plugs. The plugs are retained until when the cement pumping is over and then released. They are also used as connections of the fluid hoses from the pumps and the top of casing.

8.3 Primary cementing procedure

Primary cementing is the most important of all cement Jobs. It is performed immediately after the casing is run into the hole. The objective is to deliver quality cement behind the casing that is the annulus between the casing and the formation or previous casing strings. Two methods are normally employed for the primary cement job namely the conventional and stub-in (stinger) method.

The conventional method could be single or multiple stage technique. In the single stage cementing technique, cement slurry is mixed in the pumping truck and the cement slurry pumped inside the casing string through the cementing head. After the entire slurry volume has been pumped, the cement slurry within the casing is displaced to the float collar using water. The two are separated by use of cementing plugs (top). The cement is prevented from flowing back by the ball valve fitted on the casing float collar or casing float shoe or using a valve fitted to the cementing head.

After landing casing and before commencing pumping cement slurry, a drilling fluid is circulated in the hole. The purpose of the drilling fluid is:

- To ensure the flow path is clear. Several factors can cause blockage of the fluid path way. These are cuttings, sloughing/ collapsing formation, boulders or the casing could seat on the hole bottom if not properly landed.

- To clean the well. If hole cleaning problems had been experienced previous to running the casing, then a high viscous mud would be pumped to lift the cuttings from the hole bottom
- To cool the well bore. Cement setting is affected by high temperature. In severe situations the cement can set instantly on contact with steam stopping any further cement flow leading to failed cementing job. Cold water is normally circulated at least for 30 minutes before commencing cementing.
- To scrap of mud wall cakes.

8.4 Factors that influence slurry design

There are many factors considered in primary cement job slurry design. The key ones include the well depth, well bore temperature, pumping time, slurry density, strength of cement required to support the pipe, lost circulation, filtrate loss and quality of mixing water.

The mixing water should be clean for the resulting slurry to develop the desired properties in particular strength. Deep wells require fairly long time to carry out and complete the cementing jobs. This means that the cement slurry must remain pumpable for the entire period during the cementing job. Temperature and pressure accelerates the setting of cement slurry. Therefore it is very important to take into consideration the effects of these parameters. Major losses of cement can result to very expensive jobs both on lost cement and operation time. The density of the slurry is designed to effectively control blowouts and to displace mud from the well bore.

8.5 Cementing additives

The desired properties for a specific cement slurry design are achieved by adding various chemicals and materials (additives) that alter the ordinary Portland cement normal behaviour. The additives are classified as follows:

i. Accelerators
ii. Lightweight materials
iii. Heavy weight materials
iv. Retarders
v. Lost circulation control materials
vi. Filtration- control agents
vii. Friction reducers and
viii. Specialty materials

Accelerators are used to shorten the cementing thickening time, light weight additives are added to the slurry to reduce the slurry density while the heavy weight additives are added to increase the density. The cement retarders are added to the cement to increase the slurry thickening time for long jobs while friction reducers are added to the cement slurry to improve flow properties of the slurry. The lost circulation control materials are added to the slurry to bridge minor formation fractures that would take up cement while filtration control additives are added to reduce the water loss from the slurry to the formation which would result to early thickening of the cement slurry.

8.6 Open-hole plug jobs

Cementing jobs are not limited to casing operations only. They are often times also used to plug major drilling fluid loss zones. Major fluid circulation losses results to loss of data obtained from cutting. They further results to poor hole cleaning and the rock cuttings repeatedly fall back into the well bore as soon as the pumps are stopped. The falling cuttings at time result into stack drill string. Cement slurry without additives is prepared and placed at the point where the losses are and the cement is allowed to set thereby sealing out the formation fractures.

9. WELL OUTPUT OPTIMIZATION

The objective of drilling a well is to obtain the maximum output from the well. Where good permeability have been encountered, it has been shown that the production casing size of 9 5/8" diameter has inhibited well output in some cases. In such fields, it is becoming increasing more common to use the 13 3/8" casing as the production casing.

It is now a common practice to drill directional wells which target faults that control fluid movement with the objective of increasing well output.

Over 60% of the well cost is incurred drilling the upper section of the well to the production casing (500 - 1500m). Drilling of forked or multi-legged well completions may become increasing common as a way to optimize investment economics.

10. FISHING

Fishing takes upto 20% of drilling well. Fishing is the process of removal of objects or obstructions that impedes further drilling. Each rig is equipped with some form of fishing tools. Fishing jobs require high skill and specialized equipment. Most companies find it more economic to rely on service companies to furnish the tools and specialized personnel when need arise.

11. MANAGEMENT OF DRILLING PROCESS

Drilling can be broken into the drilling operations that involve the actual drilling process and running of casings, cementing process, specialized drilling fluids operations, e.g. air drilling services, directional drilling services, well logging, drill pipe inspection services and sometimes rig moving services. Various contracts are drawn to avail all these services depending on the well design and anticipated drilling problems. A representative of the company is appointed to represent the client on a 24 hr basis. Other specialized requirements like fishing are obtained as and when need arise.

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APPENDIX A: Bit classification chart

IADC Bit Classifications

SERIES	FORMATIONS	TYPE	1 STANDARD ROLLER BEARING	4 SEALED ROLLER BEARING	5 SEALED ROLLER BEARING GAUGE PROTECTION		6 SEALED FRICTION BEARING	7 SEALED FRICTION BEARING GAUGE PROTECTED		
					Elastomer	Metal	Elastomer	Elastomer		Metal
					GX	MX			GX/GT/STX	MX
MILLED TOOTH										
1	SOFT	1	R1	GTX-1	GTX-G1	MX-1			GT-G1H, GT-G1, STX-1, GT-1	MX-1
		2								
		3	R3	GTX-3	GTX-G3	MX-3				MX-3
		4								
2	MEDIUM	1					ATJ-4	ATJ-G4		
		2	DR5							
		3								
		4								
3	HARD	1								
		2	R7							
		3								
		4						ATJ-G8		
TUNGSTEN CARBIDE TOOTH										
4	SOFT	1			GTX-00, GTX-03, GTX-03H	MX-00, MX-03, MAXGT-00, MAXGT-03			GT-00, GT-03, HX-03, HX-03C, STX-03	MX-00, MX-03
		2			GTX-03C				STX-05C, HX-05C	
		3			GTX-09, GTX-09H, GTX-11, GTX-11H	MX-09, MX-09H, MX-11, MAXGT-09			GT-09, GT-09C, STX-09, STX-09C, STX-09H, HX-09, GX-11, GX-11C	MX-09, MX-09G, MX-09H, MX-09C, MX-09CG, MX-11, MX-11H, MX-11S
		4				MX-18, MAXGT-18			GT-18, GT-18C, STX-18, H-18H, HX-18, GX-18	MX-18, MX-18H, MX-18C
5	SOFT MEDIUM	1			GTX-20, GTX-20G, GTX-20H, GTX-22	MX-20, MX-20H, MX-22, MAXGT-20			GT-20, GT-20S, STX-20, HX-20, HX-20H, GX-20, GX-22, GX-23	MX-20, MX-20G, MX-20H, MX-22
		2			GTX-20C	MX-28G, MAXGT-20CG			GT-20C, GT-28, GT-28C, HX-28, HX-28C, GX-20C, GX-25, GX-28	MX-20C, MX-20CH, MX-28, MX-28G,
		3				MX-30H, MAXGT-30		XL-30A	STX-30, STX-35, GT-30, GT-30H, HX-30, GX-30	MX-30, MX-30G, MX-30H
		4			GTX-30C, GTX-33	MAXGT-30CG			GT-30C, STX-30C, HR-30C, HR-35, HR-35C, HR-38C	MX-35C, MX-35CG
6	MEDIUM	1							HR-40, HR-44, HR-44G, STX-40	MX-40, MX-40G, MX-44, MX-44G
		2			GTX-40C			XL-40A	STX-44C, HR-40C, HR-44C, HR-44CH	MX-40CG, MX-40C, MX-44C, MX-44CH
		3						XL-50A	STX-50, HR-50, HR-50R, HR-50RG, HR-55RG, HR-55, HR-55R, HR-55H	MX-50R, MX-50RG, MX-50, MX-55
		4							STX-60, HR-60, HR-66, HR-68, STX-66	MX-66
7	HARD	1								
		2								
		3							STR-70, STX-70, HR-70	
		4								
8	EXTRA HARD	1							HR-80, HR-88, STX-80, STX-88	MX-88
		2							HR-89	
		3							HR-90, HR-99, STX-90, STX-99, HR-95	MX-99
		4								

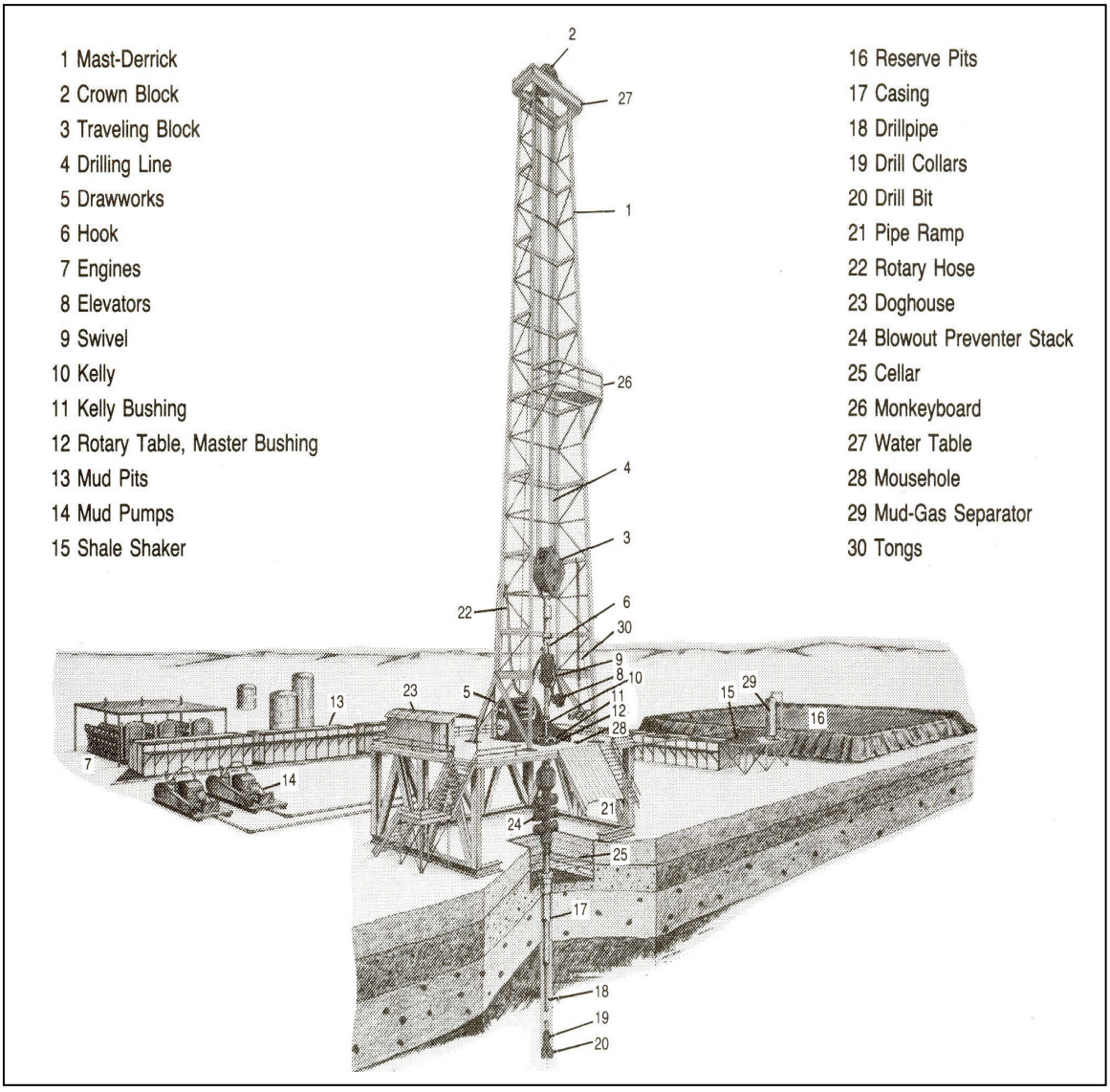
APPENDIX B: Bit record chart

BIT RECORDS

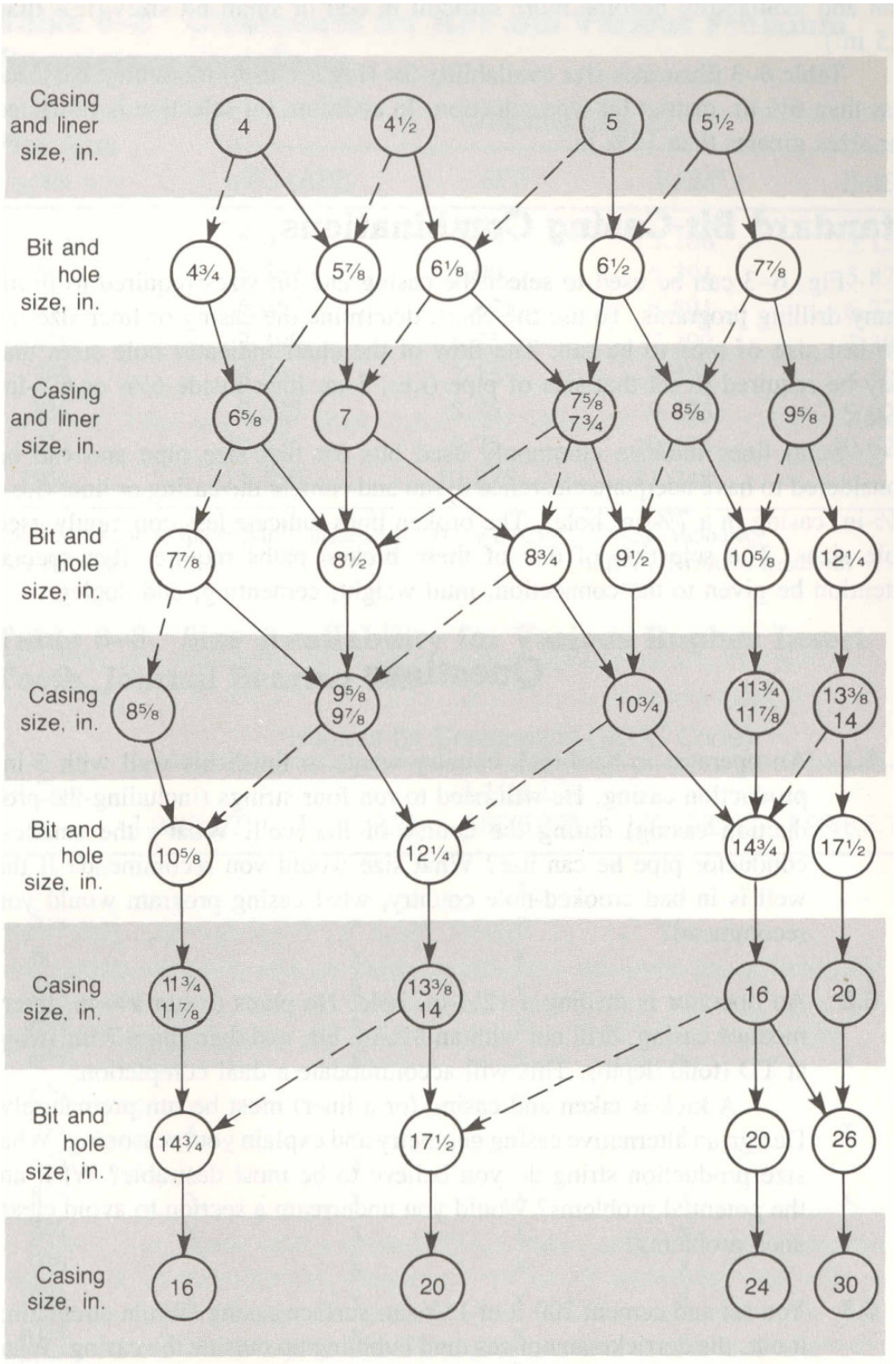
COUNTRY: KENYA			FIELD: OLKARIA DOMES		AREA: OLKARIA		LOCATION: 20/1857.87E, 9900842.95N		WELL NO.: OW901	
CONTRACTOR: KENGEN		RIG NO.: N370	OPERATOR: KENGEN		DRAWWORK POWER: 500 HP					
SPUD: 10TH SEPTEMBER 1998			PUMP No. 1 7-P-50	LINER: 6 1/4"	PUMP No. 2 7-P-50	LINER: 6 1/4"	PUMP POWER: 500 HP		MUD TYPE: WATER BASE	
DRILL PIPE 4 1/2" XH		TOOL JOINT	SIZE: 6 1/4"	TYPE: XH	DRILL COLLAR OD: 6 1/4"	NUMBER: 6OR12	OD: 6" OR 6¼"	ID:	LENGTH: 2 13/16"	3 1/2"

NO.	SIZE	MAKE	TYPE	JET 32ND IN	SERIAL	DEPTH OUT	METERS	HOURS	METER / HOUR	ACCU. DRLG HRS	WT 1000 KG	RPM	VERT DEV. (DEG)	PUMP PRESS.	PUMP OPERATION	MUD SPM 1	MUD SPM 2	MUD WT	MUD VIS	MUD W.L	DULL COND T	DULL COND B	DULL COND G	DULL COND OTHER	FORMATION REMARK
1	26"	SEC.	S33J	OPEN	488036	64	64	55	116	86.75	2	40			90%		80	1.01	55		1	1	1		HARD & ROUGH
2	17 1/2"	SEC.	S84F	OPEN	490656	261.4	197	56	352	56					90%			MUD & WATER							MED. SOFT
3	12 1/4"	SEC.	M85TF	OPEN	515914	466.6	248	119	208	117	6	80	1 V2	350	90%	110	110				1	1	1/8		HARD/MED
4	12 1/4"	SEC.	M85TF	OPEN	513078	712	225	55.5	406	55.5	6	80		540	90%	130	130	WATER			1	1	1		SOFT
5	12 1/4"	SEC.	S86F	OPEN	523890	773.9	61.9	12	516	12	6	80		450	90%	110	130	AIR H2O/FOAM							SOFT & ROUGH
6	8 1/2"	TSK	A40	OPEN	26440-T	988.6	215	54.45	394	54.45	4	80-90		400	90%	130		AIR H2O/FOAM			1	8	1/8		
7	8 1/2"	HUGHES	ATJ55	OPEN	T-45-BH	1227	228	63.5	359	63.5	4	90	2	450	90%	60	60	AIR H2O/FOAM			2	8	4		MED. SOFT
8	8 1/2"	TSK	A40	OPEN	26851-T	1335	108	32	338	32	45	90		600	90%	70	70	AIR H2O/FOAM			1	4	1		MED. SOFT
9	8 1/2"	TSK	K70	OPEN	26880-T	1694	359	67	387	67	4	90		650	90%	90	90	AIR H2O/FOAM			1	6	1		MED. SOFT
10	8 1/2"	TSK	K70G	OPEN	26871-T	1902	68	23	296	23	5	90		750	90%	100	90	AIR H2O/FOAM			1	4	1		MEDIUM
11	8 1/2"	TSK	K70G	OPEN	26873-T	1938	176	54.5	54.50	54.5	5	80		950	90%	100	100	AIR H2O/FOAM			1	6	1		MEDIUM
12	8 1/2"	HUGHES	ATJ55	OPEN	T-46-BH	2105	266	74.1	359	74.1	6	80-90		1000	90%	100	100	AIR H2O/FOAM			8	8	8		MED. HARD
13	8 1/2"	TSK	K70G	OPEN	26879-T	2200	95.4	26.5	360	26.5	7	80-90		1200	90%	100	100	AIR H2O/FOAM			4	8	1		MED. HARD

APPENDIX C: Description of key rig parts



APPENDIX D: Typical bit-casing geometries



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DRILLING IN MENENGAI FIELD – SUCCESS AND CHALLENGES

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ABSTRACT

Geothermal drilling in the Menengai field started in February 2011 The project was initiated following a detailed exploration conducted in 2004 that pointed to the existence of an exploitable geothermal resource within the caldera. Three exploration wells were done which prove the existence of the resource in Menengai. Six appraisal wells were drilled to appraise the size of the reservoir. A feasibility study was carried out to determine the extent of the geothermal resource in the field and the 100MWe area was determined. For the 100 MWe project 22 wells will be drilled and completed by the end of 2014. Currently production wells are being drilled. For the purpose of realizing the 100 MWe, geothermal development company (GDC) has since acquired 4 rigs for drilling in Menengai and is expecting 3 more by January 2014. Major problems experienced in Menengai are formation related while other problems include stuck pipe, high pressure and temperature and also obtaining specialize equipment and services locally.

1. INTRODUCTION

Menengai is a major Quaternary caldera volcano forming one of fourteen geothermal sites in Kenya. It is located within the axis of the central segment of the Kenya Rift (Figure 1) just north of Nakuru town and a few kilometres south of the equator. The Menengai geothermal field is characterized by a complex tectonic activity associated with two rift floor tectono-volcanic axes (TVA) Molo and Solai that are important in controlling the geothermal system (Njue, 2011).

Geothermal drilling in the Menengai field started in February 2011. The aim was to determine geothermal resource availability, hydrothermal capacity and chemical characteristics of the resource which is steam. The project was initiated following a detailed exploration conducted in 2004 that pointed to the existence of an exploitable geothermal resource within the caldera. Currently drilling of production wells is ongoing following completion of exploration and appraisal wells. By July 3, 2013 fifteen wells had been completed.

2. STAGES OF DRILLING

There are several stages of drilling and these include:

- **Exploration drilling -** prove existence of resource
- **Appraisal drilling -** prove the extent and size of the reservoir field to enable designing of power plant.
- **Production drilling -** drill wells with enough steam equivalent in megawatt to the design plant
- **Make–up wells drilling -** during utilization if the main steam pressure decline due to utilization more wells are drilled.
- **Work over wells drilling -** if deposit (e.g. calcite) occurs inside the casing, work over rig is brought in to drill out the deposit.

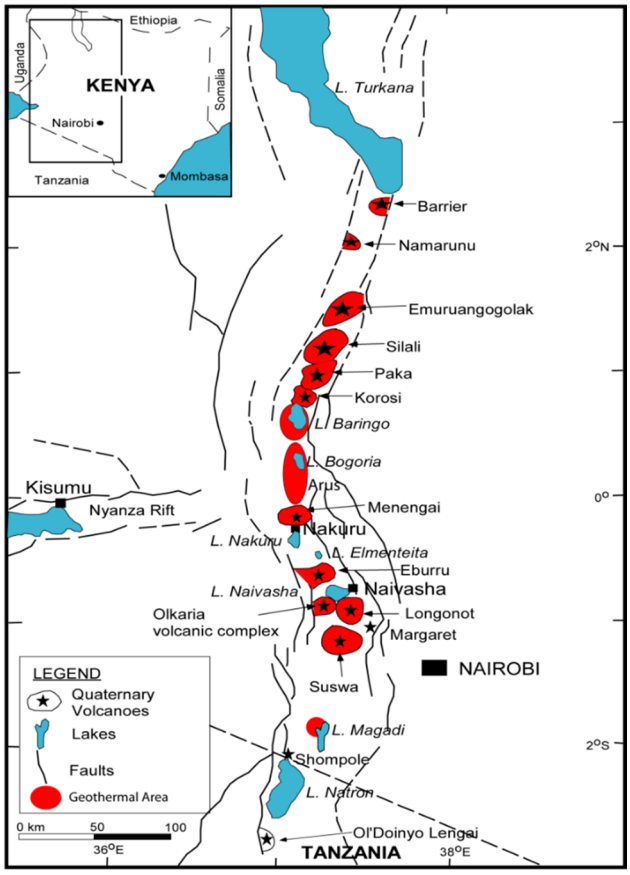

FIGURE 1: Position of Menengai within the

Drilling in Menengai started with three exploration wells which were then followed by six appraisal wells. A feasibility study was carried out to determine the extent of the geothermal resource in the field and the 100 MWe area was determined. A 100 MWe power plant has since been design.

Production drilling in the Menengai field is currently ongoing and 22 wells have been projected for the 100 MWe steam. 20 wells will be production wells while 2 will be reinjection wells. The 20 production wells are expected to averagely produce 5 MWe each. The plan is to drill 19 wells before 18-Oct-14

2. DRILLING IN MENENGAI

2.1 Rigs

GDC acquired two new ZJ70D rigs (Figure 2), (Simba 1 and Simba 2) in 2010 and later in 2012 acquired two more ZJ70D rigs (Kifaru 1 and Kifaru 2). Simba 1 and Kifaru 2 are top drive rigs while Simba 2 and Kifaru 1 are Kelly driven. All the rigs have the capacity to reach a depth of 7000 m 3-1/2" drill pipes with a max hook load of 4500 kN, 45 m open front mast and approximately 10m platform floor height. The drive mode is AC-SCR-DC. The rigs are equipped with 4 diesel generator sets and 1 auxiliary generator for power supply and uses AC-SCR-DC drive. In addition the rigs are equipped with a complete air drilling system containing five air compressors and two boosters. Figure 2 shows one of the ZJ70D rigs used in Menengai

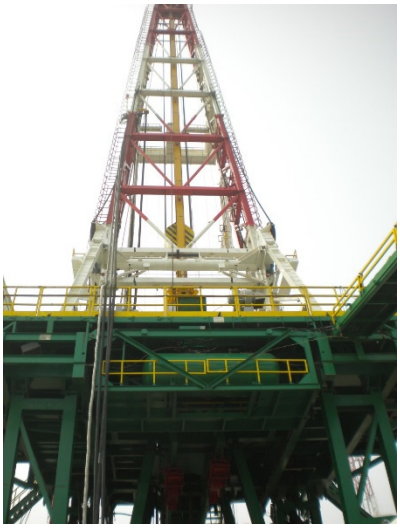

FIGURE 2: One of the ZJ70D rigs

GDC has procured more 3 more rigs that are expected in the country by January 2014. These will fast track drilling operations to enable the company realise its vision of delivering 100 Mw by end of 2014.

2.2 Bits

The aim of drilling is to i) make hole as fast as possible by selecting bits which produce good penetration rates, ii) run right bits to achieve long working life to reduce trip time, iii) use bits which drill a full-size or full-gauge hole during the entire time they are on the bottom.

Tricone roller tungsten carbide insert bit (Figure 3) has been used in the Menengai field because of their versatility and performance. The bit type is available with a large variety of tooth design and bearing types and, thus, is suited for a wide variety of formation characteristics. Figure 4 shows a bit selection chart. Code 517 indicates a soft formation bit while code 617 indicates a medium formation bit both used in the Menengai field. In surface section of the hole only 1 bit is used before running in the 20" surface casing. This section is so shallow that one bit usually lasts for several wells. As the well gets deeper several bits are used for each section before casing depth is reached and even more bits are required in the final hole section. The 26" hole is drilled using a tri-cone roller mill tooth bit down to 80m, while the other hole sections are drilled with tri-cone roller tungsten carbide insert bit.

Rotary bits drill the formation using primarily two principles; 1) rock removal by exceeding its shear strength and; 2) removal by exceeding the compressive strength. Shear failure involves the use of the bit tooth shearing, or cutting, the rock into small pieces so it can be removed from the area below the rock bit. Shear failure mechanism requires that the formation exhibits low compressive strength that will allow the insertion of the tooth. The mechanism is employed while drilling softer formations (Ngugi, 2008).

FIGURE 3: A typical roller corn bit used in Menengai

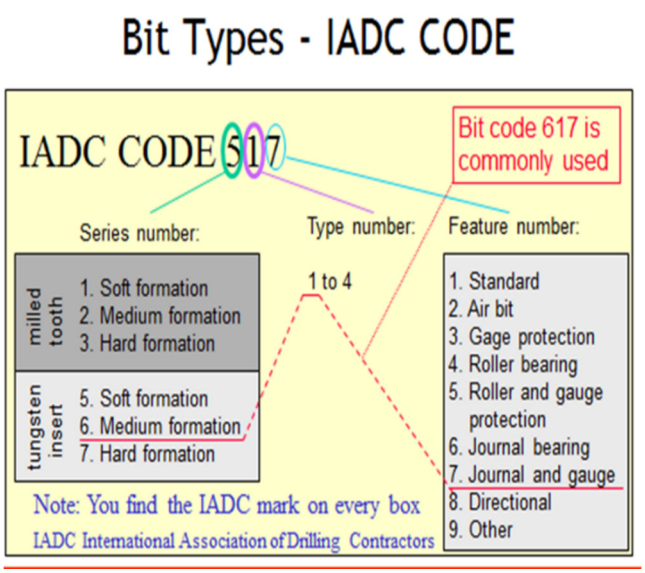

FIGURE 4: A chart used for bit selection

For hard formation rocks a compressive failure mechanism is used since shearing wears the bit tooth as it is twisted or dragged across the formation face. Compressive failure of a rock segment requires that a load be placed on the rock that exceeds the compressive strength for that given rock type. The load must remain, or dwell on the surface long enough for rock failure to occur. This is the basis for hard–rock drilling characteristics of high bit weight and low rotary speeds (Ngugi, 2008).

2.3 Drilling each hole section and casing

Based on the expected well operation condition and the expected drilling site geology, the casing depths are prescribed and detailed in the drilling programme but actual depths are chosen by reference to geology and hole conditions. Menengai geothermal wells have targeted depths of 2500 and the drilling programme is as follows. Figure 5 represents a Casing programme for Menengai wells.

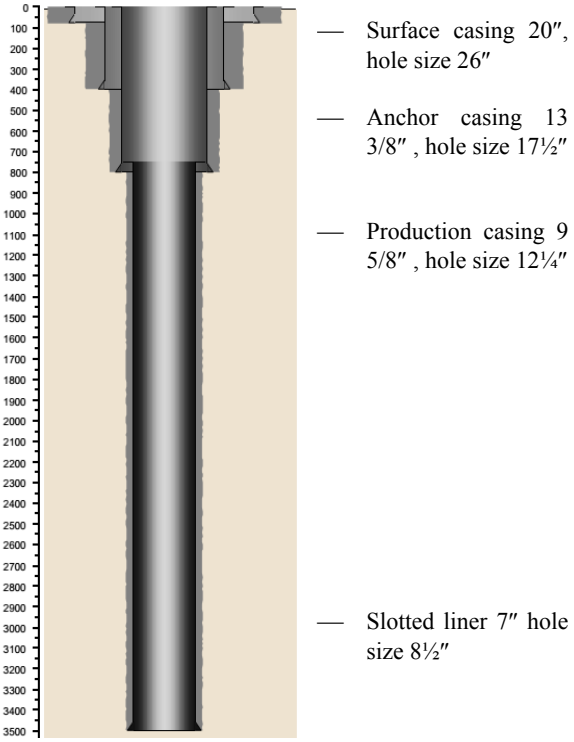

FIGURE 5: Casing programme for Menengai wells

- Drilling a 26” hole (0 – 80 m) for the Conductor (surface) casing with 20" diameter. This section is usually hard and rough with a low ROP of 0.5 m - 0.7 m/hr. the WOB is usually high leading to high vibration. Water is commonly used as the drilling fluid. This section takes 7 to 10 days.
- Drilling a 17½” hole to (80 - 400 m) for the Intermediate casing of 13⅜" diameter. This section is medium hard and rough. The ROP is between 1.5 m - 2 m/hr. Drill with water and if hole cleaning problems arises, aerated water and foam is used. This section take between 10-15days
- Drilling with a 12¼” hole (400 -1000 m) for the Production casing of 9⅝" diameter. The formation is medium soft formation with layers of soft. Drilling is carried out using aerated water and foam with hi-vis mud gel sweeps done every half and full kelly to condition the well The formation in this section is incompetent and tends to collapse.
- Drilling with an 8 1/2” hole to the final depth of 100 – 2200 m for the Slotted liner of 7" diameter set.

There are many purposes to be considered for casing and cementing related to the need to mechanically and hydraulically isolate a well for its entire life. They include:

I. Securing weak formations that may collapse into the well bore and trap the drill string;
II. Sealing leaky intervals to prevent lost circulation; covering bulging shale intervals that can stick the drill string;
III. Isolating high-pressure zones to allow safe drilling; and allowing safe entry and retrieval of equipment.

The casing string is screwed together to form longer lengths of casing and a thread compound is used on the two ends to ensure a tight seal. Centralizers are placed on the exterior of the casing string to centralize the casings within the wellbore and ensure that all voids are filled and channelling does not occur during cementing. The bow spring centralizer is usually used.

The liner string is run into the well in the final section reaching from the lower end of the production casing to the bottom. The liner string is left to rest at the bottom.

2.4 Cementing

Casing requires a sheath of cement, which must endure for long periods and must be able to withstand large variations in temperature and all the rigours of drilling, completion and production. Below is a mention on reasons of cementing.

- Seal off ground water
- Seal unwanted aquifers
- Support the well to prevent cave in
- Anchor the wellhead
- Provide conduit for the well fluid to flow to surface

After landing casing and before commencing pumping cement slurry, a drilling fluid is circulated in the hole to clean the well and ensuring the flow path is clear, cooling the wellbore to prevent hardening of cement due to high temperatures and to scrap off mud wall cakes.

TABLE 1: Cement consumption for 5 wells in Menengai

Cement consumption for Menengai geothermal project					
Well	**Casing cementing**		**Cement plugs**		**Total per section**
	Casing size	**Amount (tons)**	**Hole section**	**Amount (tons)**	
MW-01	20"	**54.33**	26"	**0**	**54.33**
	13 ⅜"	**102.92**	17 ½ "	**0**	**102.92**
	9 ⅝ "	**46.96**	12¼ "	**0**	**46.96**
				Total consumption for MW-01	**204.21**
MW-07	20"	**27.55**	26"	**0**	**27.55**
	13 ⅜"	**35.26**	17 ½ "	**36.81**	**72.07**
	9 ⅝ "	**71.17**	12¼ "	**0**	**71.17**
				Total consumption for MW-07	**170.79**
MW-09	20"	**180.34**	26"	**0**	**180.34**
	13 ⅜"	**110.750**	17 ½ "	**0**	**110.750**
	9 ⅝ "	**57**	12¼ "	**0**	**57**
				Total consumption for MW-09	**348.09**
MW-12	20"	**72.87**	26"	**0**	**72.87**
	13 ⅜"	**76.89**	17 ½ "	**87.79**	**164.68**
	9 ⅝ "	**79.69**	12¼ "	**17.17**	**96.86**
				Total consumption for MW-12	**334.41**
MW-16	20"	**34.46**	26"	**0**	**34.46**
	13 ⅜"	**140.59**	17 ½ "	**25.42**	**166.01**
	9 ⅝ "	**154**	12¼ "	**12.24**	**166.24**
				Total consumption for MW-16	**366.71**

The cementing technique used is usually the inside casing. Cement slurry is mixed in the pumping truck and the cement slurry pumped inside the casing string through the cementing head. After the entire slurry volume has been pumped, the cement slurry within the casing is displaced down to the float collar using water. The water and cement are separated using of cementing plugs. The heavier cement in the annulus is prevented from U-tubing by back-pressure valves in the bottom of the casing string. If cement is not received on the surface the cement job is let to set for 8 hours then a back fill is carried out through the annulus with 8 hours in between backfills until cement is received on the surface. Normal Portland cement is usually used. The process is time and temperature dependent.

Cementing jobs are also done to plug major drilling fluid loss zones. Major fluid circulation losses result in loss of data obtained from cutting. They further lead to poor hole cleaning and the rock cuttings repeatedly fall back into the well bore as soon as the pumps are stopped. The falling cuttings at time result into stuck drill string. To stop circulation losses cement slurry without additives is prepared and placed at the point where the losses are and the cement is allowed to set, thereby sealing out the formation fractures (Ngugi, 2008).

Table 1 shows cement consumption for 5 wells drilled in Menengai. It shows that the 17 ½ " hole consumes a lot of cement as there were several loss zones in this section.

2.5 Circulation and drilling fluids

Drilling fluid used in the upper parts of the well is simple water based bentonite mud. When fractured zones are encountered above the production casing shoe depth, attempts are made to seal these losses using Loss of Circulation Materials (LCM), and in extreme cases cement plugs are done. The final hole section is drilled with water and in areas of lost circulation aerated water and foam is used.

The purpose of drilling fluids primarily is to remove the cuttings from the bottom of the hole as fast as they are created to facilitate further and efficient hole making process. In addition, the fluid transports the cuttings to surface. The two functions constitute what is normally referred to as hole cleaning. (Ngugi, 2008). Cooling of the wellbore is also an important function of the drilling fluid in geothermal wells. In that case the ingoing fluid is usually maintained at a maximum temperature of 40°C, which is the maximum recommended operating temperature for the pumps. High temperature may also cause damage to the drill bit.

Water is the major drilling fluid used in Menengai other drilling fluid include water based bentonite mud, air and aerated water and foam. The choice of drilling fluid depends on the formation of the section being drilled. In case of lost circulation, loss circulation materials (LCM) are used. In instances where circulation cannot be regained only water is used with sweeps of high viscosity gel each time a new drill pipe is added or more frequently depending on the hole problems. During the drilling of the final section for 7" (perforated or slotted?) liner, only water or aerated water with foam is used. This is done to avoid sealing the production zones with mud. From the well the drilling fluid is usually pumped to a pond to cool before it is pumped back down hole.

Drilling water in Menengai is supplied from 10 drilled boreholes and sometimes brine from discharging wells. The water from the boreholes is pumped to 4 tanks of 4 million litres at an elevated ground. The water is the supplied to the wells trough gravity. Brine from discharging wells is used to supplement drilling water.

2.6 Advantages and disadvantages of top drive rigs over kelly driven rigs

Advantages of top drive:

- Top drive drill is faster-it is possible to drill with three pipes (stand), which means fewer connections, thus reducing the tripping time.
- Top drive drilling is safer- Fewer instances of personnel contact with the equipment hence reducing chances of accidents.
- Top drive reduce instances of sticking - Since the top drive system allows the circulation of the drilling fluid and rotation while pulling out of the hole, this prevents the settling of the drill cuttings which can be responsible for the bottom hole assembly becoming stuck, thus saving the rig crew time and improving the time it takes to complete the well.

Disadvantages of top drive:

- Highly automated – The high automation applied in the top drive system requires a highly skilled and experienced operational and maintenance crew. Hence, when there is a lack of such personnel, then the advantages desired from the top drive system may not be realised. It is also sensitive and prone to breakdown especially in hard formations as experienced in Menengai.

3. DRILLING CHALLENGES

Water supply for drilling - Currently four rigs are drilling in the Menengai caldera and all depend on the same supply. The rigs consume approximately 1500-2000l/min each. Drilling water in Menengai is supplied from 10 drilled boreholes and sometimes brine from discharging wells. The water from the boreholes is pumped to 4X 4 million litres tanks at an elevated ground. The water is the supplied to the wells trough gravity. The formation in Menengai is highly fractured and drilling crew experience frequent long lost circulation periods. This means that there should be a constant supply of drilling water in to the drilling sites.

Formation challenges - The geology in Menengai presented the biggest challenge to drilling, slowing down drilling activities creating drilling problems:

- Hard formation especially on the top sections which causes large vibrations resulting in surface equipment damage. The top section is usually drilled using a tricone bit that depends on rotary action to drill. This section is usually shallow, therefor the rigs have no place for collars hence the weight on bit is far too low and large vibrations are experienced. Consideration to use air hammers in the future are underway. This goes to show that bit selection is an important factor and so is the weight on bit.

- Lose formation that keeps on collapsing during drilling. Such was experienced severely in well MW05.

- Lost circulation problem is pronounced in Menengai and this is due to the fractured nature of the Menengai formation. Drilling practices may also lead to induced fractures aggravating loss circulation problems.

- Changing lithologies at various depths also create a set of variables that affect bit durability. The crooked hole is a result of change in formation that is beyond control of the driller but with the right choice of BHA it can be minimised while a tapered wellbore is usually a result of under gauge bit. Reaming is usually done to straighten a crooked hole or to enlarge a tapered or tight well bore. This in turn slows down the drilling progress.

Information on geology is obtained from drill chips/cuttings and lithology logs. Too little knowledge about the formation being drilled may lead to the wrong choice of bit. Incorrect bit type causes low ROP and eventually equipment failure. Having the right information on the geology of the area is paramount in making sound decision in planning for the well.

Server loss of circulation - Due to the fractured nature of the rock in the Menengai field severe loss of circulation is experienced.

Kicks and blowout - Reservoir conditions affecting drilling in Menengai include extremely high temperatures and pressure especially at depths of below 1000m. This results kicks and blowouts.

Stuck pipe - Sticking is a major problem experienced in Menengai. Most of the sticking followed a period of problematic circulation and moment of stopped circulation such as after pipe connection.

Stopped circulation meant that the cuttings were not removed from the hole and were left suspended as a result these cuttings fall to the bottom and on the string. Loss of circulation results in poor hole cleaning and if enough efforts are not made to regain it, sticking is inevitable.

Lack of specialized services tools and service - Drilling is relatively new in Kenya and the rig is a new equipment in the market therefore most critical rig parts and services are not readily available in Kenya.

Drill string failure and fishing - Drill string failure experienced in Menengai was as a result of drillstring failure from stuck pipe. In the effort to free the stuck pipe the drillstring was subjected to high torque and large weight on bit causing it to strain and eventually fail. Excessive tension from over pull and fatigue from repeated stress can also lead to drillstring failure. Some of the drill string failure experienced include twist off due to high torques and snap pipe due to over pull.

Fishing is carried out to remove any foreign unwanted objects in the well bore by using special fishing tools. The foreign objects in the wellbore are majorly as a result of drill string failure.

Addressing Challenges

1. Plugging loss zones & high viscous mud- this is done to regain loss of circulation in the problematic loss zones.
2. Hammer drilling- The hammer technology is being considered for future drilling especially for the hard abrasive top section to increase the rate of penetration.
3. Brine from discharging wells is used to supplement drilling water.
4. Drill string inspection after 200 rotating hrs. to reduce instances of drill string failure.

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Presented at *Short Course VIII on Exploration for Geothermal Resources,*
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GEOTHERMAL RESOURCE ASSESSMENT – CASE EXAMPLE, OLKARIA I

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ABSTRACT

Stakeholders are always eager to know the geothermal power potential of newly explored prospects so as to gain confidence in availing more resources for further work. At all levels of exploration whether at surface or deep drilling, there is always some uncertainty on data available and estimation of power potential becomes a big challenge. Stochastic (Monte Carlos Simulation) method is frequently used to estimate power potential of geothermal fields at early stages of exploration where data is scanty and uncertainties quite high. In this paper, this method is introduced and case example of its application to Olkaria I geothermal field presented.

1. INTRODUCTION

After successful exploration of a geothermal prospect, stakeholders are always eager to know its power potential. This comes as early as after completion of surface geo-scientific exploration or even after initial exploration drilling. The earlier estimates of power potential give confidence to the project owners to source for more resources to undertake subsequent stages of development. With high uncertainty and scanty data available during initial stages of exploration, stochastic and risk analysis methods are frequently used to estimate the range and probable distribution of stored heat reserves and hence, exploitable energy base of the newly explored geothermal prospect or fields. These methods have been borrowed from the oil industry where they have been used for a long time to estimate probabilistic hydrocarbon-in-place and oil and gas reserves in sedimentary basins.

2. MONTE CARLO METHOD

Monte Carlo Method is also called Monte Carlo Simulation or Stored Heat Method. The technique involves using random numbers and probability to solve problems. It iteratively evaluates a deterministic model using sets of random numbers as inputs. Deterministic models use a certain number of input parameters in few equations to give a set of outputs. They give the same results no matter how many times the problem is recalculated. Stochastic models on the other hand, use variable (random) inputs and give different results depending on the distribution functions of the input parameters. They are often used when the model is complex, nonlinear, or has more than just a couple uncertain parameters. The simulation can have as many evaluations as determined by available computers and time. The random numbers turn the deterministic model into a stochastic model.

In Monte Carlo Method, the objective is to determine how random variation, lack of knowledge or error affects sensitivity, performance or reliability of the system being modelled. The inputs are randomly generated from probability distributions to simulate the process of sampling from actual population. The distribution chosen for the inputs should closely match the existing data or should best represent the current state of knowledge. Data generated from the simulation can be represented as probability distribution curves or converted to error bars and confidence intervals etc. General steps in Monte Carlo Simulation are:

1. Create a parametric deterministic model, $y = f(x_1, x_2, \ldots, x_q)$.
2. Generate a set of random inputs, $x_{i1}, x_{i2}, \ldots, x_{iq}$.
3. Evaluate the model and store the results as y_i.
4. Repeat steps 2 and 3 for $i = 1$ to n
5. Analyse the results using histogram, summary statistics, confidence intervals, etc.

3. APPLICATION TO GEOTHERMAL RESOURCE ASSESSMENT

3.1 Introduction

In the case of geothermal resource assessment, energy reserve is estimated from data generated from geological mapping, geochemical studies, resistivity surveys, infrared surveys, seismic data, magnetics, gravity, ground-water temperatures, heatflow surveys and results of exploratory drilling. These data are valuable in determining the distribution of input parameters for the simulation. Out of these surveys, the following important inputs are determined:

1. Resource area – obtained from geological mapping and geophysical measurements.
2. Resource temperature – obtained from geochemical studies, groundwater temperatures and exploratory drilling.
3. Thickness of the reservoir – obtained from exploratory drilling and geophysical measurements.

Other parameters such as porosity, rock density, specific heat capacity of fluid and rock are taken from data collected from drilled wells or other fields of similar geological settings or reservoir characteristics and also from handbooks. These data are then used in volumetric stored heat model outlined below.

3.2 Deterministic model for volumetric stored heat

Volumetric stored heat estimates the heat in place for area of interest with the following reasonable assumptions made about:

a) The percentage of that heat that can be expected to be recovered at the surface,
b) The efficiency of converting that heat to electrical energy.

This calculation takes into account only a volume of rock and water that is reasonably likely to contain adequate permeability and temperature for generation of electricity using prevailing contemporary technology. Hot rock that is deeper and is unlikely to be economically drillable is not included. The estimates of recoverable heat using this method do not imply any guarantee that a given level of power generation can be achieved. To achieve some level of guarantee, wells capable of extracting heat from the rock by commercial production of geothermal fluid must be drilled and tested.
The total heat in place is given by the equation:

$$H = A.h.(H_r + H_w) \quad (1)$$

where,

H = Stored heat (J)
A = Resource Area (m^2)
h = Reservoir thickness (m).

The subscripts r and w denote rock, and water (fluid).

Heat contained in the rock is given by:

$$H_r = (T_i - T_f).(1-\phi).C_r\rho_r \quad (2)$$

where,

T_i = Average reservoir temperature (°C)
T_f = Base temperature (°C)
C = Specific heat capacity (kJ/kg °C)
ρ = Density (kg/m^3)
ϕ = Porosity.

Heat contained in the water (fluid) is given by:

$$H_w = \rho_{wi}.\phi.(h_{wi} - h_{wf}) \quad (3)$$

where,

h = Enthalpy (kJ/kg)

and the subscripts *wi*, and *wf* denote water at reservoir temperature and base temperatures respectively.

The final estimate of power potential is then calculated using the following equation:

$$E = \left[\frac{H.R_f.\eta}{F.L}\right] \quad (4)$$

where,

E = Power plant capacity
R_f = Recovery factor
η = Conversion efficiency
F = Plant capacity factor
L = Plant life.

3.3 Simulation of the volumetric stored heat model

Most of the parameters used to calculate the power potential in section 3.2 above are not known with certainty. All we can say is the range of most probable values of each of those parameters and to reflect the uncertainties, input variables such as resource area, reservoir temperature, porosity, specific heat capacity and reservoir thickness should be quantified as separate probability distributions. Each step of simulation samples the independent variables and so, a complete representation of all possible outcomes can be achieved if the number of steps is large. The simulation process retrieves possible values for the independent variables randomly selected from the assigned probability distributions. Each sample set computed at every simulation step represents a possible combination of input

parameters. Sampling can be done from an assigned probability distribution using computer generated pseudo-random numbers between 0 and 1. The outcome is entirely random and falls within the limits of an assigned input distribution.

Probability distribution of the input variables is usually based on the scientific judgement using all of the relevant information available and the assumptions of the modeller. The distributions in most cases take the form of normal distribution, uniform (rectangular) distribution and triangular distribution. Normal and triangular distributions are suitable when actual data are limited but known that values in question fall near the centre of the limits. In the absence of any other information, rectangular distribution is a reasonable default model. After a successful simulation, the output gives the probability of exceeding a certain level of power potential.

4. CASE EXAMPLE – RESOURCE ASSESSMENT OF OLKARIA I

4.1 Introduction

The greater Olkaria geothermal field covers an area of more than 80 km^2 and is divided into several sectors (Figure 1) for exploitation purposes. Sectors that are already under exploitation are Olkaria East (Olkaria I), Northeast (Olkaria II), Olkaria West (Olkaria III) and Olkaria Northwest. Olkaria Domes is currently under appraisal drilling.

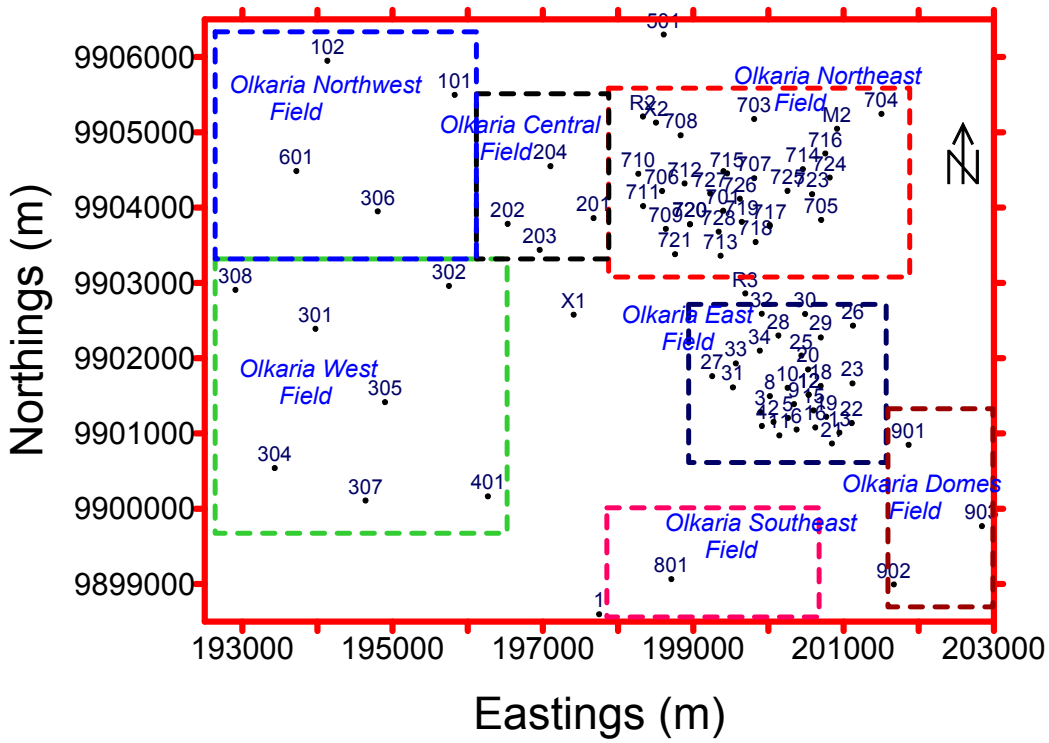

FIGURE 1: Location of production sectors within the greater Olkaria geothermal field

The first 15 MWe turbine in Olkaria I started generation in 1981 and the field has been producing 45 MWe since its full commissioning in 1985 while Olkaria II, which was commissioned in October 2003 is now producing 70 MWe. Olkaria III started production from its phase 1 in the year 2000 and has been producing 12 MWe from a binary power plant, since then. Olkaria I plant has done its design life and now studies are being done to find out if the reservoir can still support further production. One of the preliminary studies that have been done is use of stored heat (Monte Carlo) method to estimate the power that could still be produced.

4.2 Reservoir properties

Olkaria I is a boiling two-phase liquid dominated reservoir capped by a 700 m thick cap rock. The field has 33 wells drilled to depths ranging from 900 m to 2484 m within a 4-km^2 area.

Initial well temperature and pressure profiles in Olkaria I follow boiling point for depth curve from the point where the steam zone intercepts the water reservoir (Figure 2). Steam zone temperatures averages at 240 °C and pressures of 33 – 36 bars. At depth, average temperature at 1500 m is 300 °C and at 2200 m the temperature is 330 °C. Productive aquifers are associated with contact between lavas, porous pyroclastics and fractured trachytes. Wells intercept these permeable aquifers at different depths spanning the whole of the drilled zone.

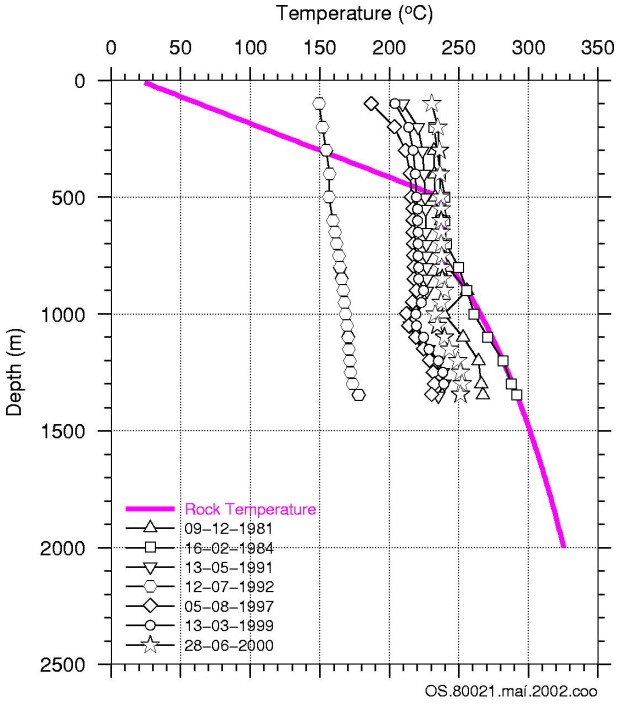

FIGURE 2: Temperatures in well OW-21, a typical Olkaria I profile

4.3 Input data for Monte Carlo Simulation

4.3.1 Reservoir area

The reservoir area in Olkaria I is defined by the 20 ohm-m anomaly (Figure 3). The wells are currently drilled in half of the defined area due to inaccessibility of the Ololbutot lava flow (Figure 4), which is a rough and rugged terrain. However, the area under this lava flow has a good potential of being a geothermal reservoir and with the current technology, it can be accessed by directional drilling. From Figure 3, the minimum area would be about 7 km^2 if the higher resistivity zones encroaching into the low resistivity area are taken into account and the maximum would be 8 km^2 if these high resistivity zones were included.

4.3.2 Reservoir thickness

Casing depths for wells already drilled in Olkaria I range from 500 – 600 m. Productive zones from the deep wells occur at various depths spanning the whole of the open hole. If all the wells are to be drilled to 2200 m, the reservoir thickness will therefore, vary from 1600 m to say, 800 m.

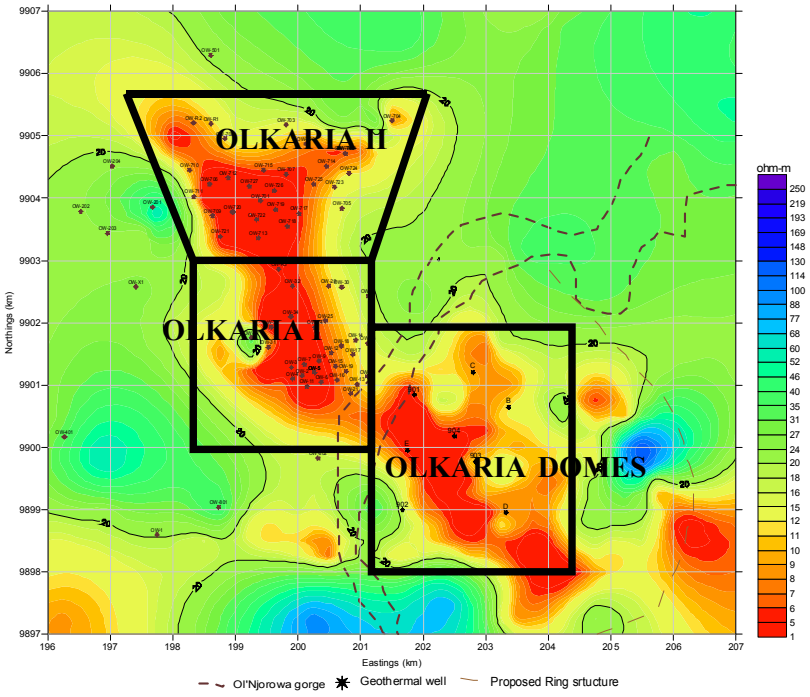

FIGURE 3: Map showing TEM Resistivity at 1000 m a.s.l.

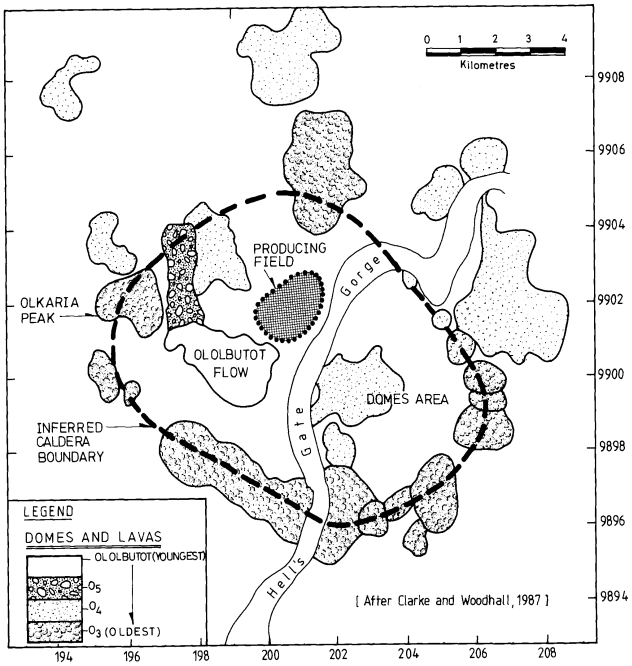

FIGURE 4: Map showing Ololbutot lava flow in relation to the production field (Olkaria I)

4.3.3 Recovery factor

Recovery factor is a function of porosity. In Olkaria I, studies from numerical simulations have come up with a porosity value of 6% (Bodvarson et. al., (1987), Ofwona (2002)). Muffler and Cataldi (1978) have defined a linear relation between porosity and recovery factor. For a porosity of 6%, the Cataldi plot gives a recovery factor of 15%. Bayrante et al., (1992) used a recovery factor of 20% for assessment of Mahanagdong project in Philippines for the same porosity. In this paper, a recovery factor of 20 % is used.

4.3.4 Reservoir fluid temperature

The reservoir fluid temperature is taken as the average of the steam zone temperature (240 °C) and bottom hole temperature (330 °C). This is about 285 °C. Base temperature of 180 °C is used because most of the wells that intercept temperatures of this magnitude in Olkaria do not discharge.

4.3.5 Rock density and conversion efficiency

A rock density of 2700 kg/m^3 is used and a conversion efficiency of 12%.

4.4 Stored heat calculation results

Various input parameters to this analysis are summarized in Table 1. Most likely estimates are given as well as estimated probability distributions and minimum and maximum values for different input parameters. These input parameters are used in the Monte Carlo simulation in excel spreadsheet. The simulation runs can be as much as time and computer allows. The more runs, the better. For this case, the runs were 2000. The results show a frequency distribution peak at a power capacity of 100 MWe but with a broad range from 80 to 150 MWe due to the inherent uncertainties of the input variables (Figure 5). Figure 6 shows that there is a 50 % chance of producing more than 120 MWe.

TABLE 1: Best estimates and probability distribution

Input	Units	Best guess	Probability distribution		
			Type	Min	Max
Area	km^2		Rectangular	7	8
Thickness	m	1,200	Triangular	800	1600
Rock Density	kg/m^3	2,700	Constant		
Rock Spec. Heat	kJ/kg °C	1	Constant		
Porosity	%	6	Triangular	1	12
Temperature	°C	285	Triangular	240	330
Base Temp.	°C	180	Constant		
Fluid Density	kg/m^3	783	Steam Table		
Fluid Spec. Heat	kJ/kg °C	4.2	Steam Table		
Recovery Factor	%	20	Triangular	15	25
Conversion Efficiency	%	12	Triangular	10	15
Plant Life	years	25	Triangular	20	30
Load Factor	%	95	Constant		

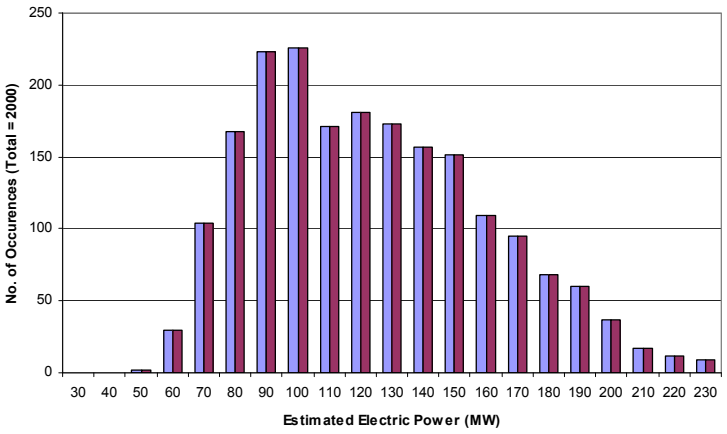

FIGURE 5: Frequency distribution of power capacity

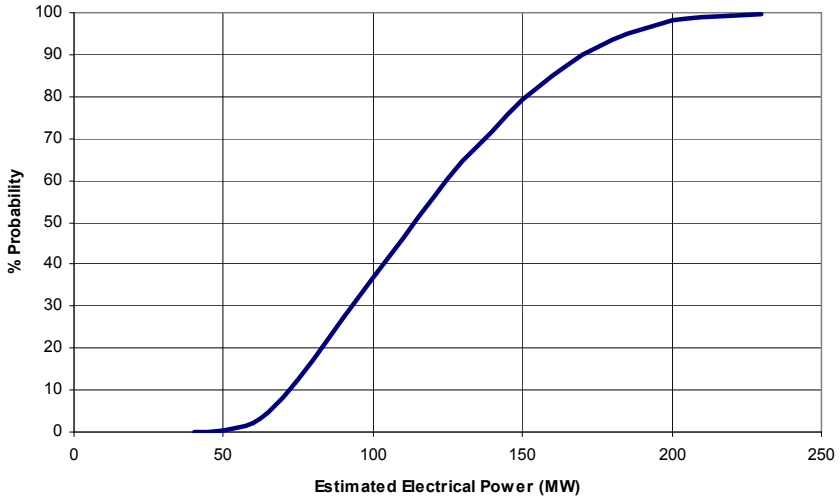

FIGURE 6: Cumulative frequency distribution

5. CONCLUSIONS

Estimation of power potential for Olkaria by Monte Carlo method produces reasonable and realistic estimates. This method has been applied in other geothermal fields around the world and will be appropriate for estimation of power potential in geothermal fields in African Rift region.

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INTRODUCTION TO GEOPHYSICAL WELL LOGGING AND FLOW TESTING

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ABSTRACT

Well logging is the practice of making a detailed record of the geologic formations penetrated by the well. The log may be either geological logs or geophysical logs. In geothermal, geophysical logging is done to identify location of fractures, the lithology and record the physical parameters like temperature and pressure. Important logs include temperature, pressure, gamma, neutron, cement bond log, calliper log, resistivity and directional surveying.

When the well has recovered sufficiently, a flow test is conducted by flowing the well to evaluate the total flow rate, enthalpy and chemical characteristics of the discharged fluids. A common method used in flow testing is the lip pressure method (Grant et al., 1982). The well is discharged under different throttle conditions to get the characteristic curve to be used in selecting operating conditions for the turbines in the power plant.

1. INTRODUCTION

Logging generally means to "make a record" of something. Well logging, also known as borehole logging is therefore, the practice of making a detailed record (a *well log*) of the geologic formations penetrated by a well. The log may be based either on visual inspection of samples brought to the surface (*geological* logs e.g. cuttings logs, core-logging or petro-physical logging) or on physical measurements made by instruments lowered into the hole (*geophysical* logs). Geophysical well logging was first developed for petroleum industry by Marcel and Conrad Schlumberger in 1927 (Schlumberger, 2000). They developed a resistivity tool to detect differences in the porosity of sandstones of oilfield at Merwiller-Pechelbronn in France. Since then, geophysical well logging has developed to become a key technology in petroleum, geotechnical, mineral, groundwater and geothermal industries. While geophysical logging in petroleum is done to determine porosity and hydrocarbon saturation, in geothermal, the main emphasis is on location of fractures and recording of physical parameters e.g. temperature and pressure. Well logging is done during all phases of geothermal development; drilling, completion, production and abandonment.

When the well has recovered from the effects of cooling during drilling, it is flow tested to evaluate its mass flow, enthalpy and chemical characteristics. This paper will attempt to give a short description of the more routine geophysical well logging methods used in the geothermal development as well as the method commonly used in flow testing of the geothermal wells.

2. GEOPHYSICAL WELL LOGGING

Knowledge of the subsurface comes primarily from drilling which is a very expensive process. Therefore, the number of holes to be drilled for studying the subsurface is limited. Geophysical logging offers an opportunity to determine the composition, variability and physical properties of the rocks around the well thereby enabling a proper understanding of the subsurface at a cheaper cost. The following are the common geophysical logging methods used in geothermal applications.

2.1 Caliper logging

A calliper tool is used to measure the diameter of a well and how it changes with depth. It works by using one or more spring loaded arms which are pressed against the well bore wall as the tool is raised from the bottom of the well. The arms move in and out from the bore wall and the motion is recorded electrically and transmitted to the surface recording equipment. Multi-arm tool gives a better resolution of the bore shape than a single arm tool.

The results of the caliper logs can be used by the drillers to calculate amount of cement to be used for cementing job if it is run in the open hole prior to cementing to identify the large cavities. Caliper logs are also used in addition to lithological logs when interpreting the well geology.

2.2 Cement bond logging

Cement Bond Logs (CBL) use sonic tools that work by transmitting a sound wave through the casing, cemented annulus into the rocks of the borehole wall. A basic sonic tool consists of two parts. One contains the transmitter and the other contains two or more receivers. The two parts are normally separated by a rubber connector to reduce direct transmission of acoustic energy along the tool from the transmitter to the receiver.

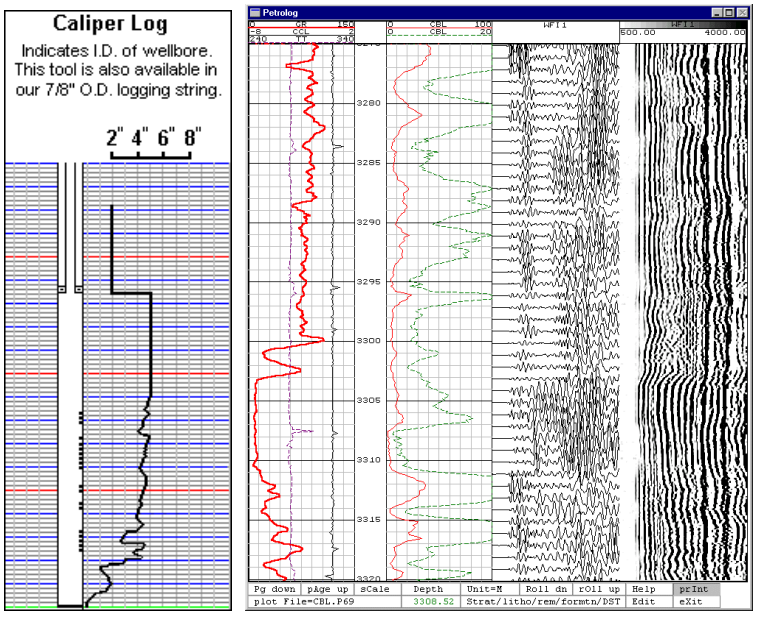

FIGURE 1: A Caliper and CBL log display (They are for different wells)

The transmitter injects a sinusoidal wave-train of acoustic energy into the formation. The detectors receive the signals whose arrival time will depend on the density of the media the signal has traversed. CBL is used for:

- Determining cement bond quality between cement and casing and also between cement and formation for zone isolation
- Correlating open hole logs to cased hole logs using the Casing Collar Locator (CCL) and Gamma Ray tool
- Indication of cement compressive strength. These tools can also measure casing thickness, micro annulus and cement channeling but do not measure cement bond to formation as well as the CBL

Once a well has been determined to be productive, casing is run in the open hole and cement is pumped to the outside of the casing to seal the casing to the borehole wall. A Cement Bond Log (CBL) is then run to inspect the integrity of the cement sealing to the casing and to the formation. This will ensure that undesired formation fluids will not flow into the well when on production or up or down the outside of the casing.

2.3 Lithological logging

Common lithological logging tools use either radioactive or resistivity methods. Principal radioactive emissions of interest in borehole geophysics are gamma rays and neutrons. Other radioactive products such as alpha particles and beta particles have low penetration capabilities and so are not useful for logging.

2.3.1 Natural gamma logging

This is the simplest geophysical well logging. These logging tools record the level of naturally occurring gamma ray emissions from rocks around the borehole. The signals comprise gamma ray emissions at different energy levels from the radioactive isotopes of Potassium (^{40}K), Thorium (^{232}Th) and Uranium (^{238}U) and their daughter products of the decay series. Distribution of K, Th and U varies widely in the crust and as a result, logging of the gamma ray signals emanating from the rocks around the borehole can provide considerable information about the geology of the borehole.

2.3.2 Neutron

Neutron-neutron and gamma ray tools are normally combined and run together. The neutron sensors measure the water content of the rock because the hydrogen atoms deflect neutron particles emitted from the tool. Porosity is a function of rock type and slow neutron count.

2.3.3 Resistivity logs

Resistance is impedance to flow of current and is a function of geometry and intrinsic resistivity of the material. Resistivity is the inverse of conductivity. Current flow in porous rock is mainly through the fluid filling the pore space and is affected by pore volume, pore connectivity and pore fluid composition, degree of alteration and mineralogy and temperature. Pore space character varies from formation to formation and for this reason, resistivity logs are often useful for exploring lithological units.

2.2.2 Self potential (SP) logs

SP method was developed by Schlumberger and measure small potential differences between the downhole movable electrode and the surface earth connection. The potentials arise from electrochemical and electrokinetic processes and are typically in the range of a few mV to a few tens of mV.

2.2.3 Induced polarisation (IP) logs

IP uses a transmitter loop to charge the ground with a high current. The transmitter loop is then turned off and the change in voltage with time is monitored using a secondary loop. In a well, the primary loop induces current flow in the rocks beyond the bore wall and the current leads to a charge build-up on conductive particles. The time dependent dissipation of this charge is then reflected as a decaying voltage. The IP can be used in detection of alteration zones.

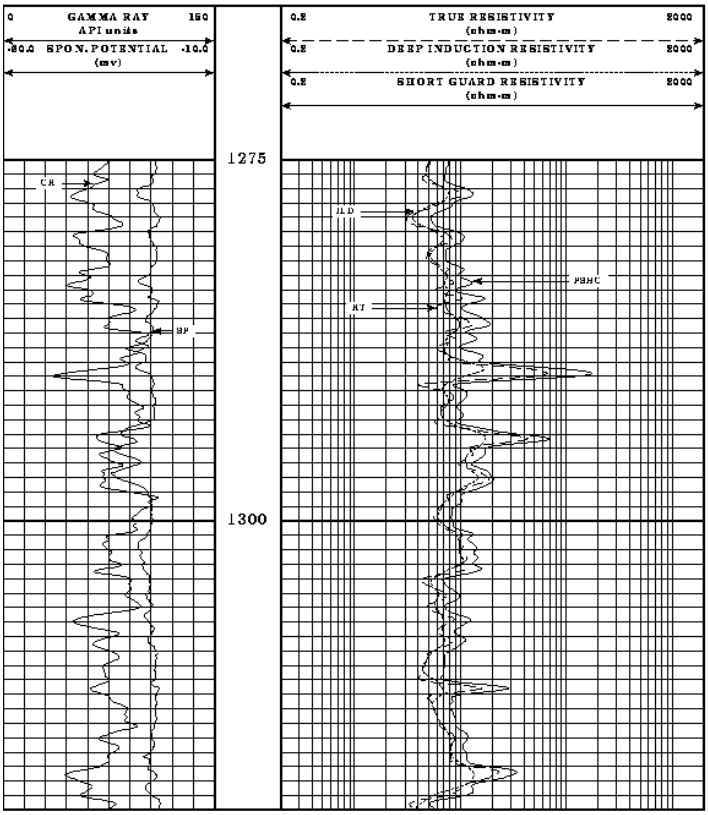

FIGURE 2: Gamma ray and resistivity logs

2.4 Temperature logging

Temperature Logs are the most important in geothermal applications. They are used to show how hot the well is and to locate aquifers. The information on aquifers is very useful in identifying the main inflow into the well for production purposes and also for cementing purposes where powerful aquifers have to be known so as to ensure good cementing jobs. Lithological tools and other electrical tools are very sensitive to temperature and so before running these tools, a temperature log would indicate whether it is safe.

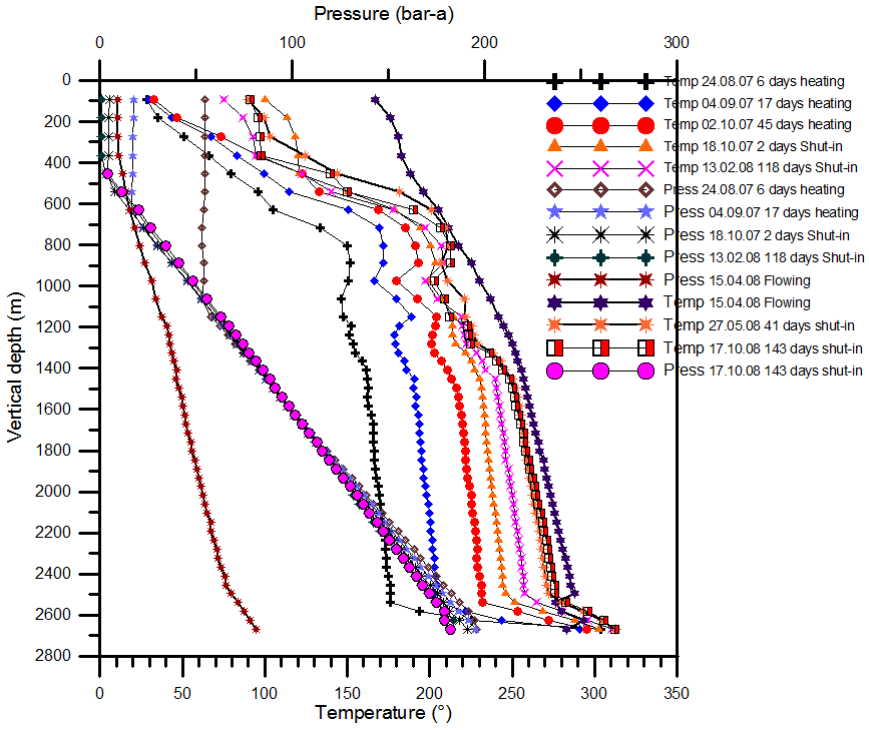

FIGURE 3: Pressure and temperature logs from one of the wells in Olkaria

2.5 Pressure logging

In most cases, pressure logs are done when the well has been drilled to the final depth. Transient pressure tests are done to estimate well injectivity index and hydraulic properties of the prominent aquifers. The injectivity index gives an idea of the well productivity. Pressure logs also indicate the type of fluids contained in the reservoir whether liquid or gas/steam as well as where the well is best connected to the reservoir.

2.6 Directional surveying

Directional drilling has gained importance in geothermal drilling in the recent past. To this effect, tools that can indicate the direction of the well profile as well as depth and azimuth are now available. Two types of directional tools are in operation i.e single-shot and multi-shot magnetic or gyro tool. Magnetic Single-Shot records one measurement, usually near the bottom of the well. It is comprised of a precision floating compass, a device to superimpose concentric circles (calibrated in degrees) with a plumb-bob type indicator, and a camera that photographs the plumb-bob and compass face to record both drift and direction. It cannot record compass directions inside regular drill collars or casing because steel pipe blanks off the Earth's magnetic lines of force. Thus, it is used only in open hole or inside non-magnetic drill collars. Magnetic Multi-Shot records multiple measurements of borehole drift and azimuth on a single run into the hole. It consists of a modified magnetic single-shot instrument with the single frame camera replaced by a multi-frame camera. It also has incorporated timing devices, including a motion sensor, and is used for multi-depth drift and direction measurements. Like the single-shot, It must be in an open hole or inside non-magnetic drill collars to measure compass directions.

Gyroscopes are impervious to magnetic interference and can be used to survey in cased wells or orient directional equipment for re-entry wells. The photographic gyroscope is used primarily to survey wellbores that have already been cased. This instrument can run in casing, tubing or drillstring, using a wireline.

The latest high precision tool is multi-shot true north seeking tool by Stockholm Precision Tools (SPT). The SPT system uses the gyro-compassing method to find direction. As it is a north-seeking gyro, all measurements are in reference to geographic north. Unlike other downhole survey or magnetic tools, the GyroTracer is not affected by magnetic interference. It can be run inside casing, tubing, drill pipe and magnetically disturbed ground. It can be run either as wire-line SRO (surface read out) or in memory mode via slickline.

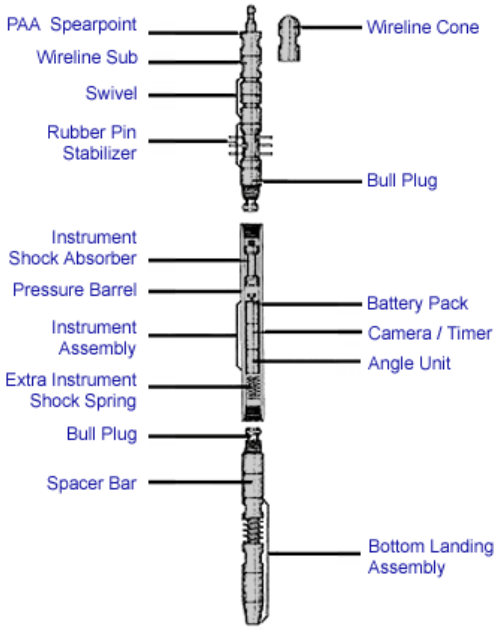

FIGURE 4: Multi-shot magnetic tool

3. FLOW TESTING

During recovery or warm up period, the water level in the well gradually rises and if there is boiling or accumulation of gas, the well will eventually build wellhead pressure above atmospheric for artesian flow. If not, the discharge can be initiated by compression, gas lift or swabbing. When the well has built up sufficient wellhead pressure and the well has recovered sufficiently, a flow test is then conducted by flowing the well through an orifice. Measurements are taken to evaluate the total flow rate, enthalpy and chemical characteristics of the discharged fluids. The lip pressure method (Grant et al., 1982) or a separator can be used to determine the total flow rate and enthalpy with a simple weir

being used to measure separated water flow. By repeating the flow tests with different sized orifices, the well productivity as a function of wellhead pressure can be determined. This is the characteristic curve for the well that can be used in selecting operating conditions for the turbines in the power plant.

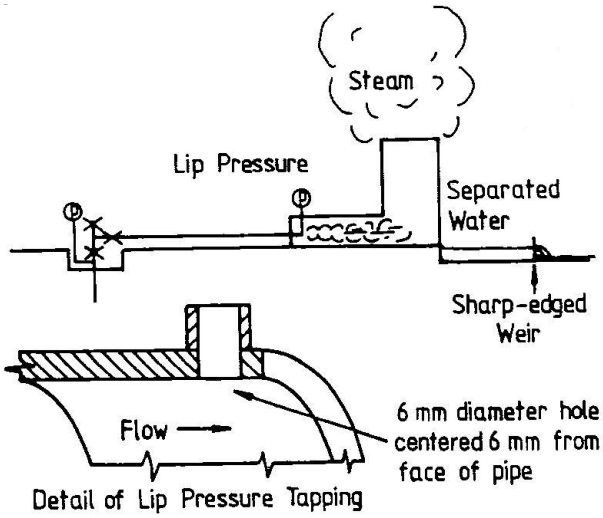

FIGURE 5: Schematic of Lip pressure method

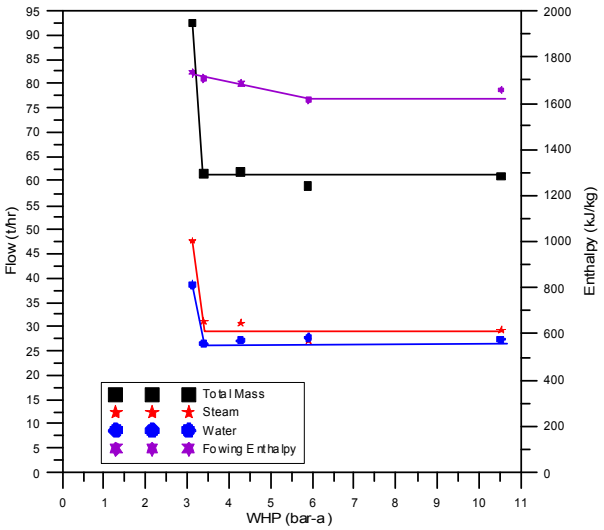

FIGURE 6: Characteristic curves of one of the Olkaria wells

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GEOCHEMICAL EXPLORATION OF GEOTHERMAL PROSPECTS: A CASE STUDY OF MENENGAI, KENYA

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ABSTRACT

Regional exploration for geothermal resources in Kenya indicates that the Quaternary volcanic complexes of the Kenya rift valley provide the most promising prospects for geothermal exploration. A number of geoscientific studies have been conducted to assess the geothermal potential of this area. This paper reports the results of a survey of fumaroles gas and condensate analysis, alongside CO_2 soil fluxes and concentrations of thoron (Rn_{220}) in soil gases. The procedures employed in the study are divided into: fumarole steam condensate and gas sampling and soil gas sampling to determine mainly the concentrations of carbon dioxide and radon radioactivity. For fumaroles, steam and condensate samples were collected for various analyses. Soil CO_2 concentrations measurements were performed using an Orsat apparatus whereas Rn_{220} soil gas concentrations were measured with a portable radon detector (emanometer). A total of 275 sampling points were measured. The obtained values ranged between zero to 12% of CO_2 in total gas and zero to 6425cpm of Rn_{220}.

The TH_2S geothermometer gave temperatures ranging from 279°C-296°C while TH_2S-CO_2 gave temperatures ranging from 274°C-304°C. The two geothermometers correlate well and from the temperature estimation, it is clear that the reservoir temperatures beneath Menengai caldera are over 270°C. Peak levels of soil CO_2 concentrations and thoron concentrations were identified to be located on major faults and within the caldera floor where hydrothermal fluids are rising and the rocks are highly fractured allowing the release of CO_2 and thoron locally marked by fumaroles. Areas identified with the highest anomalies for CO_2 and thoron soil gas concentrations can be seen in the contour maps presented. The caldera, Molo TVA and also Solai graben are the important geological structures associated with these anomalies.

1. INTRODUCTION

The Menengai Geothermal Prospect is located in the central section of Kenyan Rift Valley, the area north of L. Nakuru and south of Lake Bogoria. The extend of the prospect covers an area of approximately 600km^2 characterized by a complex geological setting with Menengai caldera being notably the major geological feature in the area and is also important for its geothermal potential. Most part of this area, in particular the southern section is discussed in this study.

The general exploration for geothermal resources in Kenya indicates that the Quaternary volcanic complexes of the Kenya rift valley provide the most promising prospects for geothermal exploration, and as a result, intensive exploration work has focussed on areas with volcanic centres located within the rift valley. Studies show that these volcanic centres have positive indications of geothermal resource that can be commercially exploited. Menengai geothermal area is one of the priority prospects in the current prospects ranking. Eleven locations with fumaroles have been identified in the region (Figure 1).

A number of thermal anomalies and diffuse degassing assessments have been carried out in most of geothermal prospect areas in Kenya, including Menengai. Results for CO_2 and Rn_{220} soil diffuse concentrations have been found to discharge more in areas that coincide with faults. The purpose of this study is to establish the soil gas concentration of CO_2 and Rn_{220} and relate with known geological structures.

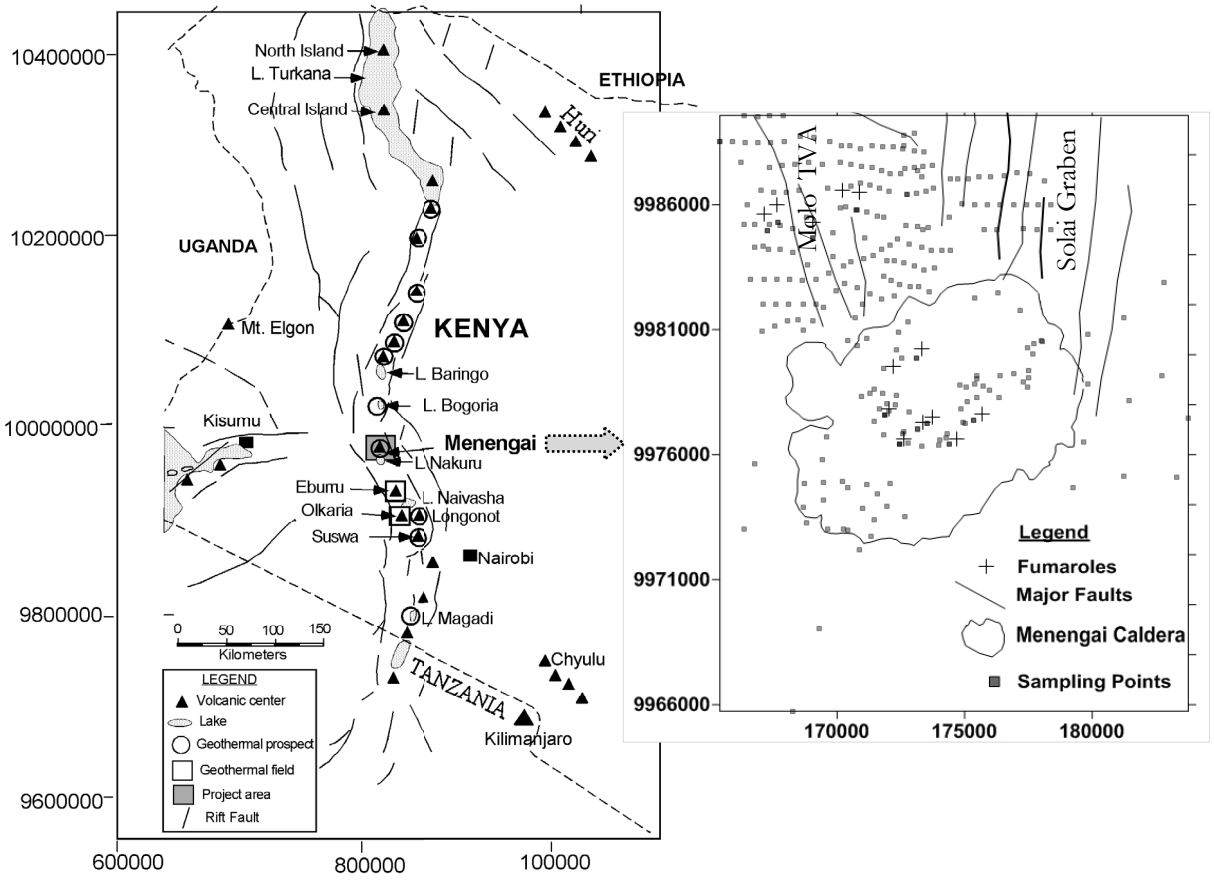

FIGURE 1: Location of Menengai geothermal prospect showing fumaroles, major faults and sampling points

2. GEOLOGICAL AND STRUCTURAL PATTERN

The Kenyan Rift is characterized by extension tectonism where the E-W tensional forces resulted in block faulting (KenGen 2004). This included leant blocks as evident in both the floor and scarps of the rift. The rift trough is truncated by several normal faults, which evidently represent persistent and wide-ranging tectonism under the rift floor. Menengai Geothermal Prospect itself is located within an area characterized by a complex tectonic activity associated with the rift triple junction; the latter being a zone at which the failed rift arm of the Nyanza rift joins the main Kenya rift. Two rift floor tectono-volcanic axes (TVA) that are important in controlling the geothermal system in study area include the Molo and the Solai TVA.

Menengai (Figure 2) has been active from about 0.4 -0.3 Ma B.P (Gislason 1989). The formation of the shield volcano began about 200,000 years ago and was followed by the eruption of two voluminous ash-flow tuffs, each preceded by major pumice falls. More than 70 post-caldera lava flows cover the caldera floor, the youngest of which may be only a few hundred years old. The caldera of Menengai volcano lies immediately north of Lake Nakuru, but ignimbrites and air-fall tuffs from the volcano cover some 1350 km^2 (Leat & Macdonald 1984) extending into Molo area (Jennings 1971). The volcano is mainly composed of strongly peralkaline, Si-oversaturated trachytes and has had a complex geochemical evolution, resulting from the interplay of magma mixing, crystal fractionation and liquid state differentiation (Leat & Macdonald 1984).

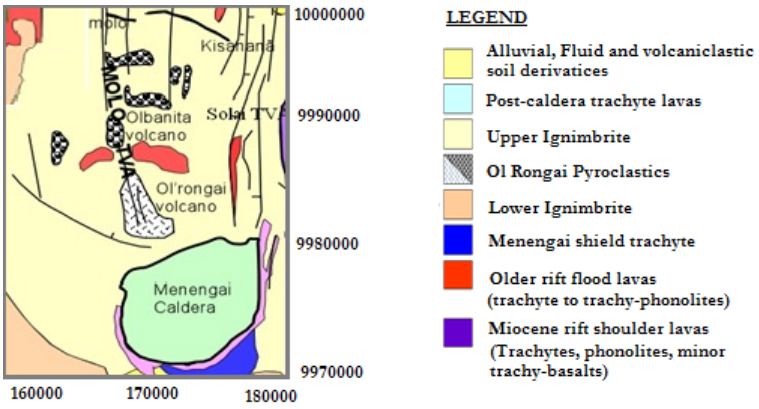

FIGURE 2: Geological map of Menengai Geothermal Prospect Area (after KenGen 2004)

3. METHODOLOGY

The procedures employed in the study are divided into: fumarole steam condensate and gas sampling and soil gas sampling to determine mainly the concentrations of carbon dioxide and radon radioactivity. For fumaroles, steam and condensate samples were collected for various analyses. A portion of the condensate collected was set aside for immediate analysis and measurements of pH, conductivity, TDS, H_2S and CO_2. Electrical conductivity and TDS of the condensate was measured using a portable TDS/conductivity meter and the pH was measured by a pH meter. Zinc acetate was added to another portion of the condensate to fix SO_4^{-2}. Another (untreated) portion was reserved for analysis of chloride (Cl^-) and fluorides (F^-) in the laboratory.

A different sample was also collected and preserved with concentrated nitric acid for later analysis of metal ions. The analysis of the metals (Na, Ca, K, Mg and Li) was done using the Atomic Absorption Spectrophotometry method and Ion Selective method. The portion for silica (SiO_2) analysis was diluted ten times to avoid polymerization of monomeric silica. The analysis of SiO_2 was done using the UV/VIS spectrophotometry method. Cl^- and F^- were analyzed by the Mohr titration and the ion selective electrode methods for the components respectively. CO_2 and H_2S gases were analyzed using titration methods by using 0.01 M hydrochloric acid (HCl) and 0.01M mercuric acetate, respectively.

The fumarole gases were sampled by directing the steam into two evacuated gas flasks for each fumarole, one at a time, containing 50 ml of 40% NaOH. The acidic gases (CO_2 and H_2S) are absorbed into the NaOH solution giving room in the evacuated flask for the minor none condensable gases usually found in thermal fluids to concentrate to measureable levels. The sample from one of the flask was used for analysis of H_2, CH_4, N_2 and O_2 by Gas Chromatography. From the second flask, CO_2 and H_2S were determined by titrating with HCl and mercuric acetate, respectively, as done for the condensate samples. The water samples from the hot springs and boreholes waters were sampled for analysis of cations and anions. The pH, TDS, Conductivity and sampling temperature were determined in the field.

The CO_2 gas as % of the total gas was measured using the Orsat apparatus. Soil gas samples were obtained using a spike, equipped with a steel outer jacket to penetrate the ground to a depth of 0.7 m. This method of obtaining gases from ground is similar to the one applied for the acquisition of Rn222 radioactivity. The soil gas sample containing radon was pumped into the decay chamber of the

emanometer consisting of a cylindrical copper can, whose walls are coated with zinc sulphide where the radon decays into other radio-nuclides by emitting alpha particles. Three background counts were recorded at two-minute intervals prior to introduction of the sample into the emanometer. An infra-red thermometer was used to take the temperature by directly pointing it into the hole made by the spike and the resultant temperature recorded. Soil gas sampling points ranged from 200m to 2km depending on accessibility, proximity to manifestations and time (see Figure 1).

The study area together with a total of 275 soil gas sampling points is presented in Figure 1. Soil gas survey sampling spacing relied mainly on accessibility of specific targeted points and the ease of getting samples, in particular on the rugged areas. Nonetheless, a random separation of about 300m in average was used. Areas covered by younger lava flow were almost impossible to sample and few samples thus represents such areas, as was seen with lava pond within the caldera. The survey involved measuring of CO_2 and Rn-$_{220}$ in the soil gas. All the measurements were done at the same point. In addition, soil temperatures were taken using an infra-red thermometer at the point where the soil gas survey was undertaken.

Measurement of CO_2 gas was done by the help of an Orsat apparatus after the soil gas was hand pumped from a depth of 1m below the surface via a hole made using a steel spike with jacket. The Orsat apparatus consist of absorption vessels, which measure about 100mls and contain a 40% KOH solution for absorbing the acidic CO_2. The corresponding volume changes in the absorption vessel represent the corresponding amounts of the gases in volumes given as percent of the total gas as a percentage.

Radon radioactivity levels were measured in the soil gas using a portable radon detector (emanometer). The soil gas was passed into the emanometer by using a hand-operated vacuum pump and Rn-$_{220}$ readings recorded in counts per minute (cpm). Three background counts were recorded at three-minute interval prior to introduction of sample into the emanometer. Upon introducing the sample, three more readings were taken at one-minute interval to give the total radon counts.

The CO_2 and Rn_{220} obtained in the survey (both 2004 and 2010 sampling programs) were corrected and used to construct concentrations contour maps (Figures 3 to 6). Natural neighbor contouring method was used because it interpolates scattered and irregularly spaced data effectively and hence produces better contours maps from irregularly spaced measurements (Ledoux & Gold 2005).

Early geochemical studies on diffuse soil degassing have been carried out in a number of geothermal areas. CO_2 soil gas investigations similar to the one used in this study have been conducted elsewhere in volcanic areas to examine unexpected rise in CO_2 flux (e.g. Farrar *et al.* 1995; McGee and Gerlach 1998; Gerlach *et al.* 1998), estimate total volcanic flux from volcanic vents and diffuse flank emissions (e.g. Allard *et al.* 1991; Chiodini *et al.* 1996), and to classify tectonic structures related to volcanic degassing (e.g. Giammanco *et al.* 1997; Bergfeld 1998).

4. RESULTS AND DISCUSSIONS

The results of descriptive statistics of CO_2, Rn_{220} and Temperature collected are presented in Table 1. The frequency distributions are described by normal distribution. The range of values for these parameters spans several orders of magnitude.

TABLE 1: Descriptive statistics of CO_2, Thoron and Temperature from 275 sampling points

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance	Skewness		Kurtosis	
	Statistic	*Statistic*	*Statistic*	*Statistic*	*Statistic*	*Statistic*	*Statistic*	*Statistic*	*Error*	*Statistic*	*Error*
Rn220	275	6427	0	6427	386	603	363391	5.14	0.15	39.49	0.29
CO2	275	12.30	0.00	12.30	1.12	1.54	2.37	5.12	0.15	30.81	0.29
Temp	275	55.90	21.20	77.10	28.70	6.99	211.52	0.05	0.15	0.62	0.29

4.1 Soil temperature measurements

The mapping of temperature variations at or below the earth's surface is an essential geothermal exploration instrument. The spatial variation of soil temperature is illustrated in Figure 3. Quite a number of anomalies can be identified in relation to the major structural setting. And as indicted by results, a higher temperature anomaly in the caldera is evident around the fumaroles with the highest fumaroles temperature of 88^{o}C. Similar to other soil surveys, soil temperature results in the caldera is mainly affected by the lava that covers the caldera floor and apart from the areas where the lava did not cover. The areas to the North outside the caldera gave an anomaly confirming the geothermal potential of the area coinciding with two major faults trending NW-SW.

4.2 Diffuse degassing measurements

The term volcanic gas defines a gas exsolved from a magmatic source of an active volcano whereas hydrothermal gas defines a gas exsolved from the envelope of hot water that surrounds the magmatic environment. Volcanic gases have composition different from the hydrothermal gases, the first is richest in SO_2 and the second in H_2S (Giggenbach 1996). CO_2 occurs in both magmatic and hydrothermal gases and is the most abundant gas after water vapor. The deep-seated faults in the crust tap magmatic CO_2, which is transmitted to the surface where it is naturally lost through the soil. Carbon dioxide (CO_2) of magmatic origin is normally channeled through deep-seated tectonic structures close to the surface of the earth and then seeps out of the ground through the soil. However, dealing with CO_2 anomalies especially in the Rift Valley ought to be treated with caution owing to the availability of localized sources of this gas as suggested by Darling *et al.* (1995). CO_2 may also originate from other sources like organic matter, which are likely to give false impressions of a geothermal source.

Thoron gas (Rn_{220}) is a short lived isotope of radon produced by the thorium (Th_{232}) decay series with a half-life of 55 seconds (Lopez *et al.* 2004). Due to its short half-life, thoron's transportation is limited to a few centimeters either by diffusive or convective flows, as compared to Rn_{222} (t ½ = 3.8 days) (Hutter 1993). As a result, the high concentrations of thoron are more likely to be due to convective movement of gases rather than diffusive processes and therefore it is difficult to achieve an exact quantitative measurement of its concentration. If we measure the disintegration of thoron, it shows a decrease during the first three minutes after collection of the sample, as opposed to the radon that presents a half-life of almost 4 days (Magana *et al.* 2002). High thoron values could be suggestive of enhanced permeability, as it may as well depend on other factors such as the degree of rock fracture and the ability of groundwater to circulate and remove thoron.

The CO_2 gas concentrations are plotted in Figure 4 while the results of radon emanations were recorded in counts per minute (cpm) for Rn_{-220} and plotted in Figure 5. To reduce interferences between CO_2 and Radon sources a ratio of Rn_{-220}/CO_2 have been plotted in Figure 6.

4.2.1 CO_2 concentrations

The concentration of CO_2 in the soil gas in the surveyed area is given as a percentage of the total gas in the soil. The degassing of CO_2 through the soil in the prospect area is considered to be mainly supplied by two sources, the one of volcanic origin emanating from deep environment and a shallow

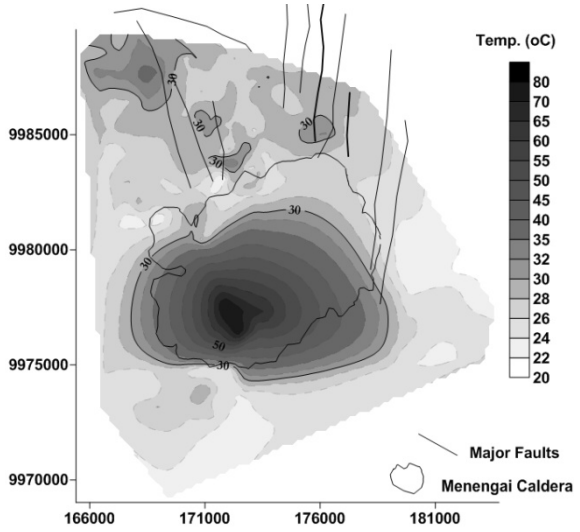

FIGURE 3: Temperature distribution in °C

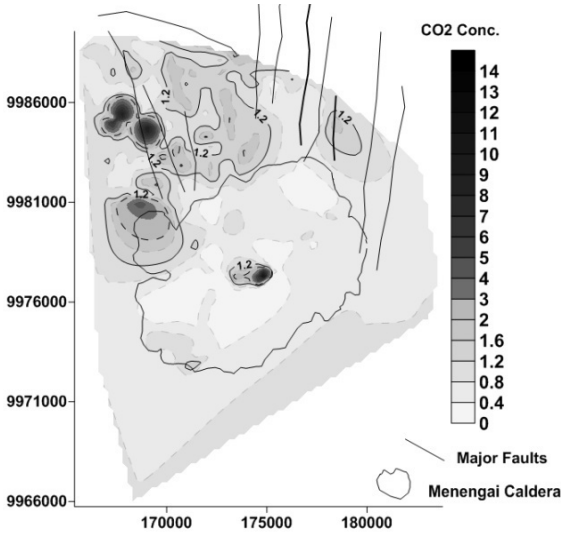

FIGURE 4: CO_2 conc. distributions

one that result from organic activity. In this study, high CO_2 values (>2.5%) are found at a belt running in a NW-SE while other areas exhibit low values (<1 %). These areas coincide with the Molo Tectono-Volcanic Axis (Molo TVA), deep seated faults and the eruption centers in the prospect area which indicate that the source could be from a magmatic body. Highest CO_2 concentration in the soil gas was observed around Ol'Rongai Hill (located along Molo TVA) and the contiguous fumaroles with CO_2 >10% which could be indicative of good permeability in the area.

The central part of the caldera around the fumaroles, as well, displays relatively high values of CO_2 (>2.8%). There are also few highs of CO_2>5 % in the western part of the caldera. The presence of thick young lava that covers most parts of the caldera interfere with the movement of CO_2 to the surface and therefore makes sampling in these parts extremely difficult, and is also noticeable in the contouring of the CO_2 distribution as shown in Figure 4. Care ought to be taken while correlating thermal and diffuse degassing anomaly with subsurface permeability. This is because the cap of young lava that covers most part of the caldera might be directing the anomaly laterally beneath the lava bed and hence giving misleading impression as a result.

4.2.2 Thoron concentrations

From the results of the absolute values of Rn_{-220}, north-western parts of the surveyed area show the highest concentrations (Figure 5). In addition, a more pronounced anomaly is evident in central part of the caldera in the areas adjoining fumaroles following similar pattern to the one revealed by CO_2 distributions. However, a mild rise in thoron values is seen in the eastern flank touching Solai Graben.

4.2.3 Thoron-CO_2 ratios

The ratio of the Rn_{220}/CO_2 gases would be a good indicator of the magmatic source of the gases since the ratio is not expected to change if they are from the same source (see Figure 6). High values of these ratios are found towards the north, north-western to the north eastern parts outside of the caldera wall with two anomalous areas at the fumaroles in Ol'Rongai area. A mantle source of CO_2 as suggested by Darling et al. (1995) is a possibility of the source of this gas due to intense faulting in the area, and these faults around Ol'Rongai are of great importance in localizing degassing of CO_2 and Rn_{-220} as well thermal manifestation anomalies. If a mantle source is inferred due to intense faulting, then the faults should be deep seated. These areas apparently coincide with high CO_2 and high Rn-220 absolute values.

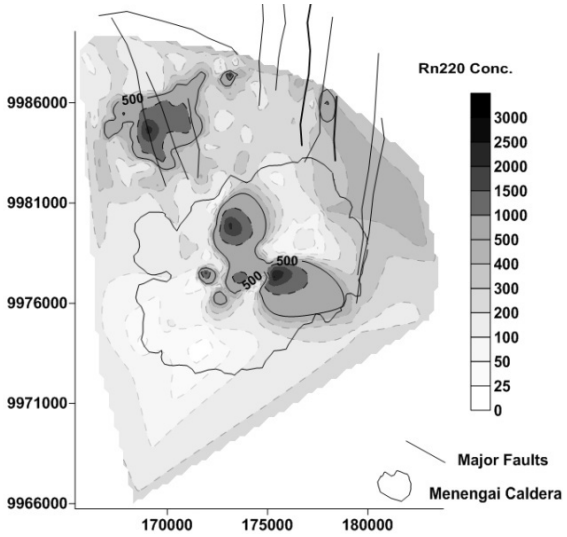

FIGURE 5: Rn_{220} conc. distributions

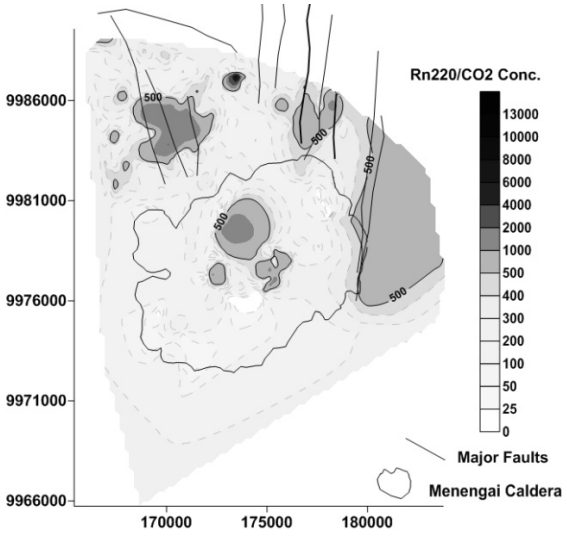

FIGURE 6: Rn_{220}/CO_2 conc. distributions

The western part of the surveyed area, which shows high absolute values of CO_2, gives low value of this ratio. This is an indication of a source other than the one of magmatic origin. This coincides with an agriculture farm and consequently the CO_2 anomaly in this area is considered to emanate from organic source, as a result. Nonetheless, a higher ratio of these gases is seen within and to the east of the caldera.

4.3 Fumarole gas analysis

Samples collected during the infill survey show atmospheric air contamination as they contain high values of nitrogen and oxygen. Fumarole temperature measurements differ significantly for the CO_2 and H_2S with CO_2 temperatures being unrealistically high.

4.4 Fumarole steam condensates

The chemical constituents analysed in the steam condensates are those which can be considered to be volatile enough to partition into the steam phase upon phase separation in a boiling system as is expected in an aquifer producing steam. Such elements include the soluble gaseous compounds such as CO_2, H_2S, F^-, and B, which are present in the geothermal steam. In addition, the concentration of other non-volatile elements like Cl^-, SiO_2 and SO_4^{-2} were determined. The pH, TDS and the electrical conductivity were also measured in the steam condensate samples.

TABLE 2: Rn-222 radioactivity and CO_2 concentration in fumarole steam

Fumarole No.	Location		Elevation (m)	CO_2 (%) vol.	Temp °C	Rn-222 (cpm)	Rn/CO_2 ratio
	Eastings	Northings					
MF-1	172400	9975900	2160	15.1	60.0	1650	109.3
MF-2	175324	9977356	1992	25.6	94.0	12194	476.4
MF-3	171868	9977563	2081	16.7	77.1	2200	131.7
MF-4	169080	9984679	2016	48.2	81.2	3700	76.76
MF-5	167712	9985324	1896	43.8	86.1	2890	66.0
MF-6	173208	9979555	1908	32.6	84.6	16848	516.8
MF-7	173682	9977020	2106	18.3	73.5	1600	87.4
MF-8	174485	9976115	2098	24.6	90.1	1580	64.2

TABLE 3: Fumarole steam condensate analysis from Menengai geothermal prospect

Fumarole No.	Fumarole Location		Condensate (ppm)														
	Easting's	Northing's	Fumarole Temp (°C)	pH	Cond (µS)	TDS (ppm)	Hg (mg/m³)	CO_2	H_2S	B	Ca	Cl	F	K	Li	Mg	SiO_2	SO_4
MF-1	173170	9977023	62	6.7	4.0	2.0	0.000	109.3	0.3	0.2	5.7	0.2	0.2	0.8	nil	0.1	12.4	3.8
MF-2	175353	9977375	88	6.8	14.0	7.0	0.024	41.1	0.1	0.1	5.2	2.5	0.2	0.5	nil	0.2	0.2	4.5
MF-3	171876	9977567	85	6.7	0.0	0.0	0.140	39.6	0.4	0.1	5.8	1.6	0.2	2.2	nil	0.8	0.4	10.3
MF-6	173112	9979852	75	6.5	23.0	11.0	0.013	54.1	0.3	0.4	3.3	1.7	1.3	0.0	nil	0.0	0.9	3.9
MF-7	173520	9977240	88	6.1	2.0	0.0	0.003	35.6	0.3	0.3	2.8	1.3	0.1	0.9	nil	0.0	0.3	9.6
MF-8	174395	9976411	88	6.0	3.0	1.0	0.003	33.9	0.1	0.2	2.8	2.0	0.3	0.9	nil	0.2	0.3	6.7
MF-9	172441	9976400	70	6.2	4.0	2.0	0.000	37.4	0.1	0.2	5.7	2.0	0.7	2.3	nil	0.4	0.4	0.2

5. DISCUSSIONS AND CONCLUSIONS

The fumarole steam was analysed for the major gases associated with geothermal activity (CO_2, H_2S, H_2, CH_4 and N_2) and the results indicate no hydrogen and methane for all the samples obtained. Most of these fumaroles were issuing at extremely low pressures and it was quite difficult to obtain condensate samples from the fumaroles. From the analytical results obtained, such weak fumaroles have compositions indicating high air/steam ratios. Such high ratios are indicative of shallow surface waters locally mixing with steam and hence the bulk composition of the gases is composed of atmospheric air.

The gas contents of fluids present in areas of high permeability and close to a hot geothermal fluid upflow are expected to be of high concentrations especially with regards to the reactive gases like CO_2, H_2S and H_2. Hydrogen and methane are lacking but high CO_2 and H_2S occurs in fumaroles MF2 and MF6. When the fluid travels for long distances there is a tendency for it to be depleted of these gases through possible reactions between the gases and the minerals forming the reservoir rocks. On the other hand, the concentration of N_2 in the fumarole steam could be an indicator of admixture with gas originating from the atmosphere. This could be taken to imply mixing of shallow ground waters with deep geothermal fluids. The N_2 gas is considered largely to be derived from air and then introduced into the geothermal system. There are possibilities of N_2 accumulating in the rocks from organic life.

Temperatures were calculated for five fumaroles sampled. The TH_2S geothermometer gave temperatures ranging from 279°C-296°C while TH_2S-CO_2 gave temperatures ranging from 274°C-304°C. The two geothermometers correlate well and from the temperature estimation, it is clear that the reservoir temperatures beneath Menengai caldera are over 270°C.

Fumarole condensate samples were analysed for pH, TDS, CO_2, H_2S, Cl^-, F^-, B, SO_4^{-2} and the electrical conductivity. All the condensates gave pH values ranging between 6 at MF-8 and 7.5 at MF-2 measured at 20°C. Low pH values imply the fluids contain high concentrations of acid gases, which form the acidic condensed water. Most of the acidic emanations are mainly magmatic with large amounts of volatile components such as H_2O,

HCl, SO_2, H_2S, CO_2 and H_2. However, chemical properties of magmatic emanations collected on the surface are expected to be different from those under the ground on account of severe distillation on the surface caused by depression of pressures and temperatures.

Volatile chemical constituents dissolved in the deep water would be transported to the surface with steam from greater depth through vaporization. High volatility elements like F^-, B, NH_3, arsenic (As) and mercury (Hg) would therefore be expected to dominate in the steam composition in addition to the geothermal related gaseous elements (CO_2, H_2S and H_2). High concentration of volatiles in a steam condensate would be proportional to strength of the discharge and temperatures of the steam source.

All the condensate samples gave F^- values ranging from <0.1-1.3 ppm while the B values range from 0.1-0.4ppm for fumaroles MF-2 and MF-6 respectively. The relatively high F^- content in the steam condensate may indicate deep crustal water circulation while at the same time the relatively high B values in the condensate may indicate high formation temperatures. Boron is considered a mobile component since it does not take part in rock forming reactions and its concentration in the geothermal fluids is controlled by the leaching rate from the reservoir rocks. At high temperatures (>250°C) boron is expected to partition into the steam phase and if boiling is occurring in the reservoir, then the temperatures should be more than 250°C. The difference in boron concentration of different fumarole steam condensates can partly be due to the compositions of the source rocks.

The Cl^- content of the condensate samples from fumaroles MF-4 and MF-8 ranged from 15.6–34.1 ppm respectively. Very high Cl^- values in a steam condensate would represent a water dominated system while extremely low values would be expected to originate from a vapour dominated system since chlorides are not known to partition into steam phase at any temperatures.

Despite the erratic distribution of sampling points, the results from acquired data can be used to make some conclusions relative to the objective. The fumaroles show close relations with geologic structures, which provides means of access for hydrothermal fluids to reach the surface. In the same way, most of the gas anomalies are located in fault zones. CO_2 and Rn_{220} emanations from the presently quiescent faults in Menengai were measured to be higher than background values.

The two fault-lines at Ol'Rongai are considered in this study to be of great importance in geothermal exploration and any future development as it reflects intensity of subsurface permeability in the area, and enhances the confidence to invest. The caldera itself as a geological structure displays a positive evidence of the existence of geothermal resource, with its thermal anomalies that coincides with CO_2 and thoron anomalies. Nonetheless, the picture portrayed by the contours within the caldera is hereby treated with caution as the pond of new lava spread across most part of the floor greatly influenced sampling spaces, and possibility of lateral flow of thermal fluids and diffuse gases at the upper zones restricted by the lava cap cannot be negated.

Generally, CO_2 concentrations are structurally controlled but may have been modified by changes in land use. As seen from the findings, the study of soil CO_2 and Rn_{220} composition as proved to be important geochemical method to identify vertical zones of high permeability. The employment of these methods in other geothermal fields could give important and relatively cheap information for field utilization and development.

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CHEMISTRY IN EXPLORATION OF A GEOTHERMAL FIELD

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ABSTRACT

Chemistry principles are some of the scientific techniques used in exploration for geothermal resources. The methods used include sampling of surface discharge from potential target areas and soil gas sampling followed by chemical analysis of the samples and finally data interpretation. The data obtained is used to assist in locating potential drill sites for geothermal generation, estimating the subsurface temperatures where the discharges are coming from and characterising the geothermal fluids using the chemistry to assess their usability for the intended purposes. This technique was used in exploration for geothermal resources in Menengai field, Kenyan Rift Valley. The results indicated availability of geothermal fluids at temperatures of up to 250 °C. The reservoir was defined by both high CO_2 and Rn-222 measured in the soil gas and also high gas content in the fumarole discharges and the high volatile constituents in the fumarole steam condensates. Three deep exploration wells were proposed to be drilled in Menengai caldera using the chemistry of the surface discharges.

1. INTRODUCTION

The area under investigation has extremely few geothermal manifestations or expressions, which makes it quite difficult in terms of exploration using chemical methods. The few geothermal manifestations present include few low-pressured fumaroles mainly located inside the caldera. The chemical survey conducted involved fumarole sampling and soil gas survey with emphasis on carbon dioxide (CO_2) and radon (Rn-222) gas compositions in the soil air. The soil gas survey was conducted along traverse lines running E-W. The traverses were 1000 m apart while the sample points were taken at 500 m in areas of high geothermal manifestations and wider apart in areas of low geothermal manifestations. Sampling was done at a depth of 0.7 m below the surface.

2. PREVIOUS WORK

Previous geochemical investigations of this area were carried out by Geotermica Italiana Srl, (1987) and Ministry of Energy in 1985-1986 under the auspices of the United Nations Department for Technical Development (DTCD). The work covered the area from Menengai caldera to Lake Bogoria to the north. The work involved sampling water points and a few soil gas surveys targeting mainly carbon dioxide. The few soil gas samples were picked mainly along the major access roads in Olbanita and Ol'rongai areas. From the previous work few surface features of geothermal importance were covered and these consisted of hot springs and fumaroles of Lake Bogoria, the steam heated pools of Molo River and gas discharging boreholes. Other areas in the prospect area around Solai graben and

areas within the Ol'rongai and Olbanita volcanoes lacked water points. High flows of discharging fluids were recorded around Lake Bogoria springs and temperature estimates using solute geothermometry from the springs and boreholes ranged from 145-190°C for borehole and spring water. Gas geothermometry estimates provided higher temperature estimates, which ranged from 170–214°C.

Soil gas survey was carried out in areas adjacent to the Solai graben and the Olbanita and Ol'rongai areas. Carbon dioxide contents of the soil gas showed higher contents around the Olbanita and Ol'rongai areas than around the Solai graben. Since the work was carried out, more boreholes have been drilled in the prospect area. Some of these boreholes had temperatures measurements that were more than ambient. Soil gas data collected around and inside the caldera was scant. To obtain more information that would assist in siting exploration wells, further work was planned which included sampling boreholes and springs as well as soil gas surveys in the prospect.

3. METHODOLOGY

The procedures employed in the study can be divided into three categories:
(1) Fumarole steam discharge sampling,
(2) Borehole water sampling and analysis and
(3) Soil gas sampling to determine mainly the concentrations of carbon dioxide and radon radioactivity in the soil air. The sampling procedures are described separately below.

3.1 Fumarole steam sampling

The fumarole discharges in this area are mainly found inside the caldera and a few locations to the north-western part of the caldera (Figure 1). Nearly all the fumaroles are characterized by low discharge pressure and are highly contaminated with atmospheric air. The discharge was trapped using a stainless steel funnel whose contact points with the ground were sealed with mud to prevent any contact with air to avoid possible contamination of the sample. The trapped steam was delivered into a gas-sampling bulb through rubber tubing via a stainless steel cooling coil immersed in cold water to trap the steam condensate. A portion of the condensate collected was set aside for immediate analysis and measurements of pH, conductivity, total dissolved solids (TDS), hydrogen sulphide gas (H_2S) and CO_2. A measured quantity of zinc acetate was added to another portion of the condensate to preserve the sample for later laboratory analyses of the sulphates (SO_4^{-2}). Another (untreated) portion was reserved for analysis of chloride (Cl^-) and fluorides (F^-) in the laboratory. The immediate analysis of dissolved H_2S gas was done on the sampling site while measurements of conductivity, TDS, pH, CO_2 (as total carbonates) and Cl^- was done at the end of each sampling day at the base camp.

Electrical conductivity of the condensate was measured using a portable conductivity meter, Cole Palmer model 1481-40 at ambient temperatures while the pH was measured using a field pH meter. Cl^- and F^- were determined in the laboratory by using the Mohr titration and the selective electrode methods for both components respectively. Both CO_2 and H_2S gases were analysed by titration methods by using 0.1 M hydrochloric acid (HCl) and mercuric acetate respectively.

The fumarole gases were sampled by directing the steam into two evacuated gas sample flasks, one at a time, containing 50 ml of a 40% NaOH solution with cold water continuously pouring on top of the flask. The acidic gases mainly CO_2 and H_2S are absorbed into the solution giving room in the evacuated flask for the minor non-condensable gases usually found in thermal fluids to concentrate to measurable levels. One flask was used for analysis of hydrogen (H_2), methane (CH_4), nitrogen (N_2) and oxygen (O_2). This was done using a Varian Sigma 300 gas chromatograph at Olkaria geochemistry laboratory. From the second flask, CO_2 and H_2S were analysed by titrating with HCl and mercuric acetate, respectively.

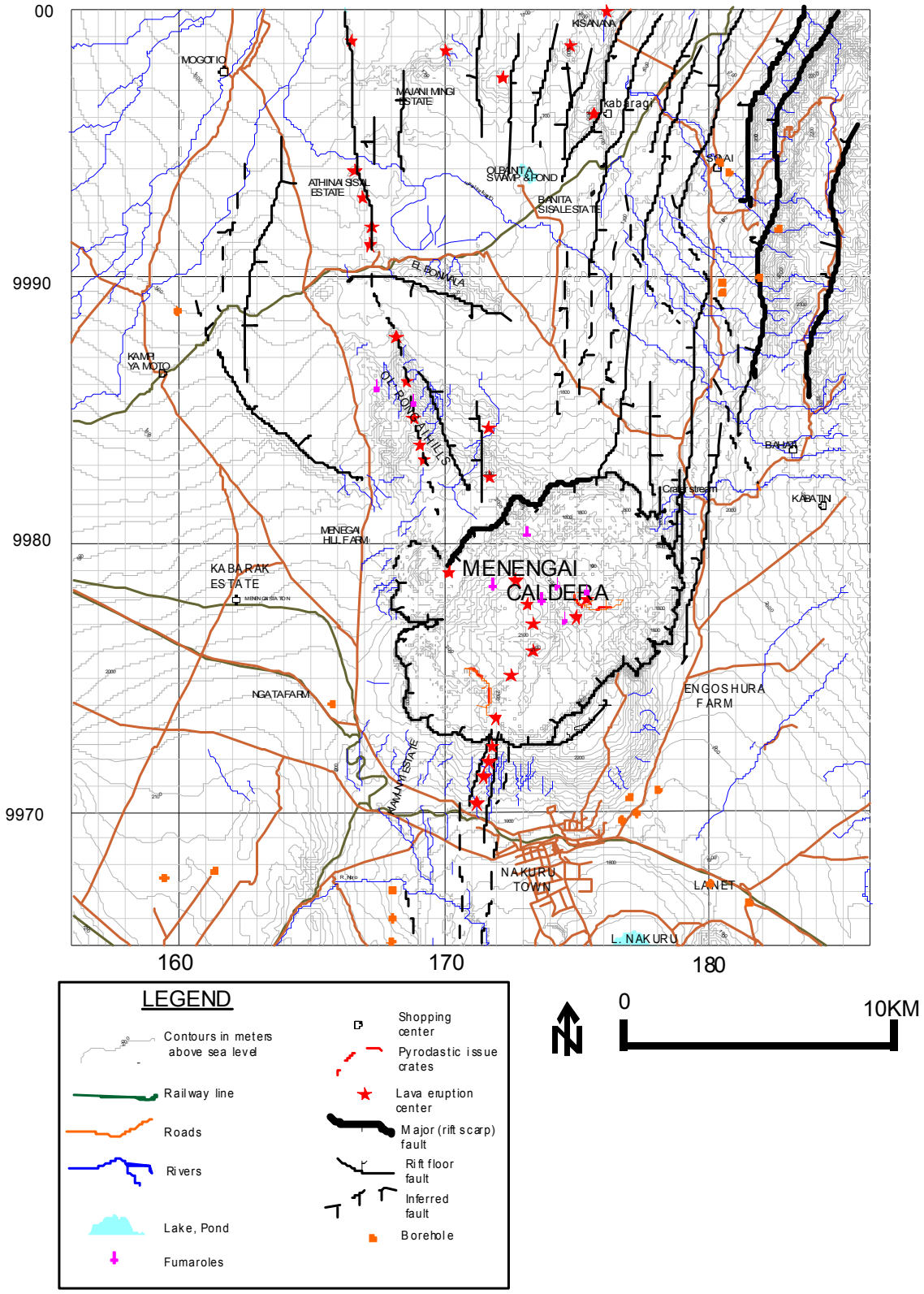

FIGURE 1: Fumarole and borehole locations in Menengai Prospect area

3.2 Soil gas survey

The survey was conducted along traverse lines running in an E-W direction. Sample points were located at an interval of 500 m except in some areas where the spacing was widened to 1000 m due to wider coverage required and low geothermal activity. The survey carried out involved measuring of CO_2, Rn in the soil gas as well as the ground temperatures measured at a depth of 0.7 m. All the measurements were done at the same point. The sample points for the soil gas survey are shown in Figure 2.

3.2.1 Carbon dioxide in the soil gas

The CO_2 gas was measured using an Orsat apparatus at a depth of 0.7 m below the surface. Gas samples were obtained by using a spike, which was equipped with a steel outer jacket to penetrate the ground to the desired depth. The spike was then removed and the outer jacket left inside the hole to allow for the sampling. A stopper and a hosepipe were fixed onto the mouth of the jacket and by using a hand operated vacuum pump, the soil air was driven into the analytical apparatus. The Orsat apparatus consist of absorption vessels, which measure about 100 ml and contain a 40% KOH solution for absorbing the acidic CO_2. The corresponding volume changes in the absorption vessel represent the corresponding amounts of the gases in volumes given as percent of the total gas.

3.2.2 Radon radioactivity measurement in soil gas

Radon radioactivity levels were measured in the soil gas and in fumarole steam by using a portable radon detector (emanometer). The soil gas was passed into the emanometer by using a hand-operated vacuum pump at a depth of 0.7 m below the ground using the same procedure as for CO_2 discussed above. The soil gas samples were collected at an interval of 500 m. Radon (Rn-222 and Rn-220) readings were recorded in counts per minute (cpm).

The soil gas sample containing the radon was forced into the decay chamber of the emanometer consisting of a cylindrical copper can. The walls of decay chamber are coated with zinc sulphide where the radon decays into other radioactive nuclides by emitting alpha particles. The alpha emissions are detected by a photomultiplier attached to the detector and the signals displayed by a rate meter. Three background counts were recorded at one-minute interval prior to introduction of sample into the emanometer. Upon introducing the sample, three more readings are taken at one-minute interval to give the total radon counts. Both the Rn-222 and Rn-220 (Tn) are detected by the emanometer but due to the difference in their half-lives, it is possible to differentiate between the two. Computations of the concentrations of both radioactive nuclides in the samples were done using computer software developed by GENZL for KPC.

3.3.3 Radon radioactivity measurements in fumarole steam

To sample the fumarole steam for the radon radioactivity and the percentage of CO_2 in the steam, the steam was condensed and the condensate trapped in a sampling flask. The dry gas was then driven into the radon emanometer by using a hand-operated vacuum pump just as is done for the soil gas sampling. The same method was employed for measuring the CO_2 in the steam using the Orsat apparatus.

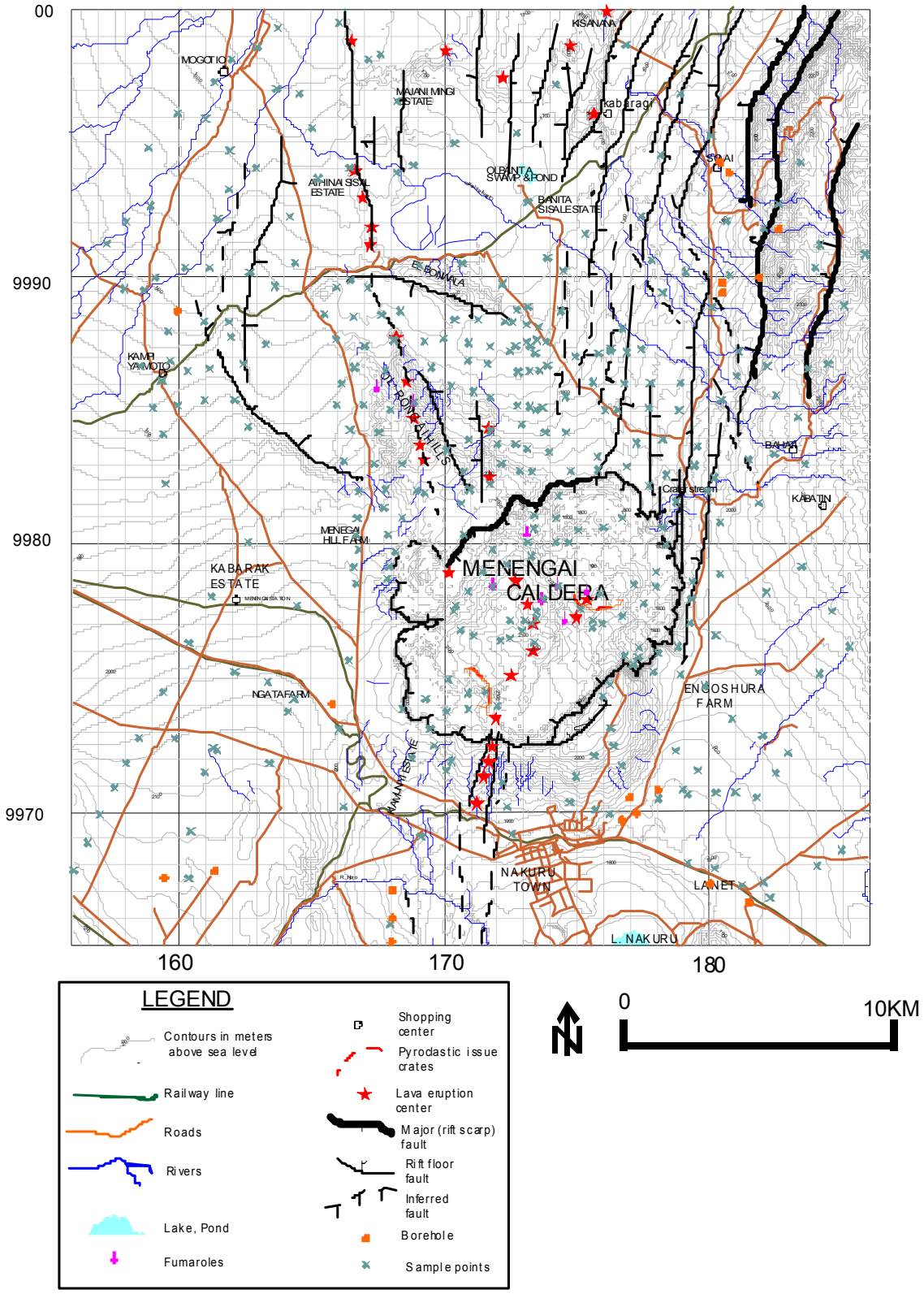

FIGURE 2: Soil gas survey sample points in Menengai Prospect

4. RESULTS

4.1 Fumarole gas analysis

The results of the chemical analysis of the fumarole gases collected are given in Tables 1, 2, 3 and 4. Only two samples gave complete gas analysis results and were the ones used for interpretation.

TABLE 1: Fumarole gas concentration in mmol/mol steam

Fumarole No.	Location	Sample Date	Temp °C	CO_2 mmol/ mol	H_2S mmol/ mol	H_2 mmol/ mol	CH_4 mmol/ mol	N_2 mmol/ mol	O_2 mmol/ mol
MF-1	E1724 N99759	29.1.04	60	0.509	0.1000	0.3	-	0.0354	0.013
MF-2	E1753 N9977	6.2.04	91.2	64.62	0.0076	0.0	0.006	0.0845	0.025

TABLE 2: Fumarole gas concentrations in mmol/Kg steam

Fumarole No.	CO_2 mmol/Kg	H_2S mmol/Kg	H_2 mmol/Kg	CH_4 mmol/Kg	N_2 mmol/Kg	O_2 mmol/Kg
MF-1	28.28	0.10	0.3	-	1.97	0.722
MF-2	3590.00	0.42	0.0	0.34	4.69	1.390

TABLE 3: Fumarole gas ratios

Fumarole No.	CO_2/H_2S	CO_2/H_2	H_2/H_2S	H_2/CO_2	CO_2/N_2
MF-1	282.8	94.25	3.0	0.011	14.4
MF-2	8547.6	-	-	-	764.8

TABLE 4**:** Fumarole gas geothermometry temperatures

Fumarole No.	TCO_2/H_2 °C	TH_2 °C	TH_2S °C	TCO_2 °C
MF-1	285.3	266.2	251.2	298.5
MF-2	-	-	265.5	371.6

4.2 Fumarole steam condensates

The chemical constituents analysed in the steam condensates are those which can be considered to be volatile enough to partition into the steam phase upon phase separation in a boiling system as is expected in an aquifer producing steam. Such elements include the soluble gaseous compounds such as CO_2, H_2S, F^-, and B, which are present in the geothermal steam. In addition, the concentration of other non-volatile elements like Cl^- and SO_4^{-2} was determined. The pH, TDS and the electrical conductivity were also measured in the steam condensate samples. The results are given in Table 5

4.3 Carbon dioxide and radon radioactivity in soil gas

The concentration of CO_2 in the soil gas in the surveyed area is given as a percentage of the total gas in the soil. It is possible that other acidic gases are likely to be absorbed together with CO_2 by KOH but their concentrations is out weighed by that of CO_2 assuming a magmatic source for the CO_2. CO_2 is considered to constitute over 90% of the geothermal gases. The results of the radon emanations were recorded in counts per minute (cpm) for both Rn-222 and Rn-220 and plotted in Figure 3.

TABLE 5: Fumarole steam condensate composition

Fumarole No.	Temp °C	pH at 20°C	CO_2 ppm	H_2S ppm	Cl^- ppm	SO_4^{-2} ppm	B ppm	F^- ppm	TDS ppm	Cond
MF-1	60	6.0	33	0.17	19.5	3.45	0.17	0.19	11	20
MF-2	94	6.0	38.5	0.176	24.14	5.1	0.07	0.96	20	50
MF-3	77	7.54	88	0.034	31.4	6.7	0.12	0.13	6	10
MF-4	81.2	5.8	143	0.17	15.62	7	0.14	< 0.1	4.0	10
MF-5	88.3	6.69	77	0.17	15.97	5.43	0.05	0.214	6	10
MF-6	84.6	6.7	33	0.74	16.33	6.74	0.2	< 0.1	5.6	10
MF-7	73.5	6.9	88	0.07	33	29	0.38	0.264	12	25
MF-8	90.1	6.9	220	0.034	34.1	8.6	0.14	1.64	8	15

Cond = conductivity given in µSM

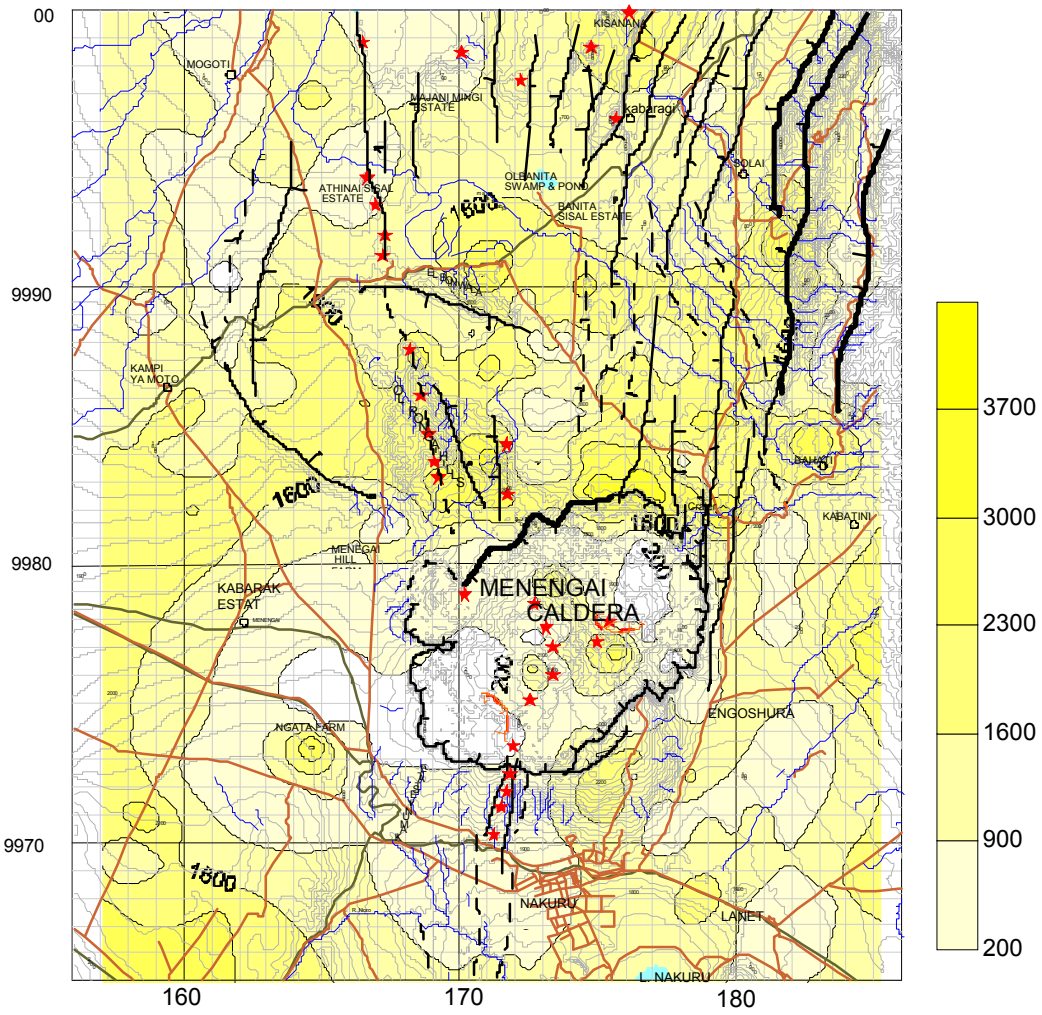

FIGURE 3: Radon radioactivity distribution in the Menengai prospect area

4.4 Carbon dioxide and radon radioactivity in fumarole steam

CO_2 and Rn-222 radioactivity were measured using the dry non-condensable fraction of the fumarole steam. The results are given in Table 6.

4.5 Borehole water

There are many water boreholes drilled in the area especially to the eastern part. All the boreholes were drilled for domestic water supply either for communities or for individual homesteads. Water samples were collected for chemical analysis and the results are given in Table 4.7. Majority of the boreholes in the western sector discharge water with elevated temperatures (above 30°C) while the ones in the south-eastern and southern parts discharge cold water.

TABLE 6: Rn-222 radioactivity and CO_2 concentration in fumarole steam

Fumarole No.	Location	Elevation (m)	CO_2 (%) vol.	Temp °C	Rn-222 (cpm)	Rn/CO2 ratio
MF-1	E 172400 N9975900	2160	15.1	60.0	1650	109.3
MF-2	E 175324 N 9977356	1992	25.6	94.0	12194	476.4
MF-3	E 171868 N 9977563	2081	16.7	77.1	2200	131.7
MF-4	E 169080 N 9984679	2016	48.2	81.2	3700	76.76
MF-5	E 167712 N 9985324	1896	43.8	86.1	2890	66.0
MF-6	E 173208 N 9979555	1908	32.6	84.6	16848	516.8
MF-7	E 173682 N 9977020	2106	18.3	73.5	1600	87.4
MF-8	E 174485 N 9976115	2098	24.6	90.1	1580	64.2

5. DISCUSSION

The area under consideration has very few fumaroles, most of which, occur within the Menengai caldera. However, a few weak fumaroles occur outside of the caldera in the north-western part of the prospect (Figure 1). The greater portion of the area shows little or no manifestations at all. This therefore, presents a problem in investigating geochemical indicators at this preliminary survey stage before thermal waters are obtained from deep wells.

It is against this background that the geochemical survey conducted in this area considered three sources of geochemical information to be able to understand the chemical and physical characteristics of the geothermal reservoir below Menengai caldera and surrounding areas. The available information is therefore derived from the chemistry of the fumarole gases (where applicable) and fumarole steam condensates; borehole water, and from soil air composition, particularly the concentration of radon radioactivity and carbon dioxide emission.

5.1 CO_2 distribution in the soil gas

High CO_2 values (>2.5%) are found at a narrow belt running in a NW-SE trend between grid lines Northings 9982000 to Northings 9910000 and Eastings 175000 to Eastings 184000 and also between Northings 9990000 and Eastings 158000 to Eastings 165000 (Figure 3). Other areas exhibit low values of <1%. The distribution of CO_2 in the soil gas is also controlled by the competence of the formation and other local sources of CO_2. Dealing with CO_2 anomalies especially in the Rift Valley should be treated with caution due to availability of localized sources of this gas as suggested by Darling et al. (1995).

TABLE 7: Borehole water analytical results

Date sampled	Location	Temp °C	pH at 20°C	CO_2	H_2S	SiO_2	SO_4	Cl	Na	Ca	K	Mg	F	Cond	TDS
12/3/04	E166346 N9973021	48.2	7.82	254.1	1.02	40.8	143	34	141	4.5	24	0.3	18	743	357
12/3/04	E168511 N9964610	39.2	7.7	147.1	0.13	30.7	14.2	18	44.3	0.8	20	0.4	4	440	215
12/3/04	E168670 N9965090	35.1	9.1	243.0	0.34	37.4	18.9	20	143	2.3	9	0.1	11	725	357
12/3/04	E1685890 N9963712	39.2	7.7	186.0	0.14	80.4	9.13	28	52	14	20	3	4	487	212
12/3/04	E168320 N9965694	37.5	8.7	116.4	0.41	16.8	14.3	17	48.5	7.2	17	1.8	5	415	192
19/3/04	E162001 N9966512	21.7	6.5	111.7	2.72	42.7	10.3	16	42.7	4.4	11	0.8	3	302	113
19/3/04	E160486 N9966214	21.7	6.7	206.0	2.0	36.4	7.3	16	30.1	5.3	11	0.8	3	455	190
5/2/04	E179955 N9966236	29.0	7.3	181.5	0.17	80.0	10.7	34	75.5	20	19	1.9	2	460	305
5/2/04	E180656 N9965524	27.0	8.2	176.0	0.3	55.0	29.4	34	17.4	16	9	1.6	3	30	16
3/2/04	E180163 N9989003	30.0	7.5	214.0	0.18	48.0	7.9	16	10.7	4.9	2	0.8	6	410	272
3/2/04	E181474 N9989679	40.0	8.2	193.0	0.1	75.5	9.1	35	46	2.3	4	0.4	8	480	359
3/2/04	E1822160 N9991512	20.0	6.8	55.0	0.18	116	4.2	17	45.8	10	18	1.8	1	150	105
3/2/04	E180350 N9993677	23.0	6.7	165.0	0.2	55.0	8.4	30	47.1	8.3	7	1.4	1	280	186
3/2/04	E180147 N9994015	26.0	8.1	24.5	0.18	48.0	21.9	62	100	16	4	0.5	7	810	532
3/2/04	E180147 N9994015	26.0	6.5	160.0	0.18	60.0	5.21	31	45.7	14	9	2.2	1	340	229
2/2/04	E176626 N9969390	35.3	8.5	270.0	0.27	30.2	14.0	33	64.4	5.8	6	0.3	7	640	422
2/2/04	E177434 N9969735	29.5	7.8	236.0	0.35	28.0	10.7	15	25.2	6	5	0.5	5	520	342
2/2/04	E180988 N9970889	29.0	7.1	176.0	0.88	30.0	6.0	19	59.3	12	13	1.1	2	360	234
2/2/04	E180988 N9970889	29.0	6.9	171.0	0.9	93.9	5.1	24	50.9	13	12	1.6	2		

5.2 Radon concentration in soil gas

From the results of the absolute values of Rn-222, the northern and north-western parts of the surveyed area show the highest concentrations (Figure 4). High radon values could be indicative of enhanced permeability where the Rn-222 passes to the surface rather fast before disintegrating into daughter products. However, the release of radon is dependent on other factors, which include the degree of rock fracture and the ability of the ground water to circulate through such rocks. Percolating ground water removes radon from fractured porous rocks by transport rather than diffusion mechanism. From the properties of radon described above, under high temperature conditions as would be expected in a geothermal reservoir, the radon will partition in the steam phase and be transported to higher elevations through permeable zones. There are however other alpha emitting isotopes but their half-lives are very short to give interference to Rn-222 like PO-214, which has a half-life of 0.000158 seconds.

Tanner (1975) calculated that the maximum mobility of Rn-222 in soil would be about 42 m. The alpha particle (α) which is emitted by Rn-222 is a Helium nuclei (^4He) which has a mobility of <50 mm in air and only a few microns in rocks. It means therefore that for an alpha particle to be detected by the radon emanometer, the Rn atom must be within about 50 mm of the detector. If the Rn-222 detected in the high concentration areas mentioned above is coming from a deep geothermal reservoir, then the areas to the north and north-western parts (Figure 4) would be areas of high permeability and therefore good prospects for further investigations. Other areas especially the south and south-eastern have relatively low absolute Rn-222 values averaging below 200 cpm and are considered of little interest. Most of the surveyed area has average Rn-222 values ranging from 2000-3700 cpm. The anomalous values may be taken to be those above the threshold reading (upper limit of the background value). Taking 1000 cpm to be the background value for Rn-222 in this area and the threshold to be twice the background, then Rn-222 values exceeding 2000 cpm are considered anomalous.

5.3 Radon-222/CO_2 ratio in the soil gas

The source of Rn-222 can be either magmatic where the uranium accumulates at the late stages of differentiation or from any other source containing radium the immediate precursor of Rn-222. When Ra-226 is present in the hydrothermal system, it indicates that the hot water percolates through the host rock thereby dissolving Rn-222, which is produced from alpha decay of the Ra-226. Upon heating up of the water the Rn-222 partitions into the steam phase and is transported to the surface through permeable zones. Due to its short half-life, Rn-222 has to travel for long distances within a relatively short period to be detected on the surface. Similarly, CO_2 have to travel through a relatively permeable zone to avoid dispersion and subsequent dilution for it to be detected in high concentrations. CO_2 may also originate from other sources like organic sources, which are likely to give false impressions of a geothermal source. The ratio of the two gases would be a good indicator of the magmatic source of the gases since the ratio is not expected to change if they are from the same source. High values of these ratios are found towards the north and north-western parts of the caldera wall (Figure 4). The values are highest between grid Northings 9982000-9985000 and grid Eastings 165000–180000. These areas apparently coincide with high CO_2 and high Rn-222 absolute values. The north-western parts of surveyed area (around Kampi Ya Moto), which shows extremely high absolute values of both Rn-222 and CO_2 has the lowest value of this ratio. This would imply presence of an external source of the CO_2 rather than from the geothermal activity. Other possible sources of CO_2 in this area could be from organic life since it is an inhabited area and considering the depth of sampling this could be a possibility. A mantle source of CO_2 as suggested by Darling et al. (1995) is another possibility due to intense faulting in the area. If a mantle source is inferred due to intense faulting, then the faults should be deep seated.

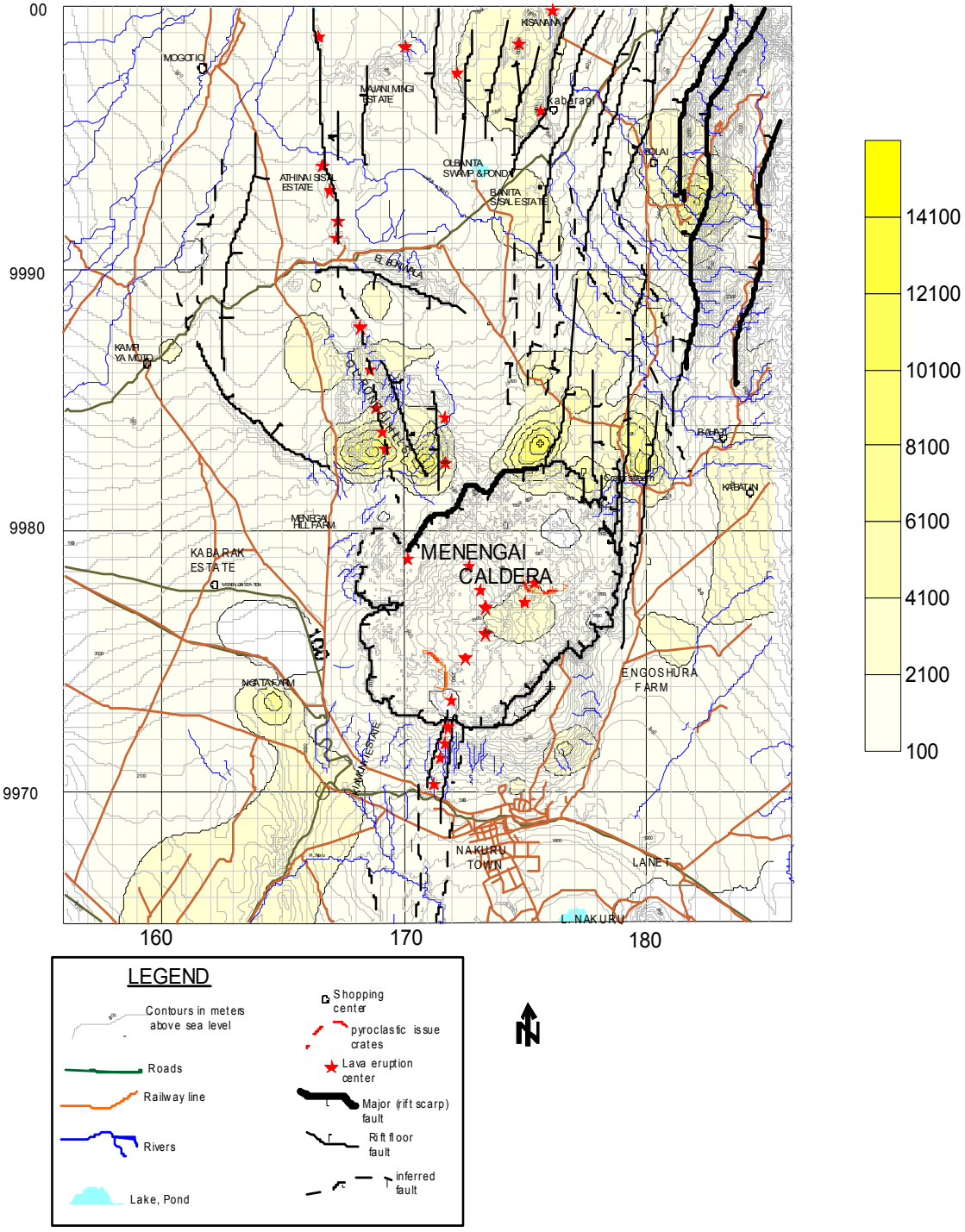

FIGURE 4: Radon/carbon dioxide ratio distribution in soil gas in the Menengai prospect

5.4 Radon-222/CO_2 in fumarole steam

The results of the fumarole steam Rn-222 and CO_2 are from the non-condensable fraction of the fumarole sample are given in Table 6. It is also possible for other gases present in the steam to be present in the non-condensable fraction of the steam (e.g. H_2S) but their concentrations are very low compared to those of CO_2. By assuming a geothermal origin of both Rn-222 and CO_2 in the fumarole steam, the ratio Rn-222/CO_2 would be a good indicator of fumaroles associated with potential

geothermal reservoirs and zones of good permeabilities, where both gases flow relatively fast. Among the sampled fumaroles, fumarole MF-6 located inside the caldera at the north-western parts, recorded the highest reading of 517 followed by fumarole MF-2 also located in the central part of the caldera, with recorded ratio of 476.4. Fumarole MF-8 also located inside the caldera but to the south of both fumaroles, MF-2 an MF-6 gave the lowest ratio value of 64.2. The fumaroles inside the caldera gave Rn-222 values ranging from 1,580-16,848 cpm.

The relatively high values recorded for fumaroles MF-2 and MF-6 indicate the two fumaroles are possibly tapping from a deep magmatic source. Though the gas chemistries of the steam did not have any H_2 for these fumaroles, only MF-2 recorded H_2S values of 0.42 mmol/kg steam. The low gas concentration of the steam from this fumarole could be due to dispersion and dilution of the gases as they migrate to the surface due to the cover of post-caldera volcanic products. These two fumaroles are located inside the outer caldera and coincide with the area, which recorded some of the highest values for Rn-222, CO_2 and Rn-222/CO_2. This could be a good indication of a potentially attractive site for further investigation.

5.5 Fumarole gas concentrations

The fumarole steam was analysed for the major gases associated with geothermal activity (CO_2, H_2S, H_2, CH_4 and N_2) and the results indicate low values for the reactive gases for most of the fumaroles sampled. Most of these fumaroles were issuing at extremely low pressures and it was quite difficult to obtain condensate samples from the fumaroles. From the analytical results obtained, such weak fumaroles have compositions indicating high air/steam ratios. Such high ratios are indicative of shallow surface waters being locally heated and the bulk composition of the gases is composed of atmospheric air.

The gas contents of fluids present in areas of high permeability and close to a hot geothermal fluid upflow are expected to be high especially with regards to the reactive gases like CO_2, H_2S and H_2. When the fluid travels for long distances there is a tendency for it to be depleted of these gases through possible reactions between the gases and the minerals forming the reservoir rocks. On the other hand, the concentration of N_2 in the fumarole steam could be an indicator of admixture with gas originating from the atmosphere. This could be taken to imply mixing of shallow ground waters with deep geothermal fluids. The N_2 gas is considered largely to be derived from air and then introduced into the geothermal system. There are possibilities of N_2 accumulating in the rocks from organic life. In terms of solubility of the common geothermal gases in water the following order prevails:

$$H_2S > CO_2 > N_2 > H_2 \qquad \text{(Giggenbach, 1980)}$$

The gas concentrations in the discharged steam are controlled by temperature dependent fluid-mineral equilibrium in the reservoir or at least in the aquifer where the steam is being formed. The H_2 gas being the most reactive and least soluble in water is a good indicator of higher underground temperatures. The H_2 content of the deep geothermal water below the zone of flashing is possibly controlled by the temperature dependent equilibrium reaction with water, sulphates dissolved from the reservoir rocks and sulphides through a possible reaction shown in equation 1 below.

$$2H^+ + 4H_2 + SO_4 \longrightarrow H_2O + H_2S \qquad (1)$$

High H_2 concentrations in the discharged steam would indicate proximity to a high temperature resource. There is only one sample (MF-1) with measurable quantities of H_2 with a value of 0.3 mmol/kg steam. This fumarole is located inside the caldera.

In the absence of H_2 and H_2S, CH_4 is considered to be the best indicator of reservoir characteristic assuming no biogenic source of the gas. Again only one fumarole (MF-1) had measurable concentration of CH_4 with a value of 0.34 mmol/kg steam.

Gas ratios from the fumarole steam have been calculated and presented in Table 3.3. From the gas solubility mentioned above, it is observed that in a boiling system the least water-soluble gases are released faster but the more soluble ones are released slowly. From this argument, close to the upflow of the hot geothermal fluids the ratio of a less soluble to that of a more soluble gas should be high and should decrease in the direction away from the upflow. There are only two gas samples whose data can be used in a comprehensive gas interpretation and are both located in the caldera. Fumarole MF-1 gave a CO_2/H_2S ratio value of 282.8 while fumarole MF-2 gave a value of 8547.6. This would imply that fumarole MF-2 is located closer to a hot geothermal source possibly an upflow and the fluids may be considered to be outflowing towards MF-1.

Presence of some hydrothermal minerals like epidote may reduce the concentration of H_2S gas where the H_2S would react with the mineral to precipitate prehnite at deep levels through a possible reaction shown in equation 2 below.

$$8\ \text{epidote}+H_2S+14H^+ \longrightarrow 8\ \text{prehnite}+Fe^{+2}+SO_4^{-2}+4H_2O \quad (2)$$

This would also affect the gas ratios involving H_2S since the concentration of H_2S in the fumarole steam is not representative of the reservoir H_2S. Darling et al. (1995) suggested a mantle source of CO_2 under the Rift Valley, which would be expected to enter the geothermal system anywhere within the rift. If this would be the case, then the concentration of CO_2 would not be expected to decline away from the source of the geothermal fluids while other gases would.

5.6 Geothermometry

Prediction of sub-surface temperatures in this area is compounded by the lack of any source of geothermal water issuing to the surface. There are many drilled water boreholes at shallow depth, which are relatively cold. A few boreholes situated to the north and north-western parts have temperatures above 30°C. These cannot be convincingly used for subsurface temperature calculations due to lack of sufficient water-rock interactions and thus have not attained equilibrium. This leaves us with only the gas based temperature indicators to rely on. Several gas-based geothermometers have been developed with the most commonly used being the CO_2, H_2 and H_2S. These are considered the best to use since the reactions controlling their concentrations seem to approach equilibrium over a large temperature range.

The temperature inferences made here are based on only two fumarole gas samples and therefore the conclusions arrived at are tentative.

The geothermometry functions used in this report are from Arnorsson and Gunnlaugsson (1985) based on the concentration of CO_2, H_2S and H_2. The following equations were used to calculate the temperatures:

$$TH_2S°C = 246.7 + 44.81*mH_2S \quad (3)$$

where TH_2S is the temperature using H_2S gas and mH_2S is the concentration of H_2S in mmol/Kg steam

$$TCO_2/H_2°C = 341.7 - 28.57*\log(CO_2/H_2 \quad (4)$$

where: TCO_2/H_2 is the temperature using the ratio CO_2/H_2 where the concentrations are in Mmol/Kg of steam.

$$TH_2 = 277.2 + 20.99\text{Log}(H_2) \quad (5)$$

$$TCO_2 = -44.1+269.25\text{Log } mCO_2 - 76.88(\text{Log}mCO_2)^2+9.52(\text{Log}mCO_2)^3 \quad (6)$$

Only two samples from MF-1 and MF-2 were conclusively used in geothermometry. All the other fumaroles had no complete chemical data with most of them having no H_2 and H_2S gas content in their

steam discharge. This was largely as a result of the very high air to steam ratio in these discharges. The temperatures calculated for MF-1 ranged from 251.2-298.5°C calculated for T_{H2S} and T_{CO2} respectively while fumarole MF-2 had values ranging from 265.5–371.6°C calculated for T_{H2S} and T_{CO2} respectively (Table 4). Fumarole MF-1 gave a TH_2 temperature of 266.2°C. The temperatures calculated using CO_2 geothermometer gave relatively high values for both fumaroles. The relatively high value given by this geothermometer may be due to probable injection of CO_2 probably from recent volcanic activity in the caldera. CO_2 may also originate in the reservoir from equilibration with a mineral buffer.

From the temperature estimation using the gas geothermometers, it is clear that the reservoir temperatures beneath Menengai caldera are over 250°C taking into consideration that both H_2 and H_2S gases are representative.

5.7 Fumarole steam condensate chemistry

Fumarole condensate samples were analysed for pH, TDS, CO_2, H_2S, Cl^-, F^-, B, SO_4^{-2} and the electrical conductivity (Table 5). All the condensates gave pH values ranging between 5.8 and 7.5 measured at 20°C. Low pH values imply the fluids contain high concentrations of acid gases, which form the acidic condensed water. Most of the acidic emanations are mainly magmatic with large amounts of volatile components such as H_2O, HCl, SO_2, H_2S, CO_2 and H_2. However, chemical properties of magmatic emanations collected on the surface are expected to be different from those under the ground on account of severe distillation on the surface caused by depression of pressures and temperatures.

Volatile chemical constituents dissolved in the deep water would be transported to the surface with steam from greater depth through vaporization. High volatility elements like F^-, B, NH_3, arsenic (As) and mercury (Hg) would therefore be expected to dominate in the steam composition in addition to the geothermal related gaseous elements (CO_2, H_2S and H_2). High concentration of volatiles in a steam condensate would be proportional to temperatures of the steam source.

All the condensate samples gave F^- values ranging from 0.1-1.64 ppm (Table 5) while the B values ranged from 0.05-0.38 ppm for fumaroles MF-5 and MF-7 respectively. The relatively high F^- content in the steam condensate may indicate deep crustal water circulation while at the same time the relatively high B values in the condensate may indicate high formation temperatures. Boron is considered a mobile component since it does not take part in rock forming reactions and its concentration in the geothermal fluids is controlled by the leaching rate from the reservoir rocks. At high temperatures (>250°C) boron is expected to partition into the steam phase (Arnorsson, pers. comm.) and if boiling is occurring in the reservoir, then the temperatures should be more than 250°C. The difference in boron concentration of different fumarole steam condensates would only be due to the compositions of the source rocks.

The Cl^- content of the condensate samples from fumaroles MF-4 and MF-8 ranged from 15.6–34.1 ppm respectively. Very high Cl^- values in a steam condensate would represent a water dominated system while extremely low values would be expected to originate from a vapour dominated system since chlorides are not known to partition into steam phase at any temperatures.
The total dissolved solids measured for the condensates range from 4-20 ppm measured for fumarole MF-4 and MF-2 respectively. High TDS values may result from:

i. Deep circulation of the geothermal fluids enhancing water-rock interaction,
ii. Long residence time in the reservoir allowing for water to dissolve more solutes and
iii. High ambient temperatures, which is common in the Kenyan rift.

From the measured TDS values, fumarole MF-2 gave the highest reading suggesting possibly deep circulating fluids or long residence time of the waters in the reservoir.

The electrical conductance of the condensates was measured and the values range from 10–50 $m\Omega cm^{-1}$ for fumarole MF-3, MF-4, MF-5, MF-6 and MF-2 respectively. The highest conductivity readings coincide with the highest TDS readings. These values are slightly lower than those measured in the Greater Olkaria geothermal field. In Olkaria field fumarole steam condensates have TDS ranging from 30–264 ppm but with an average of 60–100 ppm. The lowest value of 10 ppm recorded for fumaroles MF-3, MF-4, MF-5 and MF-6 suggest a dilute fluid around this area which could result from modification of the deep original geothermal fluids through possible mixing reactions (could result from dilution processes). High values are recorded at fumarole MF-2 and this could probably suggest deep geothermal fluids discharge around this area.

H_2S and CO_2 are some of the primary gases associated with volcanic gaseous emissions and are therefore usually found in geothermal reservoir fluids. The concentration of H_2S is mainly affected by oxidation reactions while CO_2 is largely affected by biogenic inputs. When an upflowing deep geothermal fluid mixes with shallow ground waters or steam condensates, oxidation of H_2S occurs and this lowers the content of this gas in the analysed portion (condensate or gas). The dissolved H_2S gas content of the condensates range from 0.034–0.74 ppm measured in fumarole MF-3 and MF-6 respectively. These values are again lower than those from the Olkaria Domes field where the measured H_2S levels range from 0.1–1.46 ppm. The very low concentrations of this gas suggest a large influence of shallow circulation ground water and or condensates. The CO_2 measured in the steam condensates ranged from 33–220 ppm for fumarole MF-1 and MF-8 respectively. These values are generally higher than the values recorded in Olkaria, which has values ranging from 50-60 ppm. Such high values of CO_2 could imply good permeability where the dissolved gas reaches the surface relatively fast avoiding any reactions, which may affect its concentration. The level of CO_2 in the condensate may be enhanced in a field where calcite ($CaCO_3$) is found, at relatively shallow levels where the steam dissolves the CO_2 as it ascends to the surface. The concentration of CO_2 is mainly controlled by the reactions shown in equations 3.7 and 3.8 below.

$$Ca^{+2} + 2HCO_3^- = CaCO_3 + CO_2 + H_2O \quad (7)$$

and

$$HCO_3^- + H^+ = CO_2(aq) + H_2O \quad (8)$$

5.8 Borehole water chemistry

Most of the water sampled from boreholes to the south and eastern parts of the area discharge cold-water with little dissolved solids. Some of the water from some boreholes is suitable for domestic use. However, some boreholes to the western part discharge warm water with some recording up to 40°C. Temperatures of about 80°C have been calculated for some borehole water samples using the silica geothermometer assuming a boiling spring model as is described in the speciation programme WATCH by Arnorson et al. (1990) and Bjarnason (1994). However, due to the shallow depth where the water is discharging, the data needs a lot of caution when making subsurface inferences.

5.9 Proposed exploration well sites

To be able to pinpoint areas of high potential in terms of geothermal resource development, several factors have been considered bearing in mind the geochemical exploration methods employed. Rn-222 radioactivity have been used in this survey to infer possible zones of high permeabilities and also areas of geothermal potential by assuming that the Rn-222 gas was being carried in the geothermal steam. Similarly, the CO_2 survey in the soil gas was conducted with the same assumption. This was in addition to the study of the few available fumarole samples in this prospect.

It would be inaccurate to use the concentration of a single component to make a decision to commit a field for exploratory drilling. Areas with coinciding anomalies of Rn-222, CO_2 and Rn-222/CO_2 ratios, supported by fumarole steam chemistry data are here considered sites for exploration drilling.

6. CONCLUSIONS

1. There exists a geothermal resource in this area possibly underneath the Menengai caldera and immediately to the north and northeast with reservoir temperatures >250°C as deduced from gas geothermometry.

2. The high values of carbon dioxide measured in the north and north-western parts of the caldera floor suggest that the area has high geothermal potential.

3. From chemical data obtained during this study, the area in the south and south-eastern portions of the caldera floor is not attractive.

7. RECOMMENDATIONS

It is recommended that three deep exploratory wells be drilled in Menengai as indicated in the proposed drill sites (Figure 5).

(a) MW-1: The proposed drill site coordinates 173000 E and 9978000 N is proposed as a priority site for an exploration well for the following reasons:

(i) The area gave anomalously high Rn-222 counts for both the soil gas and in the fumarole steam, which would infer good permeability and possibly a high temperature geothermal reservoir.
(ii) The high Rn-222 anomaly coincides with high CO_2 values in this area.
(iii) The Rn-222/CO_2 ratio is also high implying that the CO_2 emanating from this zone could be of magmatic origin .
(iv) Gas chemistry indicates the caldera floor to be the hottest with temperatures of over 250°C.

(b) Well MW-2: A second drill site has been proposed at approximate coordinates 168000 E and 9984000 N (Figure 5). The site is located outside the caldera floor to the north-western part near Ol'rongai hills. The site would be useful in testing the occurrence of a geothermal system as indicated by the high radon and CO_2 values.

(c) Well MW-3: A third drill site has been proposed at approximately 175500 E and 9983000 N (Figure 6). This area is in the north immediately adjacent to the caldera wall. The site exhibits high values of both radon and CO_2.

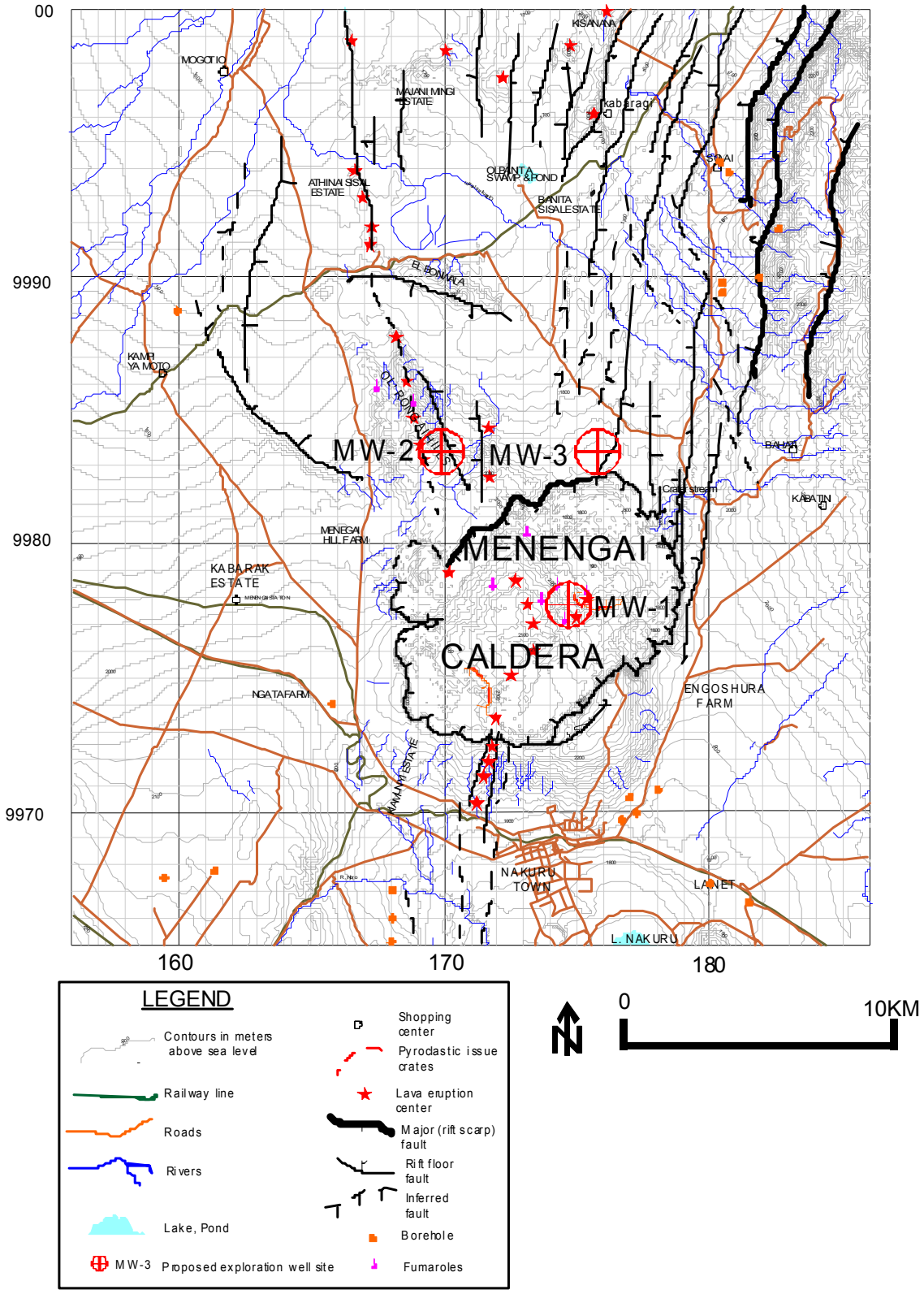

FIGURE 5: Map of Menengai prospect area showing the locations of the proposed drill sites based on geochemical studies

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ENVIRONMENTAL IMPACT ASSESSMENT: GENERAL PROCEDURES

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ABSTRACT

Environmental Impact Assessment (EIA) can broadly be defined as a systematic process that examines environmental and social consequences of development actions, in advance. The legal, methodological and procedural foundations of EIA were established in 1970 by enactment of the National Environmental Policy Act (NEPA) in the United States of America (USA). At the international level, lending banks and bilateral aid agencies have EIA guidelines that apply to projects financing and recipient countries. Most developing countries have also embraced and formalized EIA process through legislation and policies. This paper highlights the evolution to the current status, legal framework, concepts, processes and principles of EIA and associated studies for proposed developments, including geothermal projects.

1. INTRODUCTION

1.1 Origin of EIA

Before the First World War, rapid industrialization and urbanization in western countries was causing rapid degradation and loss of natural resources. This continued to the period after the Second World War giving rise to concerns for pollution, quality of life and environmental stress. In early 60s, investors realized that the projects they were undertaking were affecting the environment, resources, raw materials and people. As a result of this, pressure groups formed with the aim of getting a tool that could be used to safeguard the environment in any development. The USA government decided to respond to these emerging issues and established a National Environmental Policy Act in 1970 to consider its goal in terms of environmental protection. The USA therefore became the first country to enact legislation on EIA. This was the first time that EIA became the official tool to be used to protect the environment. The United Nations Conference on the Environment in Stockholm in 1972 and subsequent conventions formalized EIA. At present, all developed countries have environmental laws whereas most of the developing countries are still in the process of adopting it (Lee, 1995). Multilateral and bilateral lenders included EIA requirements in their project eligibility criteria (OECD, 1996).

1.2 EIA in developing countries

Until recently, EIA as a new concept was not readily understood and accepted as a tool in developing countries. Developers resisted and argued that it was anti-development because laws and policies

supporting it dictated that developments causing negative impacts should be discontinued. In a nutshell, EIA was considered just another bureaucratic stumbling block in the path of development. Secondly, it was conceived as a sinister means by which industrialized nations intend to keep developing countries from breaking the vicious cycle of poverty.

Thirdly, the experts in the developing countries were foreigners who were viewed as agents of colonization. However, the need for EIA has become increasingly important and is now a statutory requirement in many developing countries.

Historically, the choice of new projects was primarily based on one criterion: economic viability. Today, a second and a third choice criteria, environmental and social impact, have become a strong yardstick, hence the triple bottom-line approach (economic, environmental and social aspects) to project viability (Modak & Biswas, 1999).

2. POLICY, LEGAL AND INSTITUTIONAL FRAMEWORK RELATING TO EIA

EIA process takes place within the legal and/or policy and institutional frameworks established by individual countries and international agencies. EIA guidelines and procedure can contribute to successful implementation of projects if these frameworks are adhered to.

2.1 EIA in the context of international environmental law

Key Multilateral Environmental Agreements (MEAs) have influenced review and improvements in EIA legal, policy and institutional arrangements. The key agreements are discussed below.

a) Convention on Environmental Impact Assessment in a Trans-boundary Context (Espoo, 1991)

This was the first multi-lateral EIA treaty. It looks at EIA in a trans-boundary context and entered into force in 1997. The Espoo Convention set out the obligations of parties to assess the environmental impact of certain activities at an early stage of planning. It also laid down the general obligation of states to notify and consult each other on all major projects under consideration that are likely to have significant adverse environmental impact across borders.

Apart from stipulating responsibility of signatory countries with regard to project proposals that have trans-boundary impacts, it described the principles, provisions, procedures to be followed and list of activities, contents of documentation and criteria of significance that apply.

b) Rio Declaration (1992)

Principle 17 of Rio Declaration on Environment and Development of 1992, calls for use of EIA as a national decision making instrument for assessing whether proposed activities are likely to have significant adverse impacts on the environment. It also emphasized the role of competent national authority in the decision-making process. Principle 15 of this declaration that is relevant to EIA practice is the application of the 'Precautionary Principle'.

Agenda 21, which was also as a result of this convention, proposed that governments should:

- *"Promote the development of appropriate methodologies for making integrated energy, environment and economic policy decisions for sustainable development, inter alia, through environmental impact assessment (9.12(b))*
- *Develop, improve and apply environmental impacts assessment, to foster sustainable industrial development (9.18)*

- *Carry out investment analysis and feasibility studies including environmental assessments for establishing forest based processing enterprises.*
- *Introduce appropriate EIA procedures for proposed projects likely to have significant impacts upon biological diversity, providing for suitable information to be made widely available and for public participation, where appropriate, and encourage the assessment of impacts of relevant policies and programs on biological diversity (15.5(k)"*(UNICED 1992).

Agenda 21 set the framework within which countries could establish their national environmental laws.

c) **UN Convention on Climate Change and Biological Diversity (1992)** cited EIA as an implementing mechanism of these conventions (article 4 and 14, respectively).
d) **Doha Ministerial Declaration** encourages countries to share expertise and experience with members wishing to perform environmental reviews at the national level (November, 2001).
e) **UNECE (Aarhus) Convention** on Access to Information, Public Participation in Decision Making and Access to Justice in Environmental Matters (1998) covers the decisions at the level of projects and plans, programs and policies and by extension, applies to EIA and SEA.
f) United Nations Conference on the Environment in Stockholm 1972.

2.2 Multilateral and bilateral financial institutions environmental and social safeguards

Development Financing Institutions (DFIs) like African Development Bank (AfDB), Asian Development Bank (ADB), European Bank for Reconstruction and Development (EBRD), European Investment Bank (EIB), Japanese Bank for International Cooperation (JBIC), AfD of France, KfW of Germany, World Bank (WB) have environmental and social safeguards to ensure that financing of projects is not only based on the precautionary principle, preventative action rather than curative treatment but sustainable development (WBCSD, 2005). Although their operational policies and requirements vary in certain aspects, the DFIs follow a relatively standard procedure for the preparation and approval of an EIA study report. Loan recipient countries are responsible for the preparation of the EIA report, and this requirement possibly more than any other has influenced the introduction and development of the EIA process in many developing countries. The EIA study should examine project alternatives and identify ways of improving project selection, siting, planning, design and implementation by preventing, minimizing, mitigating and compensating for adverse environmental impacts.

Just like other banks, the World Bank has a criteia for screeing projects as follows:

Category A: If the project is likely to have significant environmental impacts that are sensitive, diverse or unprecedented. These impacts may affect an area broader than the communities benefiting from infrastructure investments.

Category B: If the projects' potential adverse environmental impacts on human populations or environmentally important areas are less adverse than those of Category A projects. These impacts are site-specific; few if any of them are irreversible; and in most cases mitigation measures can be designed more readily than for Category A projects.

Category C: If the project is likely to have minimal or no adverse environmental impacts. Once the project is assessed and determined as Category C, no further action would be required. Some examples of Category C projects include: Education (i.e. capacity-building, etc., not including school construction), Family planning (World Bank 1999) etc.

All projects financed by the DFIs should also comply with the requirements of relevant multilateral environmental agreements (MEA) to which the host country is a party, including the Montreal Protocol on Ozone Depleting Substances (ODA), the UN Framework Convention on Climate Change

(UNFCCC) and the Kyoto Protocol on Greenhouse Gas (GHG) emissions and the Aarhus Convention on Environmental Information disclosure.

All international organizations and bilateral agencies frequently update their procedures and it is important to obtain the current versions from the organization.

2.3 National legislations relating to EIA

National legislations may include a statutory requirement for an EIA to be done in a prescribed manner for specific development activities. Most legislations list projects for which EIA is mandatory. The statutory requirement to carry out an EIA for specific projects will, for example, require registered EIA/ Audit experts to carry out the study, a designated national authority with the help of lead agencies and technical committees to review the EIA reports and approve the proposed projects.

Other national legal requirements that govern utilization and protection of natural resources like water, fisheries, forests, wildlife, public health, etc, must be identified and complied with during an EIA study process.

2.4 Institutional framework

Institutional systems relating to EIA vary from country-to-country reflecting different types of environmental governance. In some countries, either the Ministry of Environment or a designated National Authority or Planning Agency, administers EIA.

Environmental issues also involve many disciplines and many government bodies with general environmental and resource management laws. Data will therefore, have to be collected and collated from a wide range of technical ministries, other government authorities and parastatals, where applicable.

3. PREPARATION OF EIA TERMS OF REFERENCE (TOR)

Terms of Reference (TOR) for EIA sets out what is expected of a practioner or a consultant when carrying out an EIA. TOR can be simple or elaborate but extremely elaborate TOR is usually not recommended. There are no universal formats for Terms of Reference, which will be suitable for every study. However, there are general rules, which should be observed when preparing ToR for the EIA.

- The TOR should commence with a brief description of the project. This should include a map of the area that will be affected either indirectly or directly.
- The TOR indicate the major issues that the consultants or practitioners should focus on, particularly the most serious likely impacts identified during scoping e.g. air emission, waste water discharge etc. The opportunities for enhancing any positive benefits from the project should also be highlighted. This component of TOR is usually submitted to designated authority for scrutiny and approval.
- The TOR should contain explicit references to which safeguard policies may be relevant and which legal requirements should be applied.
- The TOR should give an indication of the team considered necessary for the study and a team leader identified. Depending on the scope of the study this may be multi-disciplinary. However, the team composition should not be rigidly imposed on the consultant.
- If international experts are doing the EIA, it is important to make provisions for local capacity building in the TOR. Apart from enabling in-country expertise to be developed, this will promote more involvement and understanding of the issues raised by the study. As most EIA studies are of relatively short duration, this is probably best achieved through the attachment of project

proponent staff to the consultants during the study or an insistence on the use of local personnel for some of the tasks.

- The expected date of commencement and time limit should be given and consultants program of work must be within the given time limit.
- The budget limit should be given in the TOR. The type of experts, and whether foreign or local, and the duration of their inputs will usually be the deciding cost factors although a large field survey or measurement or modeling program with laboratory analysis could significantly increase costs. Any assistance to be provided by the Client to reduce costs should be clearly stated in the TOR.
- Consultant payments proposal should be made and tied to specific milestones e.g. the consultant will be paid 20% of their fee upon receipt of draft report by client etc.
- Reporting requirements should be clearly stated and should comply with local or international reporting guidelines. The format of EIS must be clear and the number of copies in soft and hard must be stated.
- The TOR should make provision for the consultants to improve the Terms of Reference in order to improve the quality of EIA report.

4. ENVIRONMENTAL IMPACT ASSESSMENT PROCESS

The first phase of an Environmental Impact Assessment (EIA) is called an Initial Environmental Examination (IEE) and the second is Environmental Impact Studies (EIS) or simply detailed EIA.

a) Initial Environmental Examination

The IEE is carried out to determine whether potentially adverse environmental effects are significant or whether mitigation measures can be adopted to reduce or eliminate these adverse effects. The IEE contains a brief statement of key environmental issues, based on readily available information, and is used in the early (pre-feasibility) phase of project planning. The IEE also suggests whether in-depth studies are needed. When an IEE is able to provide a definite solution to environmental problems, an EIA is not necessary. IEE also requires expert advice and technical input from environmental specialists so that potential environmental problems can be clearly defined.

b) Environmental Impact Assessment

EIA is a process used to systematically examine the potential environmental consequences or impacts, both beneficial and adverse, of a proposed development project and to ensure that these effects are taken into account in the project design phase. The EIA is therefore based on predictions. These impacts can include all relevant aspects of the natural, social, economic and human environment. The study therefore requires a multi-disciplinary approach and should be done very early at the feasibility stage of a project. In other words, a project should be assessed for its environmental and social viability.

EIA should therefore be viewed as an integral part of the project planning process. Unlike the environmental audit (EA), which is conducted on on-going and existing operating projects, the EIA is applied to new projects and the expansion aspects of existing projects. The phases of an EIA from screening to follow-ups are illustrated in Figure 1 below:

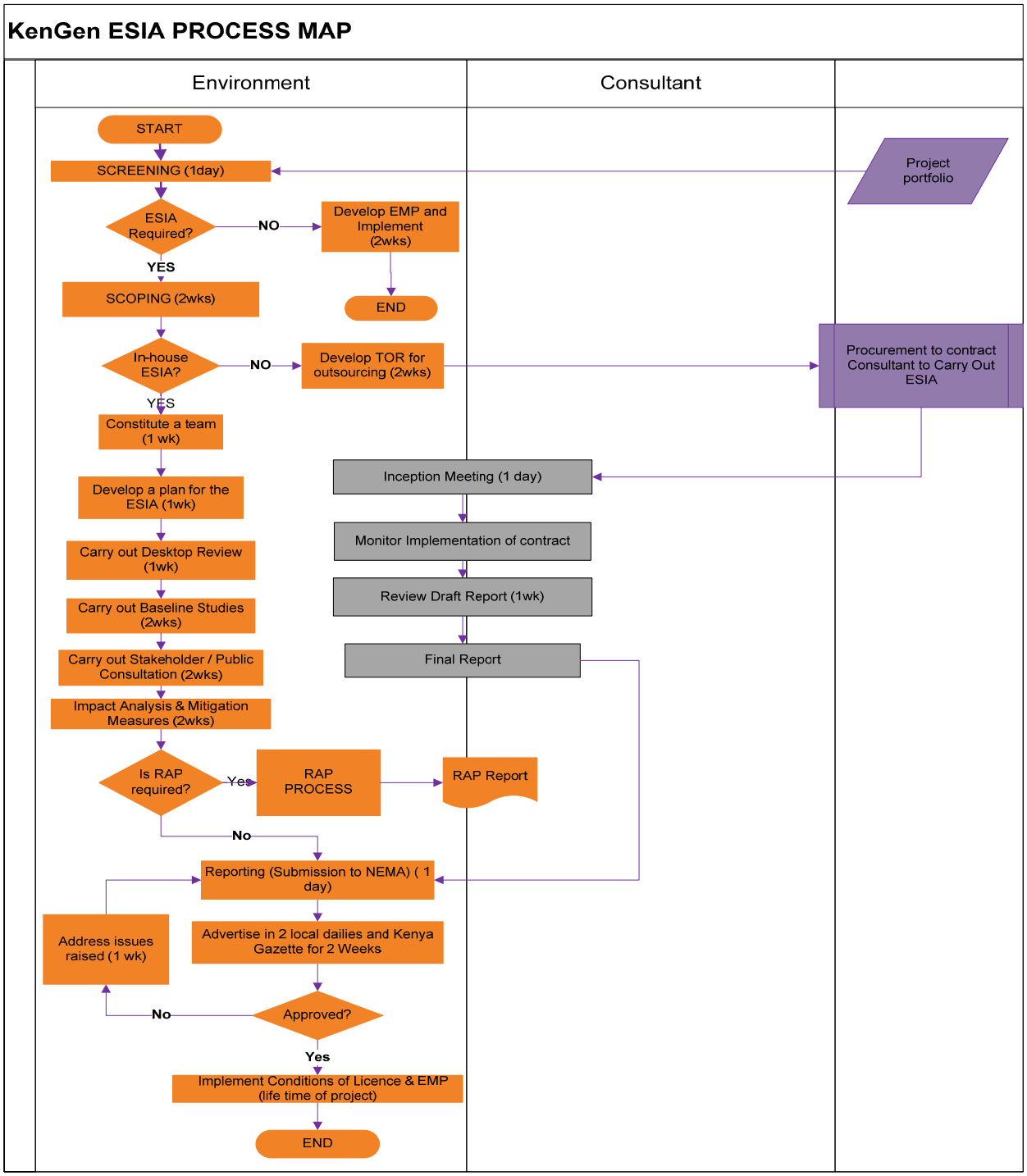

FIGURE 1: Generalized EIA and RAP Process Flow-Chart (KenGen Process Maps, 2011)

4.1 Screening

The EIA process kicks off with project screening. Screening is done to determine whether or not a project proposal should be subject to EIA and, if so, at what level of detail. A guideline for whether or not an EIA is required is country specific depending on the laws or norms in operation. Legislation often specifies the criteria for screening and full EIA. Development banks also screen projects presented for financing to decide whether an EIA is required using their set criteria.

The output of the screening process is often a document called an **Initial Environmental Examination or Evaluation** (IEE) (See Section 4.1). The main conclusion will be a classification of the project according to its likely environmental sensitivity. This will determine whether an EIA is needed and if so, to what detail.

4.2 Scoping

The aim of EIA is not to carry out exhaustive studies on all environmental impacts for all projects. Scoping is used to identify the key issues of concern at an early stage in the planning process (Ahmed & Sammy, 1987). The results of scoping will determine the scope, depth and terms of reference to be addressed within the Environmental Statement. Scoping is done to:

- Identify concerns and issues for consideration in an EIA
- Ensure a relevant EIA
- Enable those responsible for an EIA study to properly brief the study team on the alternatives and on impacts to be considered at different levels of analysis
- Determine the assessment methods to be used
- Identify all affected and interested parties
- Provide an opportunity for public involvement in determining the factors to be assessed, and facilitate early agreement on contentious issues
- Save time and money
- Establish Terms of Reference for EIA study

Scoping should be an ongoing exercise throughout the course of the project. The following environmental tools can be used in the scoping exercise

Checklists – These are standard lists of the types of impacts associated with a particular type of project. Checklists methods are primarily for organizing information or ensuring that no potential impact is overlooked. They comprise list of questions on features of the project and environmental impacts. They are generic in nature and are used as aids in assessment.

Matrices – The matrix methods identify interactions between various project activities and environmental components. They incorporate a list of project activities with a checklist of environmental components that might be affected by these activities. A matrix of potential interactions is produced by combining these two lists (placing one on the vertical axis and the other on the horizontal axis). They should preferably cover both the construction and the operation phases of the project, because sometimes, the former causes greater impacts than the later. However, matrices also have their disadvantages: they do not explicitly represent spatial or temporal considerations, and they do not adequately address synergistic impacts.

Networks – These are cause-effect flow diagrams used to help in tracing the web relationships that exist between different activities associated with an action and environmental system with which they interact. They are also important in identifying direct and cumulative impacts. They are more complex and need expertise for their effective use.

Consultations with decision-makers, directly affected communities, environmental and other interest groups to ensure that all potential impacts are detected. However, there can be danger in this when excessive consultation is done and some unjustifiable impacts included in the ToR.

4.3 Baseline data collection

The term "baseline" refers to the background information on the biophysical, social and economic settings of the proposed project area. Normally, information is obtained from secondary sources, or the

acquisition of new information through field samplings, interviews, surveys and consultations with the public. The task of collecting baseline data starts right from the period of project inception. However, a majority of this task may be undertaken during scoping and actual EIA.

Baseline data is collected for two main purposes

- To provide a description of the current status and trends of environmental factors (e.g., air pollutant concentrations) of the project area against which predicted changes can be compared and evaluated in terms of significance, and
- To provide a means of detecting actual change by monitoring once a project has been initiated

Only baseline data needed to assist prediction of the impacts contained in the TOR and scoping report should be collected.

4.4 Impact analysis and prediction

Predicting the magnitude of a development likely impacts and evaluating their significance is the core of environmental assessment process (Morris & Therivel, 1995). Prediction should be based on the available environmental baseline data of the project area. Such predictions are described in quantitative or qualitative terms.

4.4.1 Considerations in impact predictions

Magnitude of impact: This is defined by the severity of each potential impact and indicates whether the impact is irreversible or, reversible and estimated potential rate of recovery. The magnitude of an impact cannot be considered high if a major adverse impact can be mitigated.

Spatial extent of impact: The spatial extent or the zone of influence of the impact should always be determined. An impact can be site-specific or limited to the project area; a locally occurring impact within the locality of the proposed project; a regional impact that may extend beyond the local area and a national impact affecting resources on a national scale and sometimes trans-boundary impacts, which might be international.

Duration of impact: Environmental impacts have a temporal dimension and needs to be considered in an EIA. Impacts arising at different phases of the project cycle may need to be considered. An impact that generally lasts for only three to nine years after project completion may be classified as short-term. An impact, which continues for 10 to 20 years, may be defined as medium-term, and impacts that last beyond 20 years are considered as long-term.

Significance of the impact: This refers to the value or amount of the impact. Once an impact has been predicted, its significance must be evaluated using an appropriate choice of criteria. The most important forms of criterion are:

- Specific legal requirements e.g. national laws, standards, international agreements and conventions, relevant policies etc.
- Public views and complaints
- Threat to sensitive ecosystems and resources e.g. can lead to extinction of species and depletion of resources, which can result, into conflicts.
- Geographical extent of the impact e.g. has trans-boundary implications.
- Cost of mitigation
- Duration (time period over which they will occur)
- Likelihood or probability of occurrence (very likely, unlikely, etc.)
- Reversibility of impact (natural recovery or aided by human intervention)
- Number (and characteristics) of people likely to be affected and their locations

- Cumulative impacts e.g. adding more impacts to existing ones.
- Uncertainty in prediction due to lack of accurate data or complex systems. Precautionary principle is advocated in this scenario.

4.4.2 Impact prediction methodologies

Several techniques can be used in predicting the impacts. The choices should be appropriate to the circumstances. These can be based on:

- Professional judgment with adequate reasoning and supporting data. This technique requires high professional experience.
- Experiments or tests. These can be expensive.
- Past experience
- Numerical calculations & mathematical models. These can require a lot of data and competency in mathematical modelling without which hidden errors can arise
- Physical or visual analysis. Detailed description is needed to present the impact.
- Geographical Information Systems
- Environmental Risk Assessment, and
- Economic Valuation of environmental impacts

4.5 Analysis of alternatives

Analysis of project alternatives is done to establish the preferred or most environmentally sound, financially feasible and benign option for achieving project objectives.

The World Bank directives requires systematic comparison of proposed investment design in terms of site, technology, processes etc., in terms of their impacts and mitigation options, capital or recurrent costs, suitability under local conditions and institutional, training and monitoring requirements (World Bank, 1999). For each alternative, the environmental cost should be quantified to the extent possible and economic values attached where feasible, and the basis for the selected alternative stated. The analysis of alternative should include a "**NO PROJECT"** alternative.

4.6 Mitigations and impacts management

Mitigation is done to avoid, minimize or offset predicted adverse impacts and, where appropriate, to incorporate these into an Environmental Management Plan or System. For each potential adverse impact the plan for its mitigation at each stage of the project should be documented and costed, as this is very important in the selection of the preferred alternative.

The objectives of mitigation therefore are to:

- find better alternatives and ways of doing things;
- enhance the environmental and social benefits of a project
- avoid, minimise or remedy adverse impacts; and
- ensure that residual adverse impacts are kept within acceptable levels

TABLE 1: Design of Mitigation Measures

Approach	*Examples*
Avoid	Change of route or site details, to avoid important ecological or archaeological features
Replace	Regenerate similar habitat of equivalent ecological value in different location.
Reduce	Filters, precipitators, noise barriers, dust enclosures, visual screening, wildlife corridors, and changed time of activities
Restore	Site restoration after construction
Compensate	Resettlement of Project Affected Persons (PAPs) or communities, facilities for the affected communities, financial compensation for the affected individuals etc.

4.7 Environmental management plan and monitoring programs

4.7.1 Environmental management plan

An Environmental Management Plan (EMP) is a detailed plan and/or schedule of measures necessary to minimize, mitigate, etc. any potential environmental impacts identified by the EIA (World Bank 1999). Once the EIA has been done and the significant impacts identified, it is necessary to prepare an EMP.

An EMP should consist of a set of mitigation, monitoring and institutional measures to be taken during the implementation and operation of the proposed project to eliminate adverse environmental impacts, offset them or reduce them to acceptable levels. The EMP should also include the actions needed to implement these measures, including the following features:

- Mitigation based on the environmental impacts reported in the EIA,
- The EMP should describe with technical details each mitigation measure.
- The EMP should then include monitoring objectives that specifies the type of monitoring activities that will be linked to the mitigation measures. Specifically, the monitoring section of the EMP provides:
    - A specific description and technical details of monitoring measures that includes the parameters to be measured, the methods to be used, sampling locations, frequency of measurements, detection limits (where appropriate), and definition of thresholds that will signal the need for corrective actions;
    - Monitoring and reporting procedures to ensure early detection of conditions that necessitate particular mitigation measures and to furnish information on the progress and results of mitigation.
- The EMP should also provide a specific description of institutional arrangements i.e. who is responsible for carrying out the mitigating and monitoring measures (for operation, supervision, enforcement, monitoring of implementation, remedial action, financing, reporting, and staff training).
- The EMP in addition, should include an estimate of the costs of the measures and activities recommended.
- It should consider compensatory measures if mitigation measures are not feasible or cost effectiveness.
- The EMP must be operative throughout the whole Project Cycle.

4.7.2 Monitoring programs

The monitoring program (MPs) is the systematic measurement of key environmental indicators over time within a particular geographic area (World Bank, 1999). Monitoring should focus on the most significant impacts identified in the EIA. Various types of monitoring activity are currently in practice. The main types are briefly described below:

Baseline monitoring: A survey should be conducted on basic environmental parameters in the area surrounding the proposed project before construction begins. Subsequent monitoring can assess the changes in those parameters over time against the baseline.

Impact monitoring: The biophysical and socio-economical (including public health) parameters within the project area, must be measured during the project construction and operational phases in order to detect environmental changes, which may have occurred as a result of project implementation e.g. air emission, dust, noise, water pollution etc. (European Commission, 1999).

Compliance monitoring: This form of monitoring employs a periodic sampling method, or continuous recording of specific environmental quality indicators or pollution levels to ensure project compliance with recommended environmental protection standards.

Monitoring should be regular and performed over a long period of time. Interruptions in monitoring may result in generating insufficient data for analysis and trending to draw accurate conclusion concerning project impact.

The main aim of EIA monitoring is to provide the information required to ensure that project implementation has the least possible negative environmental impacts on the people and environment.

What to avoid in monitoring:

- Overestimation of data needed as this can lead to drowning in data without information.
- Under-estimation of time and cost for data analysis
- Weak coordination between the data collection with project time table and seasonal factors
- Ignoring requirements for baselines

4.8 Environmental impact statement

The final EIA study report is referred to as an Environmental Impact Statement (EIS). Most national environmental laws have specified what the content of EIS should have. Multilateral and bilateral financial institutions have also defined what should be contained in an EIS. Ideally, the content of an EIS should have the following:

- Executive summary
- Policy, legal and administrative framework
- Description of the environment
- Description of the proposed project in detail
- Significant environmental impacts
- Socio-economic analysis of project impacts
- Identification and analysis of alternatives
- Mitigation action/mitigation management plan
- Environmental management plan
- Monitoring program
- Knowledge gaps
- Public involvement
- List of references
- Appendices including
    - Reference documents, photographs, unpublished data
    - Terms of reference
    - Consulting team composition
    - Notes of public consultation sessions

4.9 Decision making

At each stage of EIA, interim decisions are made. These decisions influence final decisions made about the EIA.

The EIS is submitted to designate national authority for review before the final decision. The authority, together with technical review panels determines the quality of EIS and gives the public further opportunity to comment. Based on the outcome of the review, the designated authority or lending institution will accept, reject or make further modifications to avoid future confrontation. If the EIS is accepted, an EIA license is issued and if otherwise, additional studies or recommendations are made before issuance of a license. The decision making process should be autonomous so that the outcome of the review is seen as fair enough. The duration of this process is usually set out in the EIA legal framework.

4.10 Effective EIA follow-up

In practice, an EMP, which is submitted with the EIS report, should be used during implementation and operation of the project. The link between EIA process and project implementation stage is often weak especially in developing countries (Welford, 1996). Despite this, they may still be no more good than intentions unless an independent check is made to ensure that the developer is acting as intended.

These weaknesses could be attributed to:

- Deficiencies in EMPs prepared during the EIA.
- Deficiencies in monitoring and enforcing compliance through use of legal instruments and financial penalties (most EIAs end after environmental clearance has been received from the environmental management authority).
- Timing of some projects especially in developing countries are implemented several years after the EIA and the EMP. In such scenarios, an update of the EIA should be done and a new EMP developed.

ISO 14001:2004 and other Environmental Management Systems (EMS) can provide the link between the EIA and environmental management requirements after the EIA (during project implementation, operation and decommissioning).

5. PUBLIC CONSULTATION AND PARTICIPATION PROCESS

5.1 Public consultation and participation process from a legal perspective

There is an upsurge in attention paid to Public Consultation and Participation (PC&P) process in recent years with increase in environmental awareness levels. Most international and national environmental legislations are now making specific and detailed provisions for public participation and disclosures. Multilateral financial agencies like the World Bank and bi-lateral aid agencies show parallel interest in ensuring that the public is involved in the EIA process (Mutemba, 1999).

These provisions usually guarantee enforcement of utility commitments to public involvement in environmental decision-making. For example the Kenyan Constitution of 2010, recognizes individual's right to a clean and healthy environment. To this end, the environmental management and coordination act provides administrative mechanism for addressing public consultations and grievances.

5.2 Designing public consultation and participation program

There is no one-size-fits-all approach to public participation (U.S. Department of Commerce**,** 1994).

There are, however, certain issues that arise in designing any highly effective public participation program. The PC&P planning team should:

- Have a clearly defined expectation for what the team hopes to accomplish with the public.
- Do stakeholder identification and mapping based on their interests and influences.
- Target those segments of the public (stakeholders) most likely to see themselves as impacted by the decision
- Be well integrated into the decision-making process
- Involve interested stakeholders in every step of decision-making, not just the final stage
- Provide alternative levels of participation based upon the public's level of interest and reflecting the diversity of those participating
- Provide genuine opportunities to influence the decision
- Take into account the participation of internal stakeholders as well as external stakeholders

Adequate consultation takes time and resources and cost money especially if the project is being implemented in remote locations with biological and cultural diversity. The EIA team must therefore make adequate budget provisions to meet these costs. Sufficient time must also be allocated within the EIA time frame.

Since stakeholder involvement requires additional expenditure, it is important to find the most cost effective way of integrating stakeholder involvement in the project life cycle. This is also necessary because it will avoid creating "stakeholder fatigue" and incurring unnecessary expenditure. The Table 2 below shows how and when the stakeholders should be involved.

TABLE 2: Public Participation in Project Cycle

Project cycle	EIA component	Public participation activity
Pre-feasibility	Environmental Screening	Identifies public groups and begins initial contact with groups.
	Initial Environmental Examination (IEE)	Continue consultations – public provides input to IEE report.
	Scoping	Identifies major issues for Scoping and TOR using public input and makes plan for public involvement.
Feasibility	Environmental Impact Assessment (EIA)	The public reviews and comments on draft EIA study report. The public provides input to design and survey.
Detailed survey and design	Integration of Environmental Mitigation Measures	Detailed design made available to the public.
Construction and operation	Environmental Monitoring	The public provides input to post-evaluation of impacts and mitigation measures.

5.3 Public participation techniques

There are techniques for getting information to the public (one-way e.g. press releases, newsletters, etc.), getting it from the public (one-way e.g. polls, surveys, questionnaires) and exchanging information (interaction between the proponent and the public e.g. public hearings, workshops, meetings, advisory groups/ task forces, etc.). When selecting a technique, it is always wise to build on existing communication channels that are familiar with the community or stakeholders involved. There is no public participation technique that will work in all circumstances. When people talk about highly successful public participation programs they are talking about programs where the techniques matched the purpose of the program, reached the interested stakeholders, and resulted in a clear linkage between the public participation process and the decision-making process.

It is worth noting that "making a decision" in public participation is not a single moment in time, but an accumulation of many smaller decisions. There are decisions being made at every step in the consultation process regardless of the technique.

5.4 Monitoring and evaluation of public consultation and participation

Most EIA projects usually have no monitoring systems for PC&P built into their structure. Monitoring and Evaluation (M&E) assess the quality of public consultations in the EIA process. Techniques for monitoring and evaluating PC&Ps include confirmation that participants understood the consultation content (correct language, level of technicality), and assessment of stakeholders' opinions of PC&P effectiveness and impact on project design and implementation. Through appropriate use of M&E, public consultation strategies can be adjusted during the project cycle to improve stakeholder participation, information dissemination strategies, and mechanisms for integrating participant feedback into project design and implementation.

6. EIA RELATED STUDIES

6.1 Social impact assessment

Social Impact Assessment (SIA) includes the processes of analysing, monitoring and managing the intended and unintended social consequences, both positive and negative, of planned interventions and any social change processes invoked by those interventions (Vanclay, 1999). The analysis should include the use of land, culture, the main economic activities e.g. tourism, agriculture, employment levels and impact on service provision e.g. education, water use, traffic, energy use etc. Its primary purpose is to bring about a more sustainable and equitable biophysical and human environment. SIA assumes that social, economic and biophysical impacts are interconnected and is therefore done to ensure that there is no mismatch between the development and socio-cultural and economic aspects of the project area.

6.2 Health impact assessment

Health is a state of complete physical, mental and social well-being and not merely absence of disease or infirmity (WHO, 1946).

In most EIAs, Health Impact Assessment (HIA) is usually included under SIA. HIA is now emerging as a key component of EIA because health is determined by a multiplicity of factors including socio-economic and environmental factors. There is no clear definition about where health concerns end and where environmental or social concerns begin. HIA is a broad concept that may be interpreted in different ways by a range of different users but all imply an interest in the safeguarding and enhancement of human health and a concern that human activities and decisions, in the form of

development projects, plans, programs and policies can affect human health in both positive and negative ways.

6.3 Strategic environmental and social assessment

Strategic Environmental and Social Assessment (SEA) is undertaken much earlier in the decision-making process than EIA. It is therefore seen as a key tool for sustainable development. SEA aims to incorporate environmental sustainability considerations into strategic decision making processes, such as the formulation of policies, plans and programs.'

7. EIA GUIDING PRINCIPLES

International Association for Impact Assessment (IAIA, 1999) and others have developed guiding principles for EIA and/ or Impact Assessment (IA). The principles listed below are a selection of some of the documented ones.

Participative: The process should provide appropriate opportunities to inform and involve the affected and interested stakeholders and incorporate their input in decision-making.
Transparency: Assessment process, outcomes and decisions should be open and accessible.
Certainty: The EIA process and timing should be agreed in advance and followed by all participants.
Accountability: The decision-makers and project proponents are responsible to all parties for their action and decisions under the assessment process.
Credibility: Assessment is undertaken with professionalism and objectivity.
Cost-effectiveness: The assessment process and its outcomes will ensure environmental protection at the least cost option to the society.
Practical: The process should result in practical outputs, which can be implemented by the project proponent.
Relevant: The process should focus on information that is relevant for development planning and decision-making.
Focused: The process should concentrate on significant environmental effects and key issues that need to be taken into account in making decisions.
Interdisciplinary: The process should ensure that the appropriate techniques and experts in the relevant disciplines are employed, including use of traditional knowledge, as relevant.
Integrated: The process should address the interrelationships of social, economic and biophysical aspects.

8. CONCLUSIONS

EIA certainly has a crucial role to play in addressing environmental and social issues surrounding projects development planning and especially geothermal projects. The integration of environment into development planning is the most important tool in achieving sustainable development. Environmental protection and economic development must thus be dealt with in an integrated manner. EIA process is necessary in providing an anticipatory and preventive mechanism for environmental management and protection in any development. Several developing countries are still at the infancy stage of operationalization of their EIA processes. The need for capacity building for quality EIA is also eminent in these countries. Despite these small setbacks, environmental impact assessment has become an integral part of project planning one, which is continually being improved for posterity.

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EIA – EXAMPLE FROM BJARNARFLAG IN ICELAND

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ABSTRACT

Environmental Impact Assessment (EIA) has been carried out four times for a geothermal power plant in Bjarnarflag, Iceland, the first one for a 20 MW_e plant, the second one for a 2×20 MW_e plant and a 132 kV power transmission line to the Krafla power plant, the third one for a 40 MW_e plant and a 132 kV power transmission line to the Krafla power plant, and the last one for a 90 MW_e plant and a 132 kV power transmission line to the Krafla power plant. The first three assessments were carried out in accordance with the first Icelandic Act on Environmental Impact from 1993. The first two reports were shelved due to negative reaction and probably an inadequate mechanism for dealing with such reaction. The third EIA got a ruling from the Planning Agency of Iceland that further assessment was required. These requirements showed up a flaw in the 1993 Act in that a scoping document to be adhered to during assessment and taken into account in comments and rulings was not needed. The last Environmental Impact Assessment was carried out with reference to an Act passed by the parliament in 2000 in which several alterations had been made, among them that a scoping document was mandatory and that in comments and rulings investigations not due according to that document could not be asked for. The Planning Agency then ruled in favour of the project. One deep well has already been drilled and two are due very soon.

1. INTRODUCTION

The first law on environmental impact assessment in Iceland was Act No. 63/1993 and Sólnes et al. (1995) carried out the initial environmental assessment in Bjarnarflag, which is a subfield in the Námafjall geothermal area (Figure 1), according to the stipulations of that Act. This was the second environmental assessment carried out in Iceland and the first one of a geothermal project. The assessment also needed to take into account Act No. 36/1974 according to which the whole of the commune within which the geothermal area lies, Skútustadahreppur, along with the river Laxá is a protected area. The main object of the protection is Lake Mývatn which is a biologically unique lake at its latitude, the geothermal inflow water contributing to its properties. The surrounding lavas also give it a special geological character. In this assessment the impact of a 20 MW_e power plant was assessed.

This was reconsidered and a year later a modified report for a 2×20 MW_e and a 132 kV power line to the Krafla power plant was issued (Hönnun, 1996). Neither of these reports was presented to the Planning Agency for a decision. A new EIA was presented by Hönnun (2000), this time a one stage 40 MW_e power plant and a 132 kV power line were assessed and subjected to the whole process (2000). Comments and stipulations were rife and the operators decided not to pursue the matter further at the

time. Shortly after that Act No. 106/2000 on environmental impact assessment was passed with significant changes to the previous act. When Landsvirkjun decided again to continue with plans for the Bjarnarflag power plant in 2003 it was decided to carry out yet another EIA but according to the new act and assess a 90 MW_e power plant and a 132 kV power line to Krafla. This assessment was subjected to the new procedure (Hönnun 2003a) and a licence to construct a power plant was issued. One new well has already been drilled and more are planned. In this article the history of geothermal utilization in Námafjall will be considered as well as details of the environmental assessments carried out.

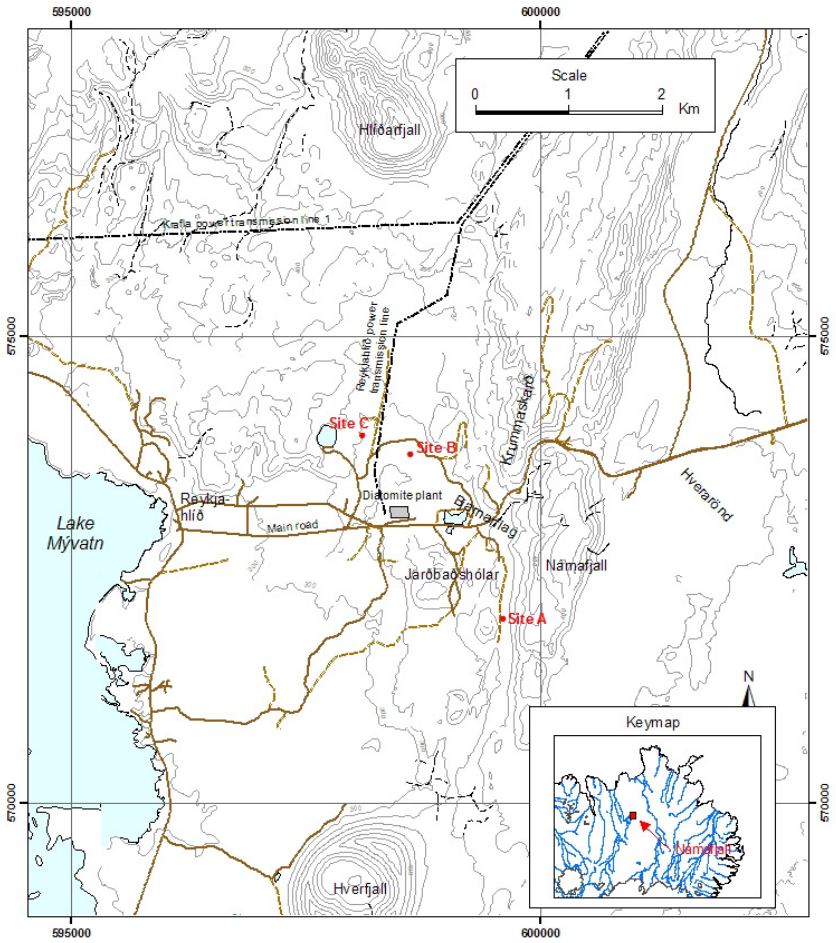

FIGURE 1: A map of the study area showing the three proposed sites, the present 11 kV power transmission line and the Krafla I power transmission line.

2. HISTORY OF UTILIZATION

For centuries sulphur was an important export from Iceland, the first record of it being in 1198 to Bergen, Norway (Sverris saga, 1920). Námafjall was one of the places which were mined for sulphur. The latest mining company went bankrupt during the Second World War. In the 1950s interest in sulphur mining on a large scale was aroused again and 16 wells were drilled in the Hverarönd area of Námafjall for this purpose. At about the same time exploration for diatomite in Lake Mývatn showed positive results and it was decided to transfer activity to the Bjarnarflag area which is closer to Lake Mývatn. The Hverarönd boreholes were abandoned and some developed into powerful fumaroles that are now tourist attractions. From 1963 to 1970 nine wells were drilled in Bjarnarflag to depths from 342 to 1312 m with a moderate size drill rig, and a tenth well to a depth of 1809 m with a larger drill rig in 1975 mostly to supply the Námafjall Diatomite Plant but also a 3 MW_e back pressure turbine that was commissioned in 1969 (the first power production by geothermal steam in Iceland) and a district heating system for the neighbouring Reykjahlíd community. Most of these wells were damaged during the Krafla fires, 1975-1984, mostly in 1977 when magma from the fires flowed twice through the drilling area. To counteract this damage two deep wells were drilled outside the volcanically active area in 1980. The operation of the diatomite plant ceased in 2004 and of the 10 earlier wells one is still in operation as well as the two wells drilled in 1980.

3. ENVIRONMENTAL IMPACT ASSESSMENT

In the early 1990s Landsvirkjun showed an interest in commissioning a power plant in Bjarnarflag. Following a concerted exploration effort a feasibility report was published (Orkustofnun – VGK, 1994). The reason was given as increased demand for electricity due to the aluminium smelter proposed by Columbia Aluminium Corporation in the industrial area of Grundartangi, in west Iceland. The plant was planned to be situated under the western slopes of mount Námafjall, south of the main road but to the south of the Krummaskard fault (Figure 1). It was assumed that three new wells needed be drilled in addition to existing wells. In an EIA that followed (Sólnes et al. 1995) advantages of this plant were considered to be low cost per energy unit, short construction time and ease of expanding it to 40 MW_e. No direct harm was expected but surface discharge of effluent might cause considerable visual disturbances although the effluent water was not expected to contaminate the local groundwater. Reinjection was however considered desirable. To minimize visual disturbances the use of multiple well pads and careful design of pipelines and power transmission lines were recommended. Regular area and production monitoring would be effected.

Subsequently it was decided to aim for a 2×20 MW_e power plant with a significantly different design. In the previous assessment the impact of the necessary power transmission line had not been assessed. Therefore it was deemed necessary to carry out a new EIA for the different plant and a 132 kV power transmission line to the Krafla I power transmission line (Hönnun 1996). Among the investigations that had been carried out after the appearance of the first EIA were an investigation into the atmospheric distribution of hydrogen sulphide in the vicinity, recording vegetation in the power plant area and along the track defining the position of the power transmission line, an investigation of the biological systems in the hot spring and fumarole areas of Bjarnarflag, Hverarönd and Krafla. Soil temperatures had also been measured to define if and where power transmission lines could be buried, the temperature of the effluent pond was determined and noise measurements had been carried out both in Bjarnarflag and Krafla. Seven new wells needed to be drilled and used along with the existing wells and this time it was assumed that spent fluids would be reinjected. The impacts expected were similar to those considered in the earlier report. The National Trust was entirely opposed to the power plant, and the The Icelandic Institute of Natural History and the Mývatn Research Station also provided severe opposition and Landsvirkjun decided not to contest this opposition and shelved the report. The grounds for the opposition were doubts about potential effects of the power plant on the groundwater system, the Lake Mývatn ecosystem and mud pool and fumarole activity at Hverarönd.

In 1999 Landsvirkjun went ahead again and stated the same reasons, i.e. growing general electricity market and plans for more energy intensive industries for the next few years and related the same advantages to the power plant as before. A new EIA with much added information including 12 appendices was published (Hönnun 2000). Now a 40 MW_e plant was planned with a capacity of 324 GWh annually, corresponding to 8100 h/year production time and time planned for construction 3 years. A 132 kV power transmission line was planned and should replace mostly the present 11 kV Reykjahlíd power transmission line which would be removed. The same site is recommended for most of the construction but alternative sites, one to the north of the main road which is inside the volcanically active area and a site further to the south of the main road were also considered. Again it was assumed that seven new wells are needed which will be drilled directionally and that effluent water will be reinjected into the geothermal reservoir. In the report environmental impact is considered at two stages, on the one hand environmental impact due to construction and on the other hand impact due to production. During construction the major impact involves surface disturbances due to excavation, construction and drilling as well as increased traffic and strain on the service industries in the area due to the relatively large workforce. During production the major impacts are due to mass removal from the geothermal reservoir, discharge of effluent water, noise level of discharging boreholes and visual effects. The most sensitive areas are Lake Mývatn and the fumarole area in Hverarönd but the data presented suggest that these areas will not be affected. Mitigation measures against noise and visual effects are proposed. Area and production monitoring are again proposed with

the addition that effect on neighbouring areas will also be monitored. The report was sent to commentators and public hearings were given and then referred to the Planning Agency which after reviewing the comments gave the verdict that a further assessment was needed. The following reasons were among those given: Alternative sites for the power plant should be assessed specifically with regard to a visual comparison; the impact of stepwise development (as had been done in the 1996 report) should be assessed, the effects of burying pipes and transmission lines should be evaluated, the location of a potential effluent pond and the effect of reinjection should be considered, the groundwater flow with the potential risk to Lake Mývatn should be assessed more thoroughly, the possible effect on surface activity at Jardbadshólar (an old bathing place) and Hverarönd should be assessed, impact on tourism treated in more detail and operations in connection with eventual termination of the activity described. The major complaint of the operators was that many of the recommendations that came after the EIA had been carried out needed new research which would have been carried out during the assessment had it been asked for. This was in fact in line with one of the main criticisms of the 1993 Act, i.e. that a scoping document open to comments was not required and that new investigations could be stipulated. Landsvirkjun however decided not to go ahead and plans for a power plant in Bjarnarflag were yet again shelved. A new law on environmental impact assessment, Act No. 106/2000, was passed amending several flaws that had been experienced with the application of the initial act among them the requirement for a scoping document.

In 2003 Landsvirkjun decided yet again to aim for a power plant in Bjarnarflag. It was decided to carry out a new EIA in accordance with the new act but this time a 90 MW_e power plant and a 132 kV power transmission line were assessed. In May 2003 a scoping document including all the stipulations of the Planning Agency in 2000 and which had been commented on (Hönnun 2003b) was presented to the Planning Agency. An EIA was carried out in accordance with this scoping document, with 15 appendices reporting previous and additional research (Hönnun 2003a, 2003c), including an extensive treatment of potential building areas, a study of the potential effects on Jardbadshólar and Hverarönd, effects on vegetation and birdlife, effects of the discharge of effluent on groundwater and of gas discharges, visual effects, a survey of tourism, assessment of burying pipes and transmission lines and a description of proposed work on a model of the area to be used as a reference to keep production sustainable. The construction of the power plant is planned in two to three stages, each stage with a capacity of 162-486 GWh per year and the total for the plant 729 GWh pear year which corresponds to a full load production for 8100 hours annually. The power transmission line planned is a 10 km line from the Bjarnarflag power plant to the Krafla power plant. The same reasons for and advantages of the project are given as before. Previous utilization is described and said to be equivalent of 15 MW_e power production for the preceding 30 years. The production from the 3 MW_e back pressure power plant will be discontinued. Site A (Figure 1) was considered to have least environmental impact but site C not an option, the power transmission line is expected to be buried to where it meets Krafla transmission line I but above ground alongside the Krafla power transmission line as far as the Krafla power station. Three alternative routes for the buried line are suggested, one from site B and two from site A. In the environmental impact assessment of the construction phase it is noted that site A has already been disturbed by levelling, potato growing and a track. Thick loose strata cover this site and can be used for construction thus minimizing the need for excavation elsewhere. Production wells will be directionally drilled from relatively small drilling pads, one south of the main road and another to the north of it. Silencers will be constructed for each drilling pad to keep the noise level within legal limits. No new tracks will be built for the construction of the power transmission lines. No archaeological remains will be disturbed, during construction employment will rise and there will be a temporary boost to some service industries. In the environmental impact assessment for the production period it is noted that new exploration results suggest that the area is more extensive than previously thought and it should be able to sustain a 90 MW_e production. With a view to changes in altitude due to volcanic activity subsidence due to production is predicted to be negligible. A tracer study shows a 100 million fold dilution of the effluent from the present effluent pond to a fissure 2 km away due to mixing with a powerful groundwater current. Thus it is considered safe to use the same effluent pond and discharge into the groundwater current as effect on Lake Mývatn another 2 km further is considered negligible. Activity at Jardbadshólar increased during the Krafla fires and is now waning

and is expected to do so from natural causes but not due to power production and it is considered very unlikely that production can affect fumaroles and mud pools at Hverarönd. Although there will be some increase in CO_2 discharge to the atmosphere it is negligible compared to the total CO_2 discharge from the country and H_2S is considered to be precipitated soon after its emission. The vegetation in the production area has little protection value and all possible sensitive vegetation is avoided by the choice of the route for the power transmission line. Animal life is not expected to be affected. Noise will be dampened by hills to the west of the power plant. The power plants buildings will hardly be seen except from the tourist viewpoint in Námaskard pass where structures other than boreholes are on the periphery of vision. Three to four new permanent job positions will be created and social and economic effects are small except that the commune will receive a considerable property tax. From experience of other geothermal power plants the number of tourists in the area is expected to increase and the spa and reception will be designed to make their visits pleasant. Several comments were received and replied to by Landsvirkjun. Some of these follow:

Comment: The EIA considers site A to be most desirable even though site B is more desirable for visual quality. *Reply:* Other factors have to be taken into consideration namely the risk of disaster which is much higher at B due to possible tectonic movements and possible lava flow. Location A is not considered unspoiled due to levelling, potato growing and the presence of a track although it was outside the area affected by the diatomite plant.

Comment: Reinjection alternatives have not been adequately assessed. *Reply:* Tracer studies of the groundwater system suggest that the present discharge system should be adequate. For the last 40 years about 200 million tons of geothermal effluent have been discharged into the groundwater current with no noticeable effect except over very short distances. However careful monitoring of the groundwater system will be continued as required by the Environment and Food Agency. Reinjection wells have been situated and will be drilled and used should any suspicion of contamination be indicated from the monitoring results.

The Planning Agency ruled that the plans for the plant could go ahead provided that area monitoring (surface manifestations, temperature and water table in springs and fissures, chemical composition of fluid in same and fumaroles, soil temperature) and production monitoring (well temperature, pressure, chemical composition) is carried out according to its stipulations. This ruling was not challenged and the first additional borehole was drilled in 2006 and two are due to be drilled in early 2008.

4. FURTHER PROCESSING AND USE OF GIS FOR THE 2003 ENVIRONMENTAL IMPACT ASSESSMENT

Noorollahi (2005) processed the data provided in the report of Hönnun (2003) and used the methods of GIS and remote sensing with the aim of choosing locations for drilling and power production taking into account economical and environmental factors. For well siting data layers including geothermal manifestations, volcanic craters and faults and fractures are overlain and intersected, followed by overlaying weighted geophysical and fracture distance raster maps to provide the suitable drill sites (Figure 2).

For environmental suitability vegetation cover and vegetation cover density maps are overlain to provide a suitable area map which then is overlain by a weighted protected area, slope and elevation and special criteria maps to select the final most suitable area (Figure 3).

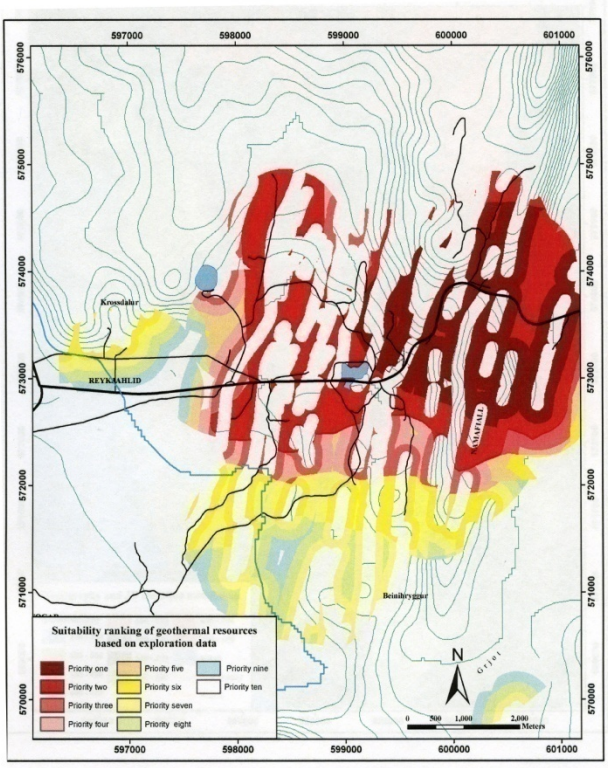

FIGURE 2: Ranking of study area according to the suitability of geothermal resources

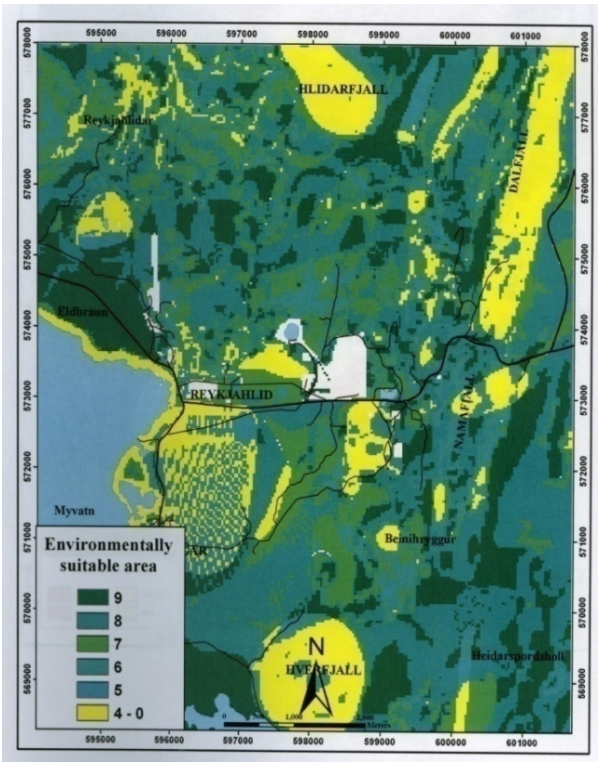

FIGURE 3: Environmental suitability map for the study area

The combined map showing the most suitable areas for drilling is shown in Figure 4 and as expected he proposed drilling pads are situated in the most suitable drilling areas evaluated earlier. For power plant selection Noorollahi (2005) considered the three alternative sites considered by the project developer (Figure 1) and evaluated thirteen different environmental, natural risk and economic factors. A relative value from 0 to 9 was assigned to each factor and then the factors were assigned a weighting with respect to each other (Table 1). For air quality data on gas concentrations in previous wells, results of measurements of gas concentrations in atmospheric air and information on the prevailing wind direction in the area was used. Effective visibility based on the visibility from a 30 m buffer on both sides of main roads, tourist stops and a residential area was calculated using ArcInfo-3D Analyst for the three sites and the relative value obtained from the result. The importance of plant species was considered as well as the plant cover area for the vegetation factor. The distances to the proposed effluent pond and the projected reinjection well are used to evaluate influence of waste water.

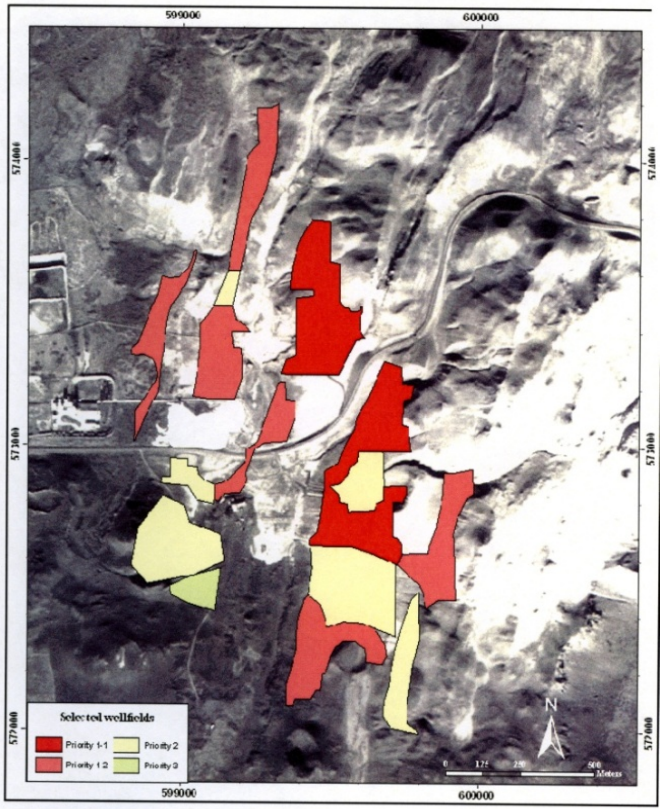

FIGURE 4: Prioritization of sites for drilling

TABLE 1: Relative influence of 13 factors on the three proposed power plant sites

Environmental & economic factors	Relative influence (%)	Site A		Site B		Site C	
		Relative value	In-fluence	Relative value	In-fluence	Relative value	In-fluence
Air pollution	9	9	81	8	72	6	54
Visual quality	9	9	81	6	54	3	27
Vegetation	9	7	63	9	81	4	36
Waste water	7	9	63	7	49	6	42
Noise	8	9	72	8	64	6	48
Land stability and subsidence risk	7	8	56	5	35	7	49
Slope and surface disturbance	7	6	42	7	49	8	56
Geology, natural risk	9	9	81	5.5	49.5	4.5	40.5
Faults, pipeline risk	8	9	72	6	48	4	32
Land use, operation	8	5	40	4	32	9	72
Distance to production field	8	8	64	9	72	6	48
Access road required	6	9	54	7	42	8	48
Transmission line	5	7	35	8	40	9	45
Accumulative weight	**100**		**804**		**687.5**		**597.5**

The distance from habitation and the inverse distance weighting method are used to estimate the effects of noise at inhabited places and tourist spots. Results of TEM soundings and a map of the intensity of alteration were combined to estimate subsidence risk. The slope and surface disturbance risk was estimated with the aid of the digital elevation map of the area. Geology and site stability risk were evaluated on the basis of results of analysis of material stability, estimates of geological stability, presence of fractures and faults and danger of lava flows. Possible routes for pipelines have been mapped with respect to faults and fractures to estimate risk. For land use the minimum area needed for the constructions is evaluated. The distances of the central points of the two well fields proposed in the drillsite study (Figure 4) from the proposed power plant site were calculated with respect to pipeline routes defined. The state, of present tracks and the length of necessary additional access roads for each site, was evaluated. The distance from the respective sites to the existing Reykjahlíd power transmission line was estimated and relative values given. The outcome of this total evaluation is that site A is the most desirable site for the power plant which is the same outcome as presented in the Environmental Impact Report (Hönnun 2003a).

5. SUMMARY AND CONCLUSIONS

Environmental impact assessment for the proposed Bjarnarflag power plant in Námafjall, NE Iceland was carried out four times from 1995 to 2003, three times according to Act No. 63/1993, but the last one according to Act No. 106/2000. The experience shows that the first act lacked an adequate mechanism to deal with serious opposition such as had been voiced in comments from the National Trust and others. The wide-ranging comments and the stipulations made by the National Planning Agency in response to the third EIA which the operators considered to amount to a demand for a new EIA process showed that a major flaw in the initial act was the lack of a provision for a scoping document that should be open to comments, and with reference to whose final version the EIA should be carried out. This had been amended in Act No. 106/2000 and comments could be replied to and mitigation measures suggested without much trouble and the ruling of the National Planning Agency was not contested. Production drilling has already started

The use of GIS techniques for situating boreholes and power plant sites shows great promise and is likely to become a widely used tool in environmental impact studies in the future.

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LEGAL REQUIREMENTS FOR GEOTHERMAL DEVELOPMENT IN KENYA

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ABSTRACT

The development of geothermal resource requires compliance with the relevant National and International laws and regulations to ensure sustainability. The Constitution of Kenya and several Acts of Parliament together regulate and manage sustainable utilisation of geothermal resources. The two main laws that specifically deal with geothermal development are Geothermal Resources Act of 1982 and its supplementary legislation of 1990, and the Environmental Management and Co-ordination Act of 1999 with its associated regulations. The other laws and regulations do not directly apply to geothermal but their implications affect geothermal development at various stages and in various ways. A number of these laws and regulations have been discussed briefly in this paper.

1. THE CONSTITUTION OF KENYA

The Constitution is the supreme law of the Republic of Kenya that binds all persons and all State organs at both National and County levels of government. Specifically, Chapter Five (5) of the Constitution of Kenya on Land and Environment, stipulates the principles of sustainable utilisation, exploitation, management and conservation of land, the environment and natural resources, as well as equitable sharing of the accruing benefits, for the benefit of the people of Kenya. This therefore is directly applicable to exploitation of geothermal resources that are resident on the Kenyan land.

2. THE GEOTHERMAL RESOURCES ACT, 1982

The Act in conjunction with the Geothermal Resources Regulations, 1990 regulates the issuance of Geothermal Resources' Licences for the purpose of exploration, drilling, extraction, utilisation and disposal of geothermal steam and associated geothermal resources in or under the licensed area. The responsibility of declaring any area a geothermal resources area and issuing the authority or license to search for geothermal resources or to drill and extract and utilise geothermal resources lies with the Minister for Energy.

3. ENVIRONMENTAL MANAGEMENT AND CO-ORDINATION ACT, 1999 (EMCA, 1999)

EMCA, 1999 is an Act of Parliament that provides for the establishment of an appropriate legal and institutional framework for the management of the environment. Prior to its enactment in 1999, there was no framework environmental legislation. Kenya's approach to environmental legislation and administration was highly sectoral and legislation with environmental management components had been formulated largely in line with natural resource sectors. For example, land, forestry, mineral oils, water etc., this was the legacy of "colonial resource" management legislation. This legislation was primarily concerned with resource allocation and exploitation and therefore had very limited provision for the regulation of the adverse impacts of that process on the environment.

Environmental conservation components were later grafted upon this structure of allocation and exploitation piecemeal, mainly in response to the emergence of critical instances of environmental degradation. The sectoral approach had also diffused power and responsibility in numerous government departments and created jurisdictional overlaps and conflicts and ignored the indivisibility of and the interrelationships within the ecosystem. It therefore became very necessary to have a focal point within the government to coordinate activities, policies and to advise the government on environmental management issues. Through administrative instructions, several institutions were created to serve in various areas of environmental management; these include the National Environment Secretariat (NES) established in 1971. The Permanent Presidential Commission on Soil Conservation and Afforestation established in 1981. Both the Secretariat and Commission had no solid foundation having been created by administrative fiats and had no legislative backing.

In the years that followed, Kenya's participation in regional and global conventions gained momentum and Kenya hosted the first major UN agency based in a developing country, namely the United Nations Environmental Programme (UNEP) which was established soon after the Stockholm Conference in 1972. Several agreements and conventions relevant to the management and protection of the environment and natural resources were adopted after the 1972 conference and the evolution of environmental thought reached a stage when it was possible to identify some fundamental principles to govern environmental management. These developments acquired a new face from 1987 when the Brundtland Commission released their celebrated report entitled "Our Common Future" and then climaxed with the Rio conference in 1992.

3.1 General principles

Section 3 of the Act enunciates the General Principles that will guide the implementation of the Act. Every person in Kenya is entitled to a clean and healthy environment and has the duty to safeguard and enhance the environment. It is worth noting that the entitlement to a clean and healthy environment carries a correlative duty. Hence, there is not only the entitlement to a clean and healthy environment, but also the duty to ensure that the environment is not degraded in order to facilitate one's own health as well as other persons' enjoyment of the environment.

These fundamental principles on the environment which include; sustainable development of the environment and natural resources, precautionary measures to mitigate environmental degradation, integration of the environmental considerations into development and planning, promotion of public participation in environmental decision making and enforcement, essentially breathed life into the environmental framework law that we have in Kenya today namely the Environmental Management and Coordination Act No. 8 1999.

EMCA was developed as a framework law, and this is due to the fact that the Act is a single piece of legislation that contains to date a comprehensive system of environmental management in Kenya. The Act provides for the establishment of an appropriate legal and institutional framework for the management of the environment in Kenya and for matters connected therewith and incidental hereto. However, since it is a framework legislation, its implementation is dependent on the promulgation of

enabling regulations that NEMA is continuously working on. The Act is still in its nascent stages and, as such, it is still too early to assess its impact on environmental management in Kenya. Until all the enabling regulations have been promulgated and are in force, it would be presumptuous to evaluate its efficacy. The institution of NEMA is still in its formative stage. It still requires critical mass of expertise not only to cover its vast array of functions, but also to build up credibility and blaze the trail in the enforcement of the law for sound environmental management in Kenya. Nevertheless, most Kenyans are aware that there exists a law for the management of our environment and that the days of environmental conservation orders or directives from the President and the chiefs are gone.

The Act is based on the recognition that improved legal and administrative co-ordination of the diverse sectoral initiatives is necessary in order to improve national capacity for the management of the environment, and accepts the fundamental principle that the environment constitutes the foundation of our national, economic, social, cultural and spiritual advancement.

3.2 Environmental management and co-ordination regulations

IN EXERCISE of the powers conferred by sections 92 and 147 of the Environmental Management and Co-ordination Act, the Minister for Environment and Mineral Resources may, on the recommendation of the National Environment Management Authority in consultation with the relevant lead agencies, make regulations prescribing for matters that are required or permitted by this Act to be prescribed or are necessary or convenient to be prescribed for giving full effect to the provisions of this Act.

The Regulations made and gazetted so far include but not limited to:

- Environmental (Impact Assessment and Audit) Regulations, 2003
- EMC (Water Quality) Regulations, 2006
- EMC (Waste Management) Regulations, 2006
- EMC (Conservation of Biological Resources, Access and Benefit Sharing) Regulations, 2006
- EMC (Fossil Fuels) Regulations, 2006
- EMC Controlled Substances (Ozone Depleting Substances) Regulations, 2007
- EMC (Wetlands, Lakeshores and Riverbanks) Regulations, 2008
- EMC (Noise and Excessive Vibrations) Regulations , 2009

3.3 Brief highlights of some EMCA, 1999 regulations

The Environmental (Impact Assessment and Audit) Regulations, 2003 - Legal Notice No.101

- Environmental Impact Assessment (EIA) is a critical examination of the effects of a project on the environment. The goal of an EIA is to ensure that decisions on proposed projects and activities are environmentally sustainable. An EIA is conducted in order to identify impacts of a project on the environment, predict likely changes on the environment as a result of the development, evaluate the impacts of the various alternatives on the project and propose mitigation measures for the significant negative impacts of the project on the environment.
- The EIA also generates baseline data for monitoring and evaluating impacts during the project cycle as well as highlighting environmental issues with a view to guiding policy makers, planners, stakeholders and government agencies to make environmentally and economically sustainable decisions. It seeks to minimize adverse impacts on the environment and reduces risks. EIA also identifies measures to mitigate the negative impacts while maximizing on the positive ones.
- The EMCA,1999 requires that during the EIA process a proponent shall in consultation with the Authority seek views of persons who may be affected by the project or activity through posters, newspaper, radio and hold at least three public meetings with the affected parties and communities. The Project proponent pays for the entire EIA process. The fee payable to NEMA is 0.05% of the project cost.

- Environmental Audit (EA) is the systematic documentation, periodic and objective evaluation of activities and processes of an ongoing project. The goal of EA is to establish if proponents are complying with environmental requirements and enforcing legislation. The purpose of EA is to determine the extent to which the activities and programs conform to the approved environmental management plan. A comprehensive EA ensures a safe and healthy environment at all stages of project operations and decommissioning.
- An initial environmental audit and a control audit are conducted by a qualified and authorized environmental auditor or environmental inspector who is an expert or a firm of experts registered by the Authority. In the case of an ongoing project the Authority requires the proponent to undertake an initial environmental audit study to provide baseline information upon which subsequent environmental audits shall be based
- Self Audits are carried out after the environmental impact assessment study report has been approved by the Authority or after the initial audit of an ongoing project. The proponent shall take all practical measure to ensure the implementation of the environmental management plan by carrying out a self auditing study on a regular basis.

Environmental Management and Co-ordination (Water Quality) Regulations, 2006 - Legal Notice No. 120

- Water Quality Regulations apply to water used for domestic, industrial, agricultural, and recreational purposes; water used for fisheries and wildlife purposes, and water used for any other purposes. Different standards apply to different modes of usage. These regulations provide for the protection of lakes, rivers, streams, springs, wells and other water sources.
- The objective of the regulations is to protect human health and the environment. The effective enforcement of the water quality regulations will lead to a marked reduction of water-borne diseases and hence a reduction in the health budget.
- The regulations also provide guidelines and standards for the discharge of poisons, toxins, noxious, radioactive waste or other pollutants into the aquatic environment in line with the Third Schedule of the regulations. The regulations have standards for discharge of effluent into the sewer and aquatic environment. While it is the responsibility of the sewerage service providers to regulate discharges into sewer lines based on the given specifications, NEMA regulates discharge of all effluent into the aquatic environment.
- The regulations provide for the creation of a buffer zone for irrigation schemes of at least fifty (50) metres in width between the irrigation scheme and the natural water body. Standards for irrigation water are given in schedule nine of the regulations.
- All firms or persons discharging effluent into the aquatic environment are required to submit quarterly discharge monitoring records to NEMA based on prescribed procedures of sampling and analysis.
- Everyone is required to refrain from any actions, which directly or indirectly cause water pollution, whether or not the water resource was polluted before the enactment of the Environmental Management and Coordination Act (EMCA) gazetted in 1999. It is an offence to contravene the provisions of these regulations with a fine not exceeding five hundred thousand shillings.

Environmental Management and Co-ordination (Waste Management) Regulations, 2006 - Legal Notice No.121

- Waste Management Regulations are meant to streamline the handling, transportation and disposal of various types of waste. The aim of the Waste Management Regulations is to protect human health and the environment. Currently, different types of waste are dumped haphazardly posing serious environmental and health concerns. The regulations place emphasis on waste minimization, cleaner production and segregation of waste at source.
- The regulations have classified various types of waste and recommended appropriate disposal methods for each waste type. Under the Waste Management Regulations, NEMA licenses

transporters, incinerators, landfills, composers, recyclers and transfer stations. Facilities to be licensed include local authorities, transporters and handlers of various types of waste. The licensing employs a risk-based approach by concentrating on facilities considered to pose a high risk to the environment.

- The Waste Management Regulations also provide an opportunity for investment in various aspects of waste management.

3.4 Environmental management

Environmental management includes the protection, conservation and sustainable use of the various elements or components of the environment.

It is an integral component of geothermal resource development due to its resultant impacts on the environment. Consequently, utilisation of geothermal energy and its composite activities fall within the categories that are stipulated in the Second Schedule of EMCA, 1999 for projects that must undertake Environmental Impact Assessment prior to commencement. The categories are:

1. General –
(a) an activity out of character with its surrounding;
(b) any structure of a scale not in keeping with its surrounding;
(c) major changes in land use.
2. Dams, rivers and water resources including –
(a) storage dams, barrages and piers;
(b) river diversions and water transfer between catchments;
(c) flood control schemes;
(d) drilling for the purpose of utilising ground water resources including geothermal energy.
3. Electrical infrastructure including –
(a) Electricity generation stations;
(b) Electrical transmission lines;
(c) Electrical sub-stations;
(d) Pumped-storage schemes.
4. Waste disposal including sites for solid waste disposal
(a) Sites for hazardous waste disposal;
(b) Sewage disposal works;
(c) Works involving major atmospheric emissions;
(d) Works emitting offensive odours.

3.5 Environmental management tools

Currently, various tools are in use for the purpose of managing the impacts that have the potential of degrading the environment. They are mainly applied in identification, planning, design, negotiation, and implementation of strategies and operations. They include:

I. Environmental Impact Assessment (EIA)

EIA means a systematic examination conducted to determine whether or not a programme, activity or project will have any adverse impacts on the environment.

II. Environmental Audit (EA)

EA means the systematic, documented, periodic and objective evaluation of how well environmental organisation, management and equipment are performing in conserving or preserving the environment.

III. Strategic Environmental Assessment (SEA)

SEA is the systematic, proactive process for evaluating the environmental consequences of policies', plans' and programs' (PPPs') proposals, in order to ensure that their environmental consequences are fully included and adequately addressed at the earliest appropriate stage of decision-making, at par with economic and social considerations.

IV. Environmental Risk Assessment (EnRA)

EnRA means a systematic examination conducted to determine whether or not a program, activity or project will pose any risks to the environment.

V. Social Impact Assessment (SIA)

SIA means a systematic examination conducted to analyse how development proposals affect people, identify and mitigate their adverse impacts, enhance benefits as well as help manage social change.

4. THE LAKES AND RIVERS ACT (Cap. 409)

This Act makes provision for the protection of bird and other wildlife in or on lakes and rivers, and protection of waterways in general.

5. THE ENERGY ACT, 2006

An Act of Parliament to amend and consolidate the law relating to energy, to provide for the establishment, powers and functions of the Energy Regulatory Commission and the Rural Electrification Authority, and for connected purposes.

The provisions of this Act applies, to every person or body of persons importing, exporting, generating, transmitting, distributing, supplying or using electrical energy; importing, exporting, transporting, refining, storing and selling petroleum or petroleum products; producing, transporting, distributing and supplying of any other form of energy, and to all works or apparatus for any or all of these purposes.
The Act emphasizes need for renewable energy, energy efficiency and conservation

6. THE WATER ACT, 2002

The Water Act 2002 is the main legislation that regulates the water sector in Kenya. It created the Water Resources Management Authority (WRMA) whose role is to regulate and manage water resources in Kenya. The Act ensures availability of water through regulating the amount of water that can be supplied in bulk by a licensee or a water service provider so that water supply to domestic water consumers is not affected. It provides that water service providers have a legal duty of providing water services to the people and also ensuring that associated works and facilities are provided, maintained and progressively improved.

The Act prioritises the allocation of water resources for essential domestic uses over other uses such as industrial use e.g. geothermal resource development. Geothermal development activities require substantial quantities of water for construction, drilling and power plant cooling operations and for domestic use by the respective working staff. Further, the Act entrenches public participation and involvement in water services' and water resources' management.

7. THE PUBLIC HEALTH ACT (Cap. 242)

Part IX, Section 115 of the Act states that no person/institution shall cause nuisance or condition liable to be injurious or dangerous to human health. Section 116 requires Local Authorities to take all lawful, necessary and reasonably practicable measures to maintain their jurisdiction clean and sanitary to prevent occurrence of nuisance or condition liable to be injurious or dangerous to human health.

Any noxious matter or waste water flowing or discharged from any premises into a public street or into the gutter or side channel or watercourse, irrigation channel or bed not approved for discharge is also deemed as a nuisance. Other nuisances are accumulation of materials or refuse which in the opinion of the medical office of health is likely to harbor rats or other vermin.

8. THE PHYSICAL PLANNING ACT, 1999

The Local Authorities are empowered under Section 29 of the Act to prohibit or control the use and development of land and buildings in the interest of proper and orderly development of an area. Section 30 states that any person who carries out development without development permission will be required to restore the land to its original condition. It also states that no other licensing authority shall grant license for commercial or industrial use or occupation of any building without a development permission granted by the respective local authority. Subject to subsection (7) no licensing authority shall grant, under any written law, a licence for commercial or industrial use or occupation of any building, or in respect of any premises or land, for which no development permission had been granted by the respective local authority. Industrial use includes manufacturing, processing distilling and brewing, warehousing and storage, workshops and garages, mining and quarrying and other similar industrial activities including petroleum filling stations.

9. THE LAND PLANNING ACT (Cap. 303)

Section 9 of the subsidiary legislation (The Development and Use of Land Regulations, 1961) under this Act, requires that before the local authorities submit any plans to the Minister for approval, steps should be taken as may be necessary to acquaint the owners of any land affected by such plans. Particulars of the comments and objections made by the landowners should also be submitted. This is intended to reduce conflict with other interests such as settlement and other social and economic activities.

10. THE PENAL CODE (Cap. 63)

Section 191 of the Penal Code states that any person or institution that voluntarily corrupts or foils water for public springs or reservoirs, rendering it less fit for its ordinary use is guilty of an offence. Section 192 says that a person who makes or vitiates the atmosphere in any place to make it noxious to health of persons/institution in dwellings or business premises in the neighbourhood or those passing along public way commits an offence.

11. THE WILDLIFE CONSERVATION & MANAGEMENT ACT, Cap. 376

This Act consolidates and amends laws relating to the protection, conservation and management of wildlife in Kenya. The main objective is to ensure that wildlife are managed and conserved in a manner that yields optimum returns in terms of scientific, cultural, aesthetic and economic gains, while at the same time taking into account the varied forms of land use and the inter-relationship between wildlife and other land uses. The Kenya Wildlife Service (KWS) is a Kenyan state

corporation that was established under the Act with the mandate to conserve and manage wildlife in Kenya, and to enforce related laws and regulations. This Act is particularly applicable to Olkaria Geothermal Project since it is situated within the Hell's Gate National Park.

12. THE FORESTS ACT, 2005

An Act of Parliament that provides for the establishment, development and sustainable management, including conservation and rational utilisation of forest resources for the socio-economic development of the country. The Act created the Kenya Forest Service whose roles among others is to manage all State forests; manage all provisional forests in consultation with the forest owners; and protect forests in Kenya in accordance with the provisions of this Act. Any activities within a forest area which are not included in a management plan shall only be undertaken with the consent of the Board granted in accordance with this section. A person intending to undertake any activity not included in a management plan within a forest area shall apply in that behalf to the Board, and the application shall be accompanied by the results of an independent Environmental Impact Assessment conducted in respect of the proposed activity. Geothermal resources are currently being developed in Eburru and Menengai Forest Reserves.

13. THE PUBLIC PROCUREMENT AND DISPOSAL ACT, 2005

An Act of Parliament to establish procedures for efficient public procurement and for the disposal of unserviceable, obsolete or surplus stores, assets and equipment by public entities and to provide for other related matters. The Act provides for the establishment of the Public Procurement Oversight Authority to ensure compliance with the procurement procedures. The Public Procurement and Disposal Regulations are meant for better implementation of the provisions of the Act. The objectives of the Act are:

(a) to maximise economy and efficiency;
(b) to promote competition and ensure that competitors are treated fairly;
(c) to promote the integrity and fairness of those procedures;
(d) to increase transparency and accountability in those procedures; and
(e) to increase public confidence in those procedures.
(f) to facilitate the promotion of local industry and economic development.

The Act is applicable with respect to:
(a) procurement by a public entity;
(b) contract management;
(c) supply chain management, including inventory and distribution; and
(d) disposal by a public entity of stores and equipment that are unserviceable, obsolete or surplus.

14. OCCUPATIONAL SAFETY AND HEALTH ACT, 2007

It is an Act of Parliament that provides for the safety, health and welfare of workers and all persons lawfully present at workplaces and for the establishment of the National Council for Occupational Safety and Health. The Act applies to all workplaces where any person is at work, whether temporarily or permanently. The purpose of the Act is to secure the safety, health and welfare of persons at work; and protect persons other than persons at work against risks to safety and health arising out of, or in connection with, the activities of persons at work.

Geothermal development activities are labour intensive, hence the need to guarantee the safety of the workers and all persons lawfully present at workplaces.

14.1 International legislations

Besides the national legislations, there are international guidelines that govern the development of geothermal resources especially those that touch on the environment and natural resources. They are listed below:

I) Vienna Convention for the Protection of the Ozone Layer, 1985

An international treaty for the control of substances that deplete the ozone layer.

II) The United Nations Framework Convention on Climate Change (UNFCCC), 1992

An international treaty to stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climatic system.

III) The Ramsar Convention on Wetlands, 1971

- It is an intergovernmental treaty that provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources. The wetlands include lakes and rivers, swamps and marshes, wet grasslands and peatlands, oases, estuaries, deltas and tidal flats, near-shore marine areas, mangroves and coral reefs, and human-made sites such as fish ponds, rice paddies, reservoirs, and salt pans. Geothermal projects are located within the Rift Valley that has five (5) Ramsar sites e.g. Lakes Baringo, Bogoria, Elementaita, Naivasha and Nakuru.

IV) Bonn Convention on the Conservation of Migratory Species of Wild Animals, 1979

It is an intergovernmental treaty concerned with the conservation of migratory species of wildlife and their habitats on a global scale.

V) African Convention on the Conservation of Nature and Natural Resources, 1968

Convention for the conservation, utilization and development of soil, water, flora and faunal resources in accordance with scientific principles and with due regard to the best interests of the people.

CONCLUSION

Compliance with the stated and other requisite legal requirements is inevitable and of paramount importance, for sustainable development of geothermal resources.

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GEOTHERMAL ENERGY DEVELOPMENT & POTENTIAL, BIODIVERSITY CONSERVATION AND TOURISM DEVELOPMENT: EXAMPLES FROM KENYA

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ABSTRACT

Geothermal energy development in Kenya is associated with the African Rift Valley which intersects Djibouti, Eritrea, Ethiopia, Kenya, Tanzania Zambia, Malawi and northern Mozambique. There is a western segment that passes through Uganda, Rwanda and Burundi. All these countries have some geothermal potential. It is only in Kenya and Ethiopia that exploitation of geothermal energy for power generation has been attempted. Electricity generation from geothermal in Kenya started in 1981 with construction of Olkaria I station. The current output in Kenya is 209 MW which is about 16% of the country's effective capacity. There is a plan to increase the generation by an additional 5000 MW by 2030. The current geothermal capacity is located in Olkaria Geothermal field mainly within Hell's Gate National Park which is a nature/wildlife conservation area. Kenya has over the years gained experience in managing the environmental issues associated with geothermal development in nature conservation areas. This has proved that geothermal development can coexist with wildlife with maximum benefit from both resources. Kenya would like to replicate this success in other geothermal sites some of which are located in either National parks or Game Reserves.

1. INTRODUCTION

Most of the East African countries rely on biomass as the primary source of energy. Electricity accounts for between 10 and 30%. The electrical energy is predominantly from hydropower (70%), followed by fossil fuel thermal. With hydropower dominating the generation, Kenya and other East African Rift countries suffer from frequent rationing of power caused by drought and siltation in the dams and also experience high variations of prices caused by the world fuel markets. Geothermal development thus offers an excellent opportunity for saving foreign currency, cushion the supply variations and meet ever increasing power demand. Geothermal energy also offers renewable, indigenous and environmentally friendly alternative to more traditional sources.

Kenya has so far produced power from her geothermal resources. Kenya relies on three major sources of energy. These are biomass (68 %), petroleum (22 %) and Electricity (9 %). Hydropower (57 %) dominates the electricity sub-sector, followed by fossil- based thermal (32 %) and then geothermal (11 %). The other forms of renewable energy (wind, solar, biogas, micro hydro etc.) account for less than 1 %. Due to unreliable rain patterns, and the fact that Kenya depends highly on hydropower, the electricity supply has becoming unreliable especially during the dry seasons. Development of

geothermal energy, which is indigenous, low cost, environmentally benign and reliable, seems to be the long-term solution to this problem. Several recent least cost power development plans (KPLC, 2005) has considered geothermal energy as a least cost source of electrical power in Kenya.

The electrical power demand in Kenya has had an increasing trend over the last five years. This is expected to rise even more with the improvement of economy. With the commitment the government of Kenya has demonstrated to exploration and exploitation of geothermal energy, geothermal energy is expected to meet a large percentage of this demand. This paper presents geothermal development and nature conservation in selected geothermal fields and prospect areas.

2. GEOTHERMAL RESOURCES POTENTIAL IN KENYA

About fourteen geothermal prospects have been identified in the Kenyan Rift valley (Figure 1). Their geothermal potential is estimated to be in excess of 10,000 MWe. Wells have been drilled in only Olkaria, Eburru and Menengai but exploitation so far has only been done at Olkaria geothermal field.

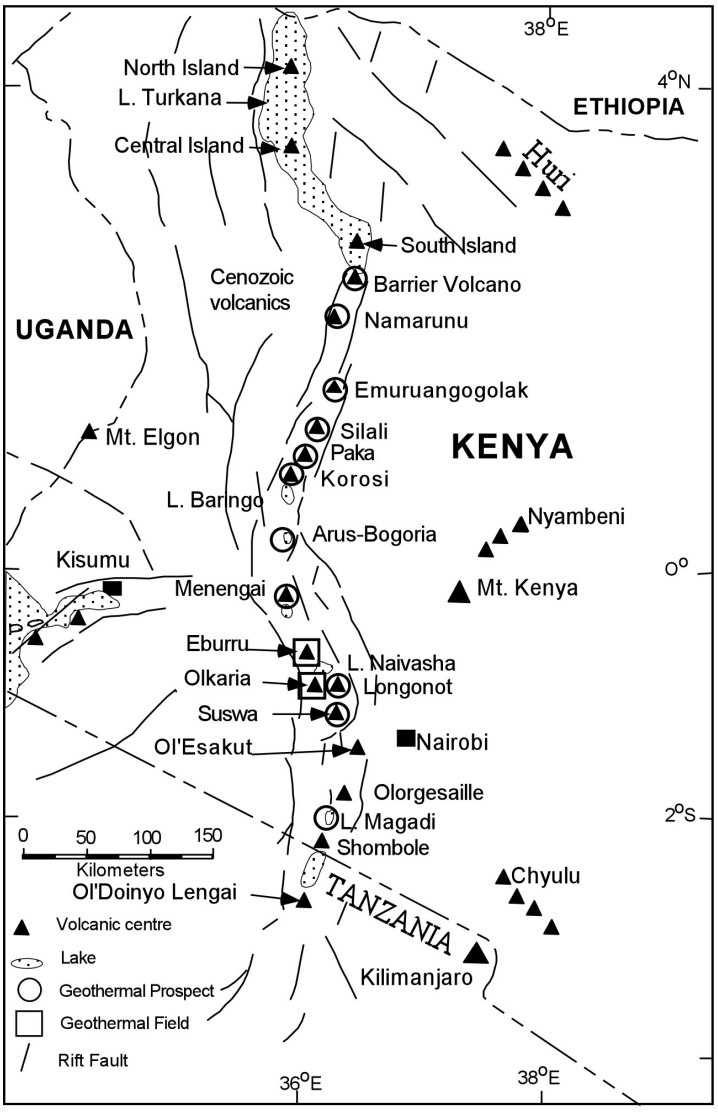

FIGURE 1: Geothermal prospects in the Kenya Rift Valley

For the sake of development, the Greater Olkaria geothermal area which is about 80 km2 has been divided into seven sectors namely Olkaria East, Olkaria West, Olkaria Northwest, Olkaria Northeast, Olkaria Central, Olkaria Domes and Olkaria Southwest. Currently, Olkaria East, and Olkaria Northeast Olkaria West and Olkaria Northwest fields are generating 209 MWe. In Olkaria Domes field, which is the fourth field targeted for development, exploration, appraisal and production wells have been drilled with 140 MWe of steam already proven with the planned construction of 140 MWe Olkaria IV geothermal power plant.

Detailed surface exploration was concluded in Suswa and Longonot, Menengai, Arus-Bogoria, Lake Baringo, Korosi-Chepchuk, Paka and Silali prospects and deep exploration wells have been sited. Exploration drilling is ongoing in Menengai field where four (4) wells have already been drilled by Geothermal Development Company.

3. GEOTHERMAL DEVELOPMENT AND UTILISATION

3.1 Electricity production

Currently, geothermal energy is being utilised in Olkaria field only. Three of the seven Olkaria sectors namely Olkaria East field, Olkaria West field and Olkaria Northeast field are generating a total of 209 MWe.

Olkaria I Power Plant: The Olkaria I power plant is owned by Kenya Electricity Generating Company Ltd (KenGen) has three turbo generating units each generating 15 MWe. The three units were commissioned in 1981, 1983 and 1985 respectively therefore the plant has been in operation over the last thirty (30) years.

Olkaria II Power Plant: Construction of 2 x 35 MW Olkaria II geothermal power station started in September 2000 was completed November 2003. An additional 35 MW Olkaria II 3rd Unit was commissioned in 2008 bring the total installed capacity of the plant to 105 MWe.

Olkaria III Power Plant: Olkaria III project is the first private geothermal power plant in Kenya. A 20 year Power Purchase Agreement (PPA) was awarded to Orpower 4 Inc. by Kenya Power and Lighting Company (KPLC) under a World Bank supervised international tender for the field development of up to 100 MWe. Currently, the plant has an installed capacity of 48 MWe in operation.

Oserian Plant: Oserian Flowers company has constructed a 5.0 MW binary plant Ormat OEC to utilise fluid from well OW-306 leased from KenGen. The plant provides electrical power for the farm's operations was commissioned in July, 2004.

3.2 Direct uses

3.2.1 Greenhouse heating

The only commercial application of geothermal energy for direct use in Kenya is at Oserian Development Company. The company grows cut flowers and other horticultural crops in greenhouses for sale in the European market. The company installed a greenhouse heating system in May 2003 using a 15 MWt well leased from KenGen. Heating the green houses increases the plants' growth rate, reduce humidity and consequently decrease diseases. The carbon dioxide from the well is also useful for the flower photosynthesis. The system is currently heating 30 hectares and there is a plan to expand the heating if more heat would be available. Oserian is therefore planning to lease more wells from KenGen for this purpose.

3.2.2 Swimming Pool heating

Hot springs have been used to heat spas in tourist hotels for example in Lake Bogoria Spa hotel which is located near the Lake Bogoria geothermal prospect.

3.2.3 Industrial Processing

The Local community at Eburru geothermal resource condenses the steam from fumarole and uses the water for domestic purposes. They also use geothermal to dry pyrethrum.

4. FUTURE DEVELOPMENTS

4.1 Electricity generation in Olkaria Fields

4.1.1 Olkaria I Units 4 and 5 power plant

The initial design of Olkaria I power plant and steamfield had proposed a life of 25 years. The units have been in operation for the last 30 years. Studies have shown that the plant and the reservoir are in good condition, and the reservoir is having more steam than is required to generate 45 MWe. An optimisation study conducted by KenGen revealed a possibility of increasing generation from this field hence a 140 MWe Olkaria I Unit 4 and 5 power is planned for this field. Additional production wells have already been drilled which have proven steam to support the plant.

4.1.2 Olkaria IV power plant

KenGen drilled three deep exploration wells in Domes field between September 1998 and May 1999. GDC has further drilled appraisal and production wells since 2008 which has proved steam equivalent of 140 MWe. This field is designated for construction of 140 MWe Olkaria IV geothermal power plant.

4.2 Menengai field geothermal drilling project

Menengai Geothermal Project is located on the outskirts of Nakuru Town, about 180 Km west of Nairobi. The geothermal field will be developed in three phases of 400 MWe each. GDC has commenced drilling in the field using two rigs that will culminate in the production of steam for the power plants. Currently, already four (4) exploration wells have been successfully drilled. The objective of the project is to develop the field to a capacity of 400 MWe by 2016. Subsequently, an additional 200 Mwe capacity is anticipated to be on line by 2016 and a further 400 MWe by 2017. The total field capacity is estimated at over 1600 MWe.

4.3 Direct uses

Oserian Development Company, which is a flower growing company has realised the advantages of heating the greenhouses using geothermal brine in heat exchangers. Apart from enhancing growth, the heat reduces humidity in the houses and inhibits diseases that would otherwise be controlled using expensive pesticides. Also, the carbon dioxide gas from the wells enhances photosynthesis of the plants. Oserian is therefore planning to lease more geothermal wells from KenGen for this purpose. Other flower growing companies are also interested and the possibility of supplying them with brine is being evaluated.

4.4 Other geothermal prospects

A prefeasibility study for multiple use of geothermal for electricity generation and water production for agriculture and domestic use is being carried out at Eburru geothermal field by GDC. The first phase of this project, which is the construction of a 2.5 MW binary plant by KenGen is on-going and

is planned to be commissioned at the end of 2012. Detailed surface exploration work at Suswa, Longonot, Arus-Bogoria, Lake Baringo, Korosi-Chepchok, Paka and Silali prospects have been completed. Exploration drilling is planned to be done in Silali prospect by GDC in 2012 after acquisition of two more drilling rigs whose delivery is expected in early 2012.

5. GEOTHERMAL DEVELOPMENT IN NATURE CONSERVATION AREAS

The geothermal prospects that are located in nature conservation area (National Parks or Game Reserves) are Olkaria, Longonot, Lake Bogoria, and Lake Baringo. The rest of the prospects are in lands owned either by Government as forests (Eburru and Menengai), privately owned or in the hands of group communities.

As indicated, Olkaria, Eburru and Menengai fields are under development with Olkaria field being is the only field that is well developed so far in Kenya currently supporting three stations within Hell's Gate National Park, a wildlife conservation area. The planned 140 MWe Olkaria IV will be located in a private land. This paper will summarize the biodiversity conservation, tourism and geothermal power development in Olkaria, Longonot, Menengai, Lake Bogoria and Lake Baringo geothermal areas. A government institution known as Kenya Wildlife Service (KWS) manages National Parks whereas Game Reserves are owned and managed by Local Authorities and communities in which they are located.

5.1 Hell's Gate National Park in Olkaria Geothermal Field

Hell's gate National Park is situated within Olkaria geothermal area located on the southern side of Lake Naivasha, which is the lifeline of economic activities in the semi-arid region of Rift Valley Province of Kenya. The geothermal resource presently supports an existing 45 MWe power station (Olkaria I), which commenced construction in 1980. An important aspect in the environmental management of geothermal developments in this area has been the existence of Hell's Gate National Park, which was established in 1984 several years after the present Olkaria I Power Station was commissioned (The World Bank Group, 2001). The park covers an area of about 6825.7 ha (68.5 km^2) and encloses both the Olkaria I power station, Olkaria II power station under construction, Olkaria III power station operated by a private developer Orpower4 Inc in Olkaria Southwest and much of the geothermal resource. Major land uses in and around the park has been geothermal development, livestock ranching, cultivation of cut flowers for export market and conservation of wildlife. Wildlife conservation as an aspect of sound environmental management has been a key component in geothermal resource development.

5.1.1 Landscape and flora in Hells Gate National Park

Three major landscapes exist depending on terrain, vegetation and wildlife use (Kenya Wildlife Service, 1992). The plains are part of the Njorowa gorge that divides the park into two unequal parts with dominant plant species being *Cynodon dactylon, Digitaria scalarum, Tarchonanthus camphoratus* and *Acacia drepanolobium* (Kiringe, 1993). About 170 plant species have been recorded in HellsGate Park.The area holds substantial number of large herbivores due to its flat terrain and suitable food material (Kenya Wildlife Service, 1992; Simiyu, 2000).Hill and mountain encompasses the geothermal development area towards the Olkaria gate. Olkaria hill with an elevation of 2240 m.a.s.l is within this region. Dominant vegetation association are *Tarchonanthus/Acacia shrubland and Cymbopogon/ Themeda / Digitaria* which do not constitute important food source for the animals hence low concentration. Cliffs, main wall and towers consist of the main walls of the gorge and the Fischer's and central towers. The area is rocky with scanty vegetation. The cliffs form important breeding and nesting grounds for various bird species such as the verreaux's eagles, Ruppell's vulture and the rare lammergeyer (bearded vultures).

5.1.2 Fauna of Hells Gate National Park

Wildlife species in Hell's Gate National Park and adjoining area of Kedong Ranch, Kongoni Ranch and Akira Ranch are mainly plains game. They include Buffalo (*Syncerus cafer*), Zebra (*Equus burchellis*), Grant's gazelle (*Gazelle grantii*), Thomson's gazelle (*Gazelle thomsonii*), Coke's hartebeest (*Alcephalus buselaphus*), Maasai giraffe (*Giraffa reticulata*) among others. Avifauna is quite diverse due to its proximity to Lake Naivasha that has numerous bird species because of habitat heterogeneity (Kenya Wildlife Service, 1992). KWS/KenGen having been undertaking quarterly wildlife population in the Olkaria and adjacent areas to determine the population density and distribution (Figure 2).

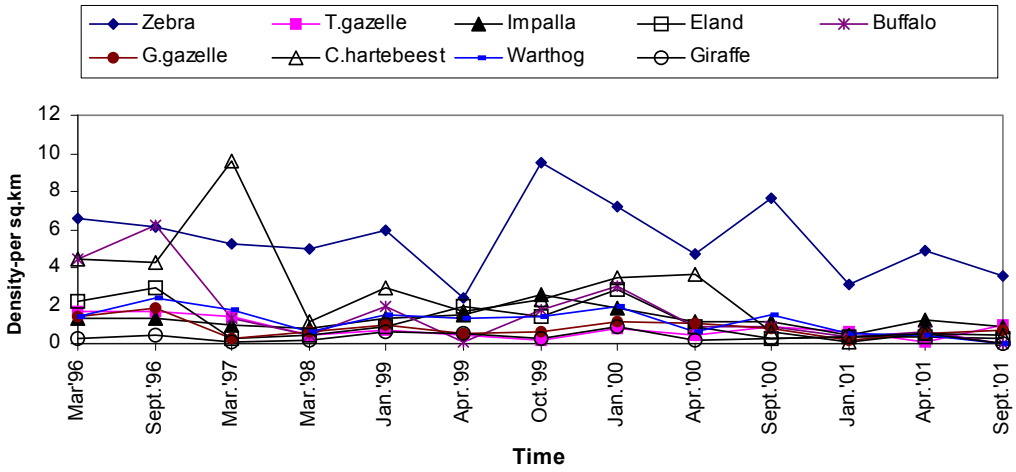

FIGURE 2: Wildlife population density Hell's Gate National Park, Olkaria (Wetangula, 2003)

5.1.3 Tourism in Hells Gate National Park

There is a marked increase in tourists visiting the Hell's Gate Park (Figure 3) some of whom are more interested in visiting the Olkaria I and II power stations rather than seeing the animals. The power stations have recorded about 2000 visitors a month on average. There are others that want to see both the animals and the power stations and even chose to camp nearby. In our view, the presence of the power stations is a major attraction to the tourists and consequently benefits the park.

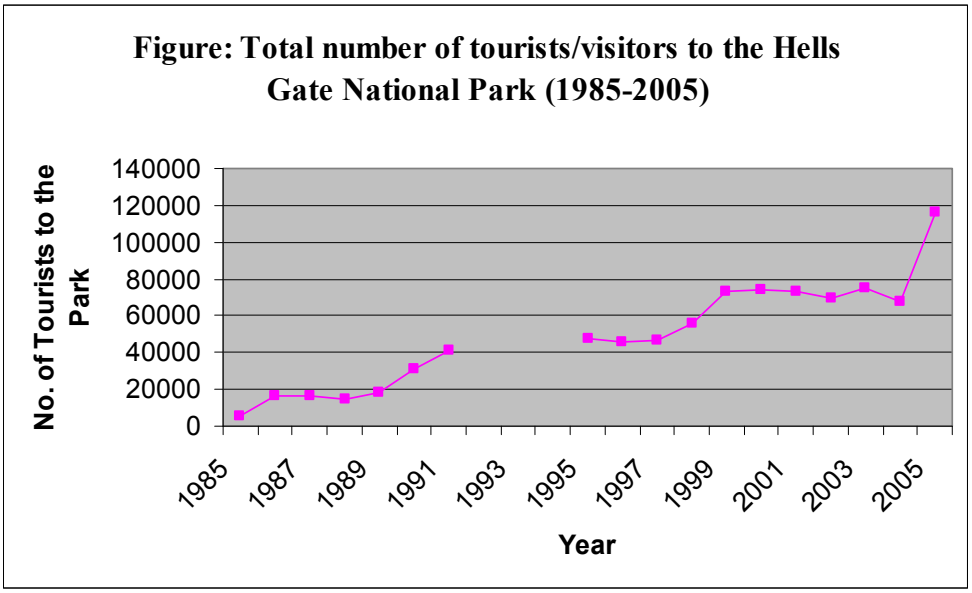

FIGURE 3: Tourists to Hells Gate National Park, Olkaria

5.2 Longonot Geothermal Prospect and National Park

Longonot National Park is Located to the east of Hell's Gate National Park about 85km North West of Nairobi. The park comprises of the Mount Longonot which is a central volcano with a crater at peak. The Longonot crater and caldera that hosts the Longonot Geothermal Prospect covers an area of about 35 km^2. KenGen carried out detailed surface surveys in this prospect between April and July 1998. Data analysis showed that Longonot Geothermal Prospect has positive indicators of a geothermal resource that can be commercially exploited. The geothermal potential of the area is associated with a large magma chamber under the caldera and summit crater on Mr. Longonot that also constitutes the heat source. The area around Longonot is marked by active manifestations that occur in the form of fumaroles, altered grounds, warm grounds, sulphur and silica depositions. Estimates deduced from gas geothermometry show that there exists a high temperature resource centred underneath the main summit crater with reservoir fluids temperatures in excess of 300ºC. Resistivity data indicates that the area starting from the Longonot crater and to the south define a low resistivity anomaly ($\leq 10\ \Omega m$) that extends over an area of 70 km^2.

Longonot National Park (wildlife conservation area) was gazetted in 1984 together with Hell's Gate National Park as Hell's Gate/Longonot National Parks. Total area of the Park is 52km^2. The park can be zoned into three-zone categories namely special zone, semi wilderness and utility zone. The *Special Zone* encompasses the V-shaped valleys and steep slopes around the crater rims and their associated vegetation. According to the park management plan, it is recommended that no motorized drives should take place in this area unless it is very necessary and have to be kept to minimum. The three proposed sites for exploratory drilling are located within this zone. *Semi-wilderness Zone* has large tracts of relatively undisturbed but accessible for semi wilderness experience. Permitted developments in this area include walking trails, picnic sites and viewing sites. Some areas are motorable while others are non motorable. The *Utility Zone* provides sites for management and other developments where premises for tourism and general park management are situated.

5.2.1 Flora of Longonot

The most dominant vegetation in the area of interest is an association of Cymbopogon/ Themeda/Tarchonanthus/Acacia/Dwarf/Shrubland. This is the most dominant vegetation type and occurs in most higher areas. Dominant vegetation species include *Tarchonanthus camphoratus* (Mleleshwa), *Themeda triandra, Acacia drepanalopium and Cymbopogon* sp. The Park is quite open due to fire which sweeps across the mountain almost every year.

5.2.2 Fauna of Longonot

The wildlife species in Longonot National Park include, Reedbuck, Zebra, Eland, Lion, Cheetah and Buffalo. The Park has low wildlife numbers due to the nature of the vegetation and terrain. During the rainy season the animals are found in large numbers especially the Zebra. The numbers decline as the dry spell sets in due to reduced grazing materials. Zebra is the most abundant species in this ecosystem. No plant or animal has been identified as endemic in this Park.

5.2.3 Tourism

The largest tourist attraction of this park is climbing up to the crater and even circling it. Only the strong ones walk round the edge of the crater a distance of about 11 km.

5.3 Menengai caldera and forest reserve

Menengai caldera also attracts many visitors because of the beautiful scenery when at the top of Lion Hill View Point. School children and University students are the main visitors of this area because access to this crater is fairly easy. Tourists who visit Lake Nakuru Park also do visit this area. Part of

the caldera is gazetted as Menengai forest reserve and is under the management of Kenya Forest Service. The other part is trust land. Currently KFS is in the process of securing this area so as to earn revenue from the visitors by charging a fee for each visit. Already some organized groups have put up some tented camps for visitors.

5.3.1 Menengai forest and associated flora

Menengai Forest is at an altitude of 9910ft above sea level with total gazetted area of 7,315.3 ha including the crater. The forest vegetations resemble that of the "true savannah". The dominant natural vegetation: Leleshwa (*Tarconanthus camphorates), Rhus natalensis, Rhus vulgaris, Euclea divinorum, Acacia sp. (A. abysinnica & A. lahai), Cussonia sp. (C. spicata & C. simplifolia)*. Dying species due to illegal over explotation inside the crater include Cidar which are now too scattered and few to due illegal harvesting. There is a big portion of open glades of grass (grassland), which are susceptible to fires. Outside the caldera, on the hilly part of the forest are Black wattle (*Acacia mearsii*) and some planted *Eucalyptus sp.* (*E. maculata, E. saligna, E. globules & E. grandis*), which are however being destroyed by the locals. *Erytherina abbysinica* used to be wide spread within the forest but has been decimated by herbalists who have been digging/exploiting it for medicinal purposes, thus could become endangered if not controlled. Areas within the caldera floor are dominated by bushed grasslands comprised of species of *Tarconanthus camphoratus* and *Acacia drepanolobium* in association with *Chloris gayana*, *Digitaria abyssinica* , *Fimbristylis exilis* (geothermal grass)and *Boma Rhode* grasses. Parches of bushed woodland (*Tarconanthus camphoratus* (Leleshwa), *Acacia* and some *Euphorbia candelabra),* mixed bushland (*Acacia drepanolobium, Dodonea viogar* and *Tarconanthus camphorates)*, and open grasslands (*Themeda triandra*, *Cynodon dactylon*, *Chloris gayana* and *Digitaria abyssinica)* forming various associations are common both within and outside the Caldera floor.

5.3.2 Fauna of Menengai

The wild animal species documented in the Menengai geothermal the project area is given in Table 1. There are very few wild animal species as large parts of it are farmlands with no open grazing and dispersal areas. Leopards, Baboons, Wild pigs and Snakes are common within Menengai Caldera. Cases of Human - Wildlife conflicts mainly due to invasions of farms by the Baboons and Monkeys have been reported.

TABLE 1: Distribution of wildlife species

Areas	**Common Wildlife Species**
Menengai Caldera	Antelopes, Dik dik, Gazelles, Monkeys (vevets, Columbus), Ant bears, Baboons, Leopards, Snakes (Puff udder), Birds (Quills, Guinea fowls, Cave spurrows, bats, weaver birds) and Wild pigs.
Solai	Leopards, Zebra, Velvet Monkeys, Baboons, Hyena, Tortoise and Snakes.
Kambi ya Moto	Porcupine, Zebra, Baboons and Impala.
Dundori	Columbus Monkey, Velvet Monkey, Wild-pigs and Baboons.
Bahati	Leopard, Mongoose, Porcupine, Baboons and Hyenas.

Source: Nakuru District KWS Warden's Office

5.3.3 Tourism in Menengai

The proposed project is within Menengai caldera, which is a tourist attraction, noted particularly for its scenic beauty (Figure 4). Some of the major tourist attraction sites like the Lake Nakuru National Park and Hyrax prehistoric sites are within proximity of the Menengai geothermal project. The tourism potential of the area has been enhanced by opening up more access roads into the caldera, which have previously been viewed as a place for bhang/marijuana growers and thieves' hideouts. Geothermal

drilling project in Menengai in itself is a tourist attraction feature which has witnessed a number of visitors to the project just like in Hells Gate National Park at Olkaria.

FIGURE 4: Wilderness of Menengai caldera as a tourist attraction feature in the area with Lion Hill viewpoint at background

5.4 Lake Baringo Geothermal Prospect and National Reserve

Lake Baringo Geothermal Prospect is one of the several important areas on the Kenya Rift floor that are associated with possible occurrence of geothermal resource. A surface exploration study encompassing geology, geochemistry, geophysics, heatflow were carried out by GDC between 16th February to 3rd March, 2011. This was a follow up to the infill work that had been carried out in July, 2010 (Figure 5). Previous survey was done by KenGen (Kenya Electricity Generation Company) in 2004. Hydrothermal activity in the Lake Baringo prospects is manifested by extensive occurrence of fumaroles, hot spring, altered grounds and thermally anomalous ground-water boreholes. One of these boreholes, the Chepkoiyo borehole, which was drilled in April 2004, self-discharged water at 98°C (local boiling point). The chemistry of the discharged fluids indicated possible input from a geothermal reservoir.

5.4.1 Fauna of Lake Baringo prospect area

Lake Baringo, fresh water lake in this geothermal prospect area that support a number of wildlife species lead to establishment of Lake Baringo Conservation Area. This conservation area was gazetted in 1994 and currently is managed by Baringo County Council. Wildlife in and around the Lake includes reptiles (crocodiles, snakes, tortoises), Hippopotamuses, over 480 bird species including ostriches, zebras and baboons) attracting many tourists, hence the area plays an important role in supporting the local and regional economy. The council in collaboration with the local community has also established a Reptile Park at Kampi Samaki. Though official information about wildlife does not exist, it is well known the lake is rich in hippopotamus and crocodiles. For example, Lake Baring Country Club estimated, by physical counting about 150 hippopotamuses and hundreds of crocodiles in 1999 though the population was higher before the 1993-94 drought (Sanyu Consultants Inc., 2001). The lake is famous worldwide for its ornithological sanctuary with more than 480 different species. Reported cases of human-wildlife conflicts are related to crocodiles attacking of children and livestock at lakeshores.

5.4.2 Tourism in Lake Baringo Prospect area

The lake has had many tourists both local and international due to the rich wildlife. Table 2 shows the visitors and revenue to Lake Baringo Conservation Area for the period 2003-2004. The number of visitors fluctuates very much according to season with the peak being in the months of July and October.

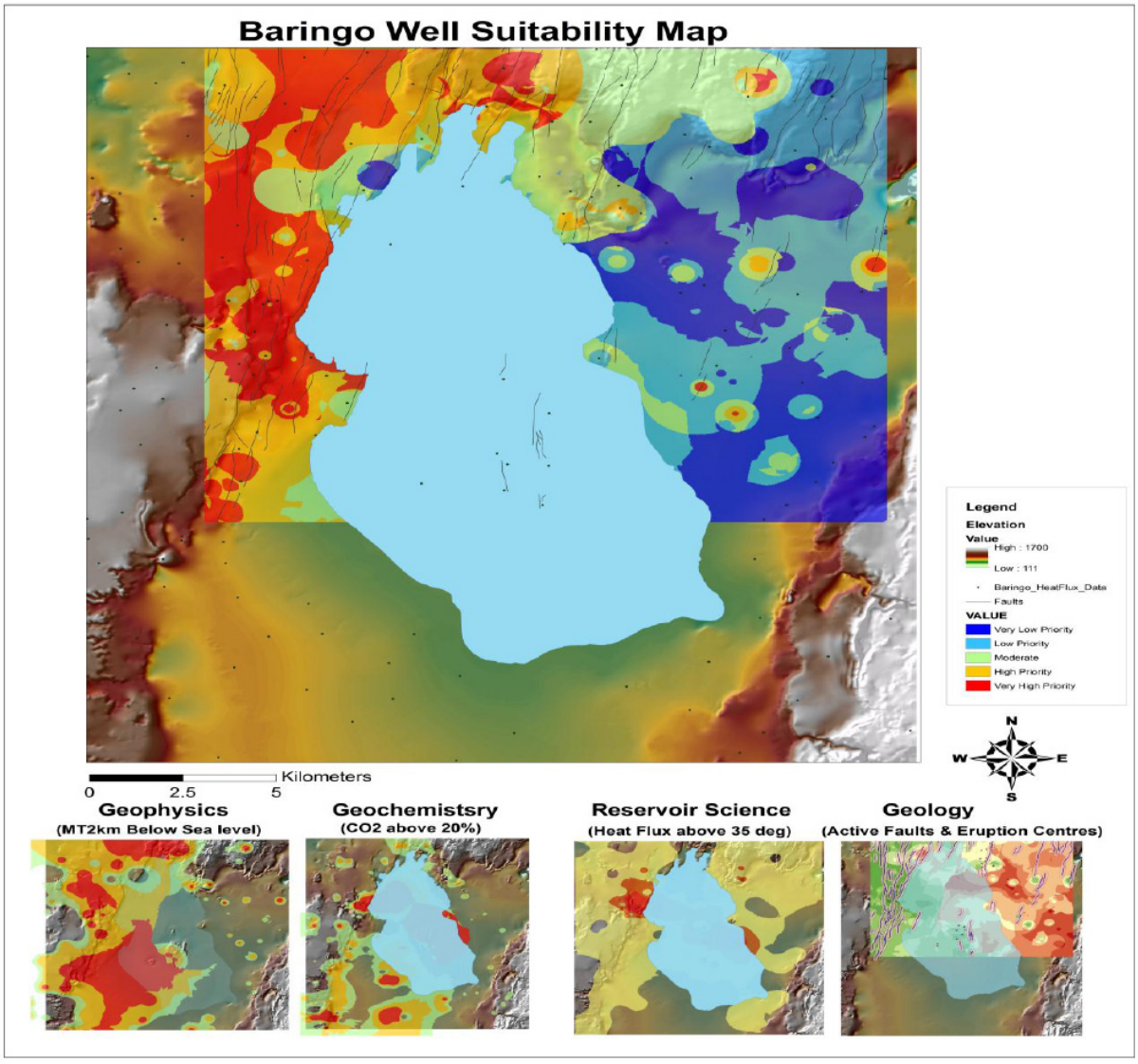

FIGURE 5: Lake Baringo prospect geothermal suitability map

TABLE 2: Visitors numbers and revenue for Lake Baringo Conservation Area

Month/Year	**No. of paying Visitors**	**No. of non paying Visitors**	**No. of paying Vehicles**	**Total Revenue KShs. @79.30 US$**
June 2003	703	167	71	60,410
July 2003	1196	261	158	155,440
August 2003	1546	319	169	147,250
September 2003	677	527	59	58,360
October 2003	1530	1098	99	89,330
November 2003	1221	134	67	56,540
December 2003	2106	149	182	139,060
January 2004	674	68	125	80,030
February 2004	603	73	128	89,520
March 2004	663	643	104	68,990
April 2004	903	533	76	61,800
May 2004	385	91	46	26,930
June				

Source: Lake Baringo Statistical Information and Conservation Centre

5.4.3 Flora of Lake Baringo prospect area

The prospect area is characterized by bush acacias especially *Acacia reficiens, Acacia mellifera, Acacia nubica* and *Acacia tortilis* dominating the landscape. Vegetation on escarpment includes evergreen bushland, abundant species of which are *Croton dichogamus, Maytenus sp., Euclea sp*. Evergreen wooded grassland can be found at the Arabal valley. The area is dominated by mainly *Balanites aegyptiaca*, *Acacia gerardii*, and *Cynodon dactylon* grass. Semi-deciduous woodland dominates the lower part of this area especially along rivers, northern part of which is called Njemps flat. Major vegetation species are *Acacia tortilis* and *Acacia elatior*. Deciduous bushland dominates western part of Lake Baringo where *Acacia mellifera*, *Acacia reficiens* and *Acacia nilotica*, *Acacia commiphora.*Grasses in the area include *Eragrostis sp*., *Tribulus terrestis*, *Heliotropium sp*., *Cynodon dactylon*, *Cynodon plectostachyus* and *Echinocloa haplocada*.

5.5 Lake Bogoria Geothermal Prospect Area and National Reserve

Lake Bogoria and part of its catchment area is rich in fauna hence has been protected as 'Lake Bogoria National Reserve' (LBNR) and covers an area of 107 km^2. It was gazetted in 1973 and is currently managed by Baringo and Koibatek County Councils. Recently the LBNR was designated as a third Ramsar site after Lake Nakuru and Naivasha. The lake is saline and covers an area of 34 km^2. It is rich in biodiversity, hosting about half of the world's population of lesser flamingos (*Phoeniconaias minor*). It is also a habitat to other bird species including greater flamingos (*Phoeniconaias rubber*), black-necked grebe (*Podiceps nigricollis*), ostriches, fish eagles and several migratory species. Due to its avifauna richness, it has been designated as an Important Bird Area (IBA). The mammalian fauna in LBNR include zebras, gazelles, buffaloes, several primates and the only relatively accessible population of greater kudus. In addition to its rich biodiversity, Lake Bogoria has numerous hot springs.

5.5.1 Flora of Lake Bogoria Prospect area

The vegetation is mainly thorny bushland dominated by the species of *Acacia*, *Balanites* and *Commiphora* with patches of riverine woodland containing *Ficus capensis*, *Acacia xanthophloea* and *Acacia tortilis*. In the lower slopes of the Siricho Escarpment, *Combretum* and *Grewia* thickets dominate.

5.5.2 Fauna and Avifauna of Lake Bogoria Prospect area

Lake Bogoria is internationally important as a main feeding ground for a large percentage of the world's population of the lesser flamingo (*Phoeniconaias minor*). The high productivity of the blue-green algae, *Spirulina platensis*, coupled with the presence of freshwater at several places results in a concentration of the lesser flamingo in large numbers, at times over two million, to give the appearance of large shimmering pink sheets across the lake. Kenya holds between a third and a quarter of the total world population of the lesser flamingo. There are no mammals inside Lake Bogoria but a small variety of animals exist in the adjacent areas. They include the rare Greater Kudu (*Tragelaphus strepsiceros*) and many other antelopes such as gazelles and impala. Other mammals found in LBNR are zebras and buffaloes. The Greater Kudu population is reported to be on the decline, as a result of the demand on their horns, which are used by the locals for ritual purposes. The zebra population is reported to have increased tremendously in the recent past.

5.5.3 Tourism in Lake Bogoria geothermal area

Tourists and visitors to the Reserve are stakeholders, in search of recreation, education and research. They include both local, national, and international tourists and visitors. According to records in the Lake Bogoria recording station, over 50,000 school children visit Lake Bogoria annually to understand and appreciate the unique physical geography of the Rift Valley, an important topic in the geography syllabus in Kenyan schools. Researchers who come to seek knowledge are among this group. The

number of visitors to LBNR fluctuates very much according to season with the peak being between the months of July and September (Figure 6).

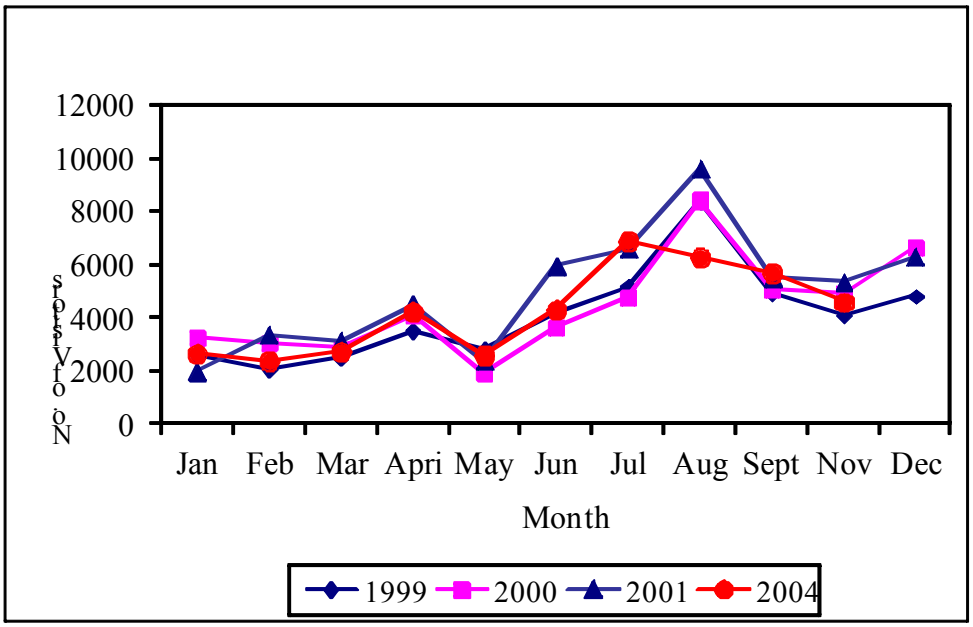

FIGURE 6: Visitors to Lake Bogoria National Reserve

6. CONCLUSION

The success achieved in the development of geothermal energy resource in nature conservation areas/ National park demonstrates that geothermal energy development, wildlife conservation and tourism development can coexist by carefully using sound environmental management systems and monitoring as have been the case in Olkaria geothermal field and Menengai geothermal field. Geothermal power Plants have been successfully developed in Olkaria field within Hell's Gate National Park while geothermal drilling is successfully ongoing in Menengai. With sound environmental management systems, properly designed operation systems can be used to mitigate most of the envisaged impacts. The developments of the geothermal projects do enhance the attraction of these nature /wildlife conservation areas and increase revenues. They are also offering many other socio-economic benefits to the communities in which they are located.

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VEGETATION TYPES AND DIVERSITY IN MENENGAI CALDERA GEOTHERMAL PROJECT AREA, KENYA

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ABSTRACT

The study was aimed at documenting the vegetation types in the Menengai Caldera. Line transects were established in each forest type and used as baseline upon which sampling plots were located. Plots of 20x20 m were placed at intervals of 50 m and marked along the transect and used to quantify species distribution patterns and vegetation dominance. Each block was divided into 4 (10x10 m) small plots within which vegetation parameters were determined. In each 10x10 m plot, all flowering plant species were enumerated. In addition, data on density, height and basal area of trees over 5 cm in diameter at breast height was estimated. The degree of forest or woodland cover was recorded on a five-point scale for three life forms i.e. trees, shrubs and herbs. The Daubenmire Cover Scale: 1:0-20%, 2:21-40%, 3:41-60%, 4:61-80% and 5:81-100% was used for determination of species population densities and frequencies. Species uniqueness (endemism, rarity, threat i.e. vulnerable, endangered) was analysed through literature review, voucher specimens and databases at the EA Herbarium. Plant species diversity for the first five plant community types was analysed using Shannon's Diversity Index (H'=Σ Pi Ln Pi). Species Evenness analysed using Shannon's Evenness Index (E=H' / H Max).

Overall, 186 different species of plants were recorded in Menengai Caldera with a vegetation cover density range of between 15% and 65%. The caldera floor is classified into 8 plant communities. There were no endemic, rare or new plant species recorded in this study, though certain tree species like *Rubus steudueri* and *Rubus apetalus* are recognized Montane forest species which were recorded in Madrugada farm. This suggests that conservation of these areas is vital. In this regard, efforts are required to conserve the forest and mitigate potential impacts from the ongoing geothermal exploration project in Menengai caldera.

1. INTRODUCTION

Forest ecosystems provide a continuous flow of goods and services that support the Kenyan economy directly or indirectly by sustaining livelihoods. Although forests cover only a small area of about 1.7% of Kenya's total land area (Toroitich, 2009), closed forests are crucial water catchments, and harbour a disproportionate amount of Kenya's biodiversity. Among these forests are the five largest blocks (also

referred to as "Kenya's water towers"), namely Mt. Kenya, Aberdares, Mt. Elgon, Cherangani and Mau Forest Complex, that has a combined area of 403,000 hectares. Menengai forest located in East Mau forms the northern boundary of Lake Nakuru and has resources that serve lots of benefits to the local communities in form of grazing, materials for construction, food fuel wood, and traditional medicine. However, there is no documentation of these. Further, although different forest resources are extracted from the forest continuously by local communities, the forest managers do not have information on how these resources influence socio-economic and the general wellbeing of those who depend on the forest.

The declining Menengai forest remains to be properly studied for flora and fauna and in particular, the key avifauna and invertebrate taxa, which support the ecosystem services such as pollination. Pollinators have a direct correlation to forest plant numbers, diversity (plant community composition) and population genetics (Calvo and Hortvitz, 1990) and they exert indirect effects on all higher trophic levels organisms that use plants for food or shelter (Abrams, 1995). Key habitat changes affect sensitive species, which may decline or disappear while still undocumented. The African pollinators Initiative, plan of action (Gemmill et al., 2003) highlights what needs to be done to conserve pollinators especially in agro-ecosystems and other habitats (Shepherd et al., 2003).

To guide current and future restoration interventions of the forest, it is important to know the types of flora and fauna and state of the resource users and the level of dependence on the relevant resources.

2. MATERIALS AND METHODS

2.1 Study site and Data Acquisition

Menengai (meaning "Mountain of God" in Maasai) lies north of Lake Nakuru and forms the northern divide of the lakes' catchment basin. It rises to a height of 2,278 masl and is the remnant of a volcano that erupted about 200,000 years ago (Leat, 1984). It is considered a dormant volcano, which is a volcano that has erupted in documented history. The last eruption occurred around 1,400 years ago (Leat, 1984).

Following the eruption, the sides of the volcanic crater collapsed inwards forming a large, gaping hole in the crust, called a caldera. Menengai caldera with an area of 90km^2 and a diameter of 12km is the second largest caldera in Africa after Ngorongoro in Tanzania. Menengai caldera is located in larger Nakuru District at 35^0 28', $35^0$36'E, and 0^o13', $1^0$10'S, and is one of the eighteen larger districts of the Rift Valley Province. The larger Nakuru district has recently been subdivided administratively, placing a large section of Menengai caldera in the Rongai and Nakuru north districts.

Rainfall recorded for the last 35 years (1976 – 2010) at Menengai caldera, Madrugada Farm -LR 6886/6, co-ordinate 36.0226^{o}E, 0.2535^{o}S, which is outside (600 m) from Menengai edge indicate that the annual rainfall ranges from 500-1500mm per annum with an annual mean rainfall of 923 mm and is not significantly different from the district annual mean of 988mm (Figure 1). The long-rain season is mainly in April to June while the short-rains season is in October/November. The rainfall shows a declining trend that may be attributed to the destruction of the forest cover. December to March is usually the dry season and the strong winds in the caldera precipitate frequent fire outbreaks. Temperatures range from 25°C-30°C.

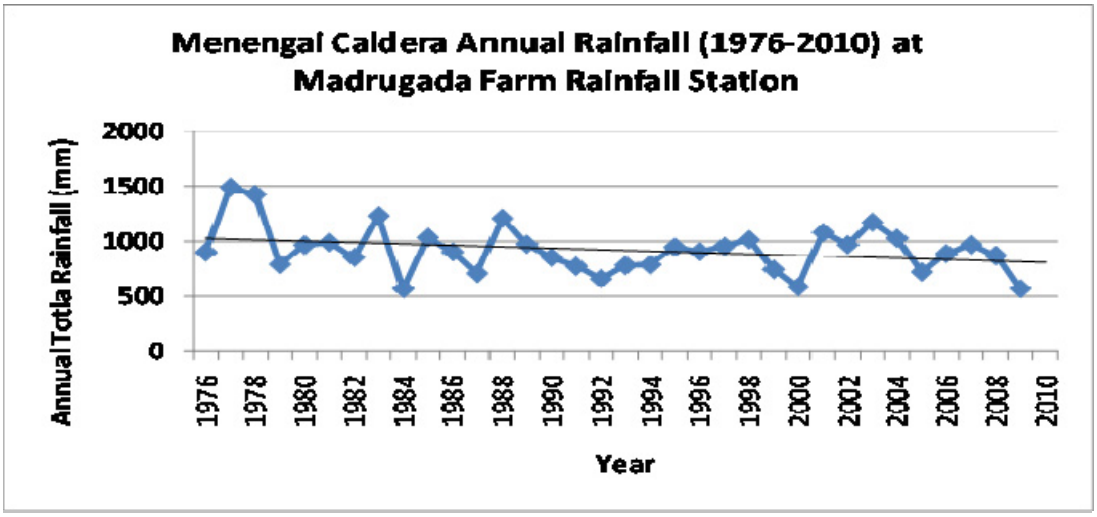

FIGURE 1: 1976 – 2010 Rainfall Madrugada farm, near Menengai caldera's edge (FOMEC, 2010)

Plant surveys were aimed at documenting the diversity of flowering plants in the Menengai Caldera forest system. Plant sampling sites were located at the Wanyororo B borehole drill sites, Central fumaroles, Southwest of the caldera (Madrugada farm), and at two geothermal well pads as shown in Figure 2 (see black circles).

Line transects were established in each forest type and used as baseline upon which sampling plots were located. Plots of 20x20 m were placed at intervals of 50 m and marked along the transect and used to quantify species distribution patterns and vegetation dominance (Mutangah, et al., 1997; KIFCON, 1993). Each block was divided into 4 (10x10 m) small plots within which vegetation parameters were determined. In each 10x10 m plot all flowering plant species were enumerated. In addition, data on density, height and basal area of trees over 5 cm in diameter at breast height (DBH) was estimated. The degree of forest or woodland cover was recorded on a five-point scale for three life forms i.e. trees, shrubs and herbs. The Daubenmire Cover Scale: 1:0-20%, 2:21-40%, 3:41-60%, 4:61-80% and 5:81-100% was used (KIFCON, 1993). The method is suitable for quantitative vegetation analysis because it allows determination of species population densities and frequencies.

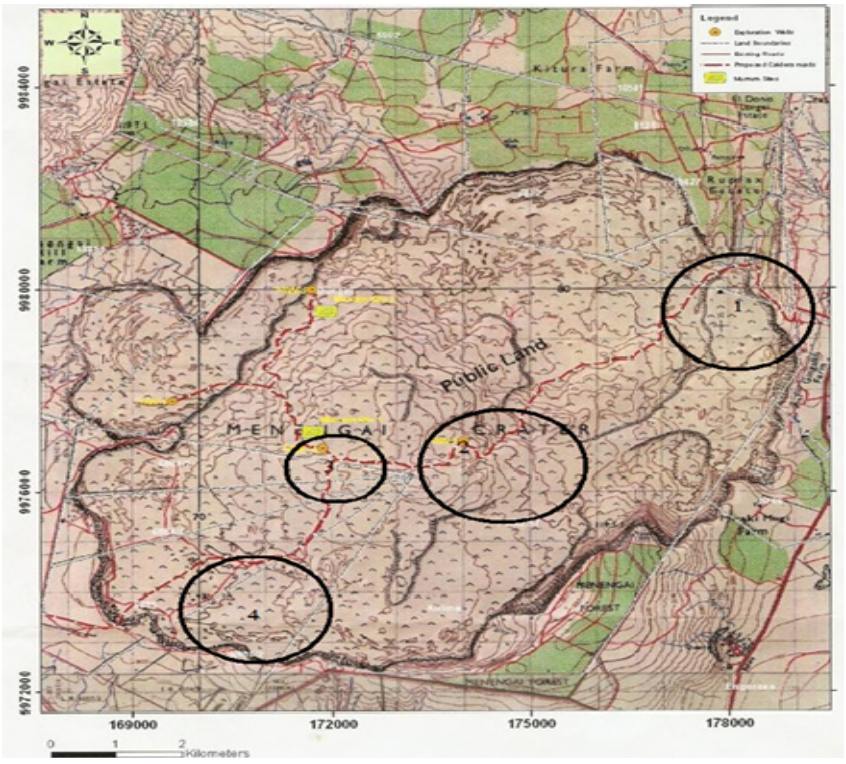

FIGURE 2: Study Area showing the plant sampling sites (modified from. KenGen. 2008)

General botanical surveys was also undertaken along each transect, within a band of 10 m on either side. These enabled a better understanding of the various habitat physiognomic structures. Mass plant collection and identification was undertaken with further verification done at East African herbarium. Plants that could not be identified *in situ* were identified at the East African Herbarium in Nairobi.

Floristic diversity was analysed using data on species richness (i.e. total number of species recorded per site) and comparison of floristic similarity between study sites. Forest structure was determined by analysing the canopy cover of different vegetation layers (herbs, climbers, shrubs and trees), diameter at breast height (dbh) and height data.

Species uniqueness (endemism, rarity, threat i.e. vulnerable, endangered) was analysed through literature review, voucher specimens and databases at the EA Herbarium. Species diversity for the different vegetation communities was computed using the modified inverse of Simpson-Yule diversity of concentration, C, for equally abundant species (Dunstan & Fox, 1996). Plant species diversity for the first five plant community types was analysed using Shannon's Diversity Index (H'=Σ Pi Ln Pi). Species Evenness analysed using Shannon's Evenness Index (E=H' / H Max).

2.2 Vegetation mapping methodology

Data was collected from various sources namely:

a) Kenya vegetation map (Map area: Nakuru District; Units: Metric Projection: UTM (Universal Transverse Mercator) Datum: WGS 1984.
b) Topographical map of Kenya at a scale of 1:50,000 covering Nakuru area (Topo Index 119-1)
c) Google Earth imagery

The initial map was developed by clipping the shapefile for the area covered by Nakuru in the vegetation map of Kenya in order to remain with the area under study. This was done in Arc GIS 9.30 software by extracting and Clipping using the Analysis Tool. The Clipped output shape file for Nakuru was later overlaid on top of the toposheet in order to add more details in the map.

Google Earth imagery was also used in the analysis. The study area was captured from Google Earth as a jpg-image and later on transferred into a GIS platform for further analysis. The image was geo-referenced and additional details for the vegetation shape files obtained through digitizing.
The layers from the analysis process; administration shape file and vegetation shape file, were combined in ArcMap to come up with the final map showing the vegetation distribution in the study area.

3. RESULTS AND DISCUSSION

The vegetation map of the study area was prepared. It shows that whole area is covered by vegetation and the cover density ranges between 15% and 65% (Table 1).

The vegetation was differentiated into 8 vegetation types namely: Bushlands (23%), Grasslands (21%), Forests (18%), Disturbed land (14%), Woodlands (10%), Rocky outcrops and lava vegetation (9%), Montane forest (3%) and riverine vegetation (2%). The vegetation cover density map of the area is shown in Figure 3.

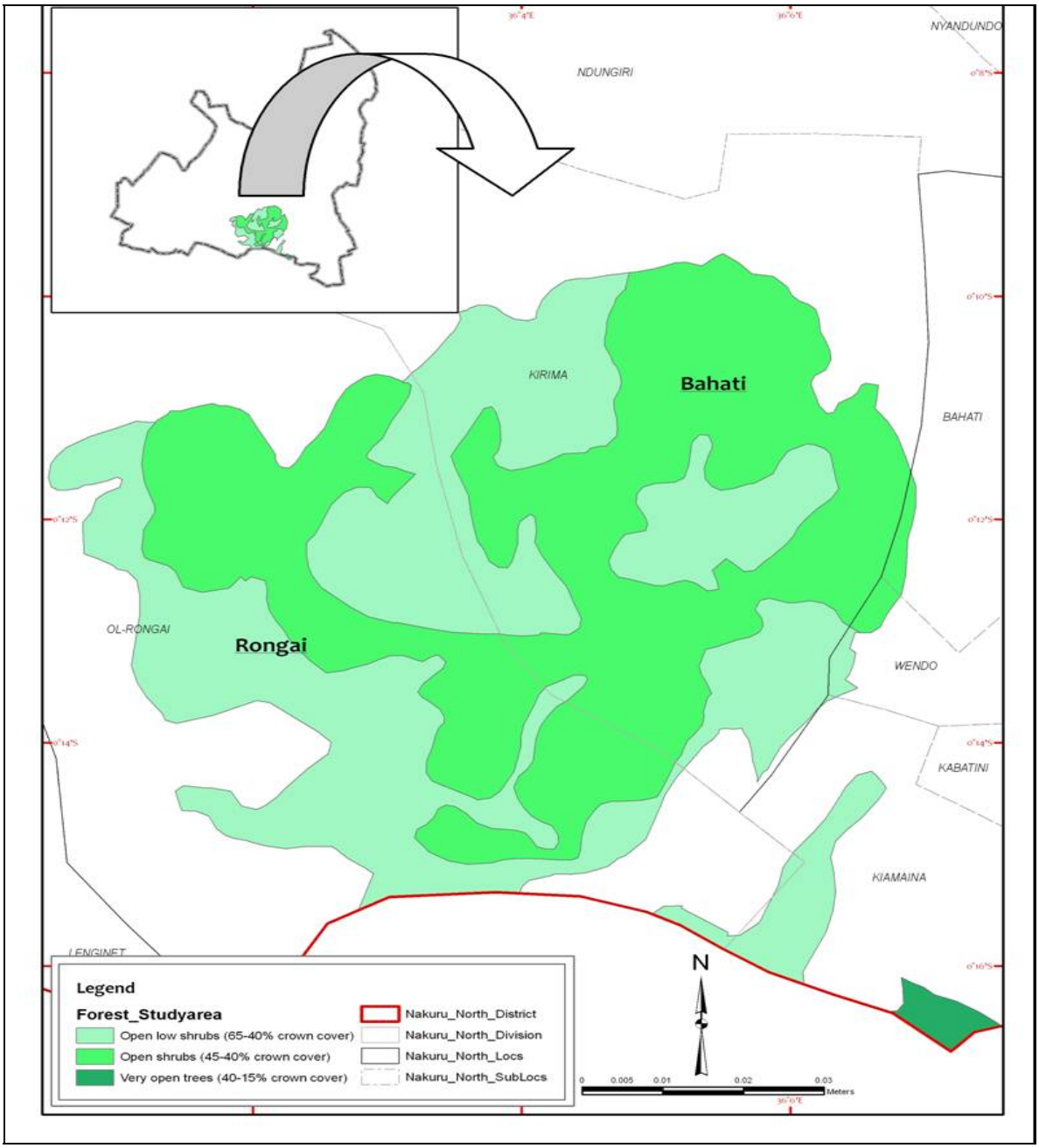

FIGURE 3: Vegetation distribution map of Menengai Caldera

TABLE 1: Plant species diversity and distribution

	Plant communities types				
	1	**II**	**III**	**IV**	**V**
Species diversity	2.48	3.41	1.57	3.24	2.69
Species evenness	0.65	0.78	0.59	0.89	0.69
Species richness	0.46	0.76	0.14	0.42	0.49

The natural vegetation in the caldera and its density, composition, and differentiation are directly related to the climate and economy of the area. The study of plant species and communities as a natural resource is of great importance. A record of 169 species of flowering plants and 17 species of grasses have been recorded in the caldera during this study (Table 2a and 2b).

TABLE 2a: Checklist of plant species recorded at the Madrugada Farm section (SW of caldera) during the entire study (June 2009-July 2010) and their biogeographical affinities

Family	**Genus**	**Species**	**Biogeographic affinities**
Malvaceae	*Abutilon*	*hirtum*	Riverine
Mimosaceae	*Acacia*	*abyssinica*	Acacia woodland
Mimosaceae	*Acacia*	*hockii*	Wooded grassland
Ericaceae	*Agauria*	*salicifolia*	
	Argyrolobium	*fischeri*	Wooded grassland
Compositae	*Berkheya*	*spekeana*	Grassland
	Chamaecrista	*falcinella*	Wooded grassland
	Chenopodium	*opulifolium*	Wooded grassland
Compositae	*Conyza*	*bonarrensis*	Weed in Arable Cultivation
	Conyza	*schimperi*	Wooded grassland
	Conyza	*stricta*	Wooded grassland
	Crotalaria	*lachnocarpoides*	Wooded grassland
Euphorbiaceae	*Croton*	*macrostachyus*	Forest & wooded grassland
	Cyathula	*cylindrica*	Wooded grassland
	Cynoglossum	*coeruleum*	Wooded grassland
Compositae	*Echinops*	*amplexicaulis*	Wooded grassland
	Erica	*arborea*	Wooded grassland
Euphorbiaceae	*Erythrococca*	*bongensis*	Open woodland & grassland
Proteaceae	*Faurea*	*saligna*	Wooded grassland
	Ferula	*communis*	Wooded grassland
	Helichrysum	*forskahlii*	Wooded grassland
	Helichrysum	*odoratissimum*	Wooded grassland
Umbeliferae	*Heteromorpha*	*trifoliate*	Bushland
	Heteropogon	*contortus*	Wooded grassland
	Hibiscus	*lunariifolius*	Wooded grassland
Lobeliasceae	*Lobelia*	*fervens*	Grassland
	Lobelia	*holstii*	Wooded grassland
	Lotus	*bequetii*	Wooded grassland
	Melinis	*repens*	Wooded grassland
	Micromeria	*imbricate*	Wooded grassland
Geraniaceae	*Monsonia*	*angustifolia*	Open woodland & grassland
Loganiaceae	*Nuxia*	*congesta*	
Rubiaceae	*Oldenlandia*	*monanthos*	Mountain grassland
	Polygala	*sphenoptera*	Wooded grassland
Proteaceae	*Protea*	*gaguedi*	Grassland
Rosaceae	*Rubus*	*steudneri*	Mountain forest & upland bushland
Rosaceae	*Rubus*	*apetalus*	Mountain forest & upland bushland
	Senecio	*mesogrammoides*	Wooded grassland
	Senecio	*ruwenzoriensis*	Wooded grassland
Solanaceae	*Solanum*	*mauense*	Forest margins
Solanaceae	*Solanum*	*mauritianum*	Wasteland
	Sopubia	*ramosa*	Wooded grassland

Family	Genus	Species	Biogeographic affinities
Labiatae	*Tetradenia*	*riparia*	Bushland
	Themeda	*triandra*	Wooded grassland
	Vernonia	*galamensis*	Wooded grassland
	Wahlenbergia	*abyssinica*	Wooded grassland
	Wahlenbergia	*virgata*	Wooded grassland
	Zornia	*setosa*	Wooded grassland
	Total	**48**	

TABLE 2b: Checklist of plant species recorded during the entire study and their biogeographical affinities. Plant species observed from June 2009-July 2010 at Wanyororo B pump station, (NE crater), the well pads (MW1, MW2, MW3 and MW4), campsite and along new road for geothermal thermal prospecting

Family	Genus	Species	Biogeographic affinities
Malvaceae	*Abutilon*	*mauritianum*	Riverine
Mimosaceae	*Acacia*	*tortilis*	Bushland
Mimosaceae	*Acacia*	*xanthophloea*	Woodland
Mimosaceae	*Acacia*	*lahai*	Woodland
Euphorbiaceae	*Acalypha*	*volkensii*	Upland grassland
Amaranthaceae	*Achyranthes*	*aspera*	Disturbed land
Compositae	*Ageratum*	*conyzoides*	Weed in disturbed ground
	Aloe	*lateritia*	
	Artemisia	*afra*	
	Arthropteris	*orientalis*	
Compositae	*Aspilia*	*mossambicensis*	Wild bushed grassland
Compositae	*Bidens*	*pilosa*	Variable common wasteland
Amaranthaceae	*Celosia*	*anthelmintica*	Dry bushland
	Chenopodium	*opulifolium*	
	Chlorophytum	*subpetiolatum*	
Verbenaceae	*Clerodendrum*	*myricoides*	Dry forest & bushland
Commelinaceae	*Commelina*	*bengalensis*	Bushland
Compositae	*Crassocephalum*	*montuosum*	Variable common wasteland
	Crotalaria	*brevidens*	
	Crotalaria	*laburnifolia*	
	Cucumis	*aculeate*	
Convolvulaceae	*Cuscuta*	*kilimanjari*	Forest
Araliaceae	*Cussonia*	*arborea*	Wooded grassland
Araliaceae	*Cussonia*	*holstii*	Bushed grassland
	Cyanotis	*foecunda*	
	Cycnium	*tubulosum*	
	Cyphostemma	*arundo*	
Solonaceae	*Datura*	*stramonium*	Disturbed land
Dioscoreaceae	*Dioscorea*	*quartiniana*	Bushland
Melastomataceae	*Dissotis*	*senegambiensis*	Grassland
Sapindaceae	*Dodonaea*	*viscosa var angustifolia*	Bushland in rocky lava sites
Dracaenaceae	*Dracena*	*steudneri*	Forest
	Dyschoriste	*radicans*	
Compositae	*Emilia*	*discifolia*	Stony area
	Erica	*arborea*	
	Eriosema	*jurionianum*	

Family	Genus	Species	Biogeographic affinities
Papilionaceae	*Erythrina*	*abyssinica*	Wooded grassland
Euphorbiaceae	*Euphorbia*	*candelabrum*	Rocky outcrops in bushland
Moraceae	*Ficus*	*glumosa*	Rocky outcrops & hillsides
Moraceae	*Ficus*	*ligens*	Rocky sites on lava
Moraceae	*Ficus*	*thonningii*	Forest & woodland
	Fuerstia	*africana*	
Compositae	*Galinsoga*	*parviflora*	Weed in moist highlands
	Geranium	*ocellatus*	
Urticareae	*Girardinia*	*diversifolia*	Wet disturbed land
	Gladiolus	*ukambensis*	
Papilionaceae	*Glycine*	*wightii*	Bushed grassland
	Gnidia	*involucrate*	
Tiliaceae	*Grewia*	*fallax*	Bushed grassland
Tiliaceae	*Grewici*	*similis*	Bushed grassland
	Guizotia	*scabra*	
	Gutenbergia	*cordifolia*	
	Helichrysum	*glumaceum*	
Rhamnaceae	*Helinus*	*integrifolius*	Bushland grassland
Labiatae	*Heonotis*	*nepetifolia*	Forest margin & Roadside
Malvaceae	*Hibiscus*	*cannabinus*	Dry grassland
Malvaceae	*Hibiscus*	*fuscus*	Grassland
	Hibiscus	*aethiopicus*	
	hildebrandtii	*Chamaecrista*	
	Hypoxis	*obtusa*	
	Impatiens	*sodenii*	
	Indigofera	*arrecta*	
	Indigofera	*spicata*	
Acanthaceae	*Justicia*	*calyculata*	Grassland weed
Compositae	*Kleinia*	*abyssinica*	Bushland
Verbenaceae	*Lantana*	*camara*	Weed in roadside &secondary vegetation
Verbenaceae	*Lantana*	*trifolia*	Bushed grassland
Verbenaceae	*Lippia*	*javanica*	Woodland
Celastraceae	*Maytenus*	*heterophyltus*	
Labiatae	*Ocimum*	*gratissimum*	Disturbed bushland
	Oldenlandia	*scopulorum*	
	Oldenlandia	*wiedemannii*	
Oleaceae	*Olea*	*europaea*	Dry forest & Woodland
Orobanchaceae	*Orobanche*	*minor*	Grassland & Forest edges
Oxalaceae	*Oxalis*	*corniculata*	Upland grassland
Anacardiaceae	*Ozoroa*	*insignis*	Wooded grassland
Graminae	*Panicum*	*maximum*	Grassland
	Pappea	*capensis*	*(Small tree)*
	Pavonia	*burchellii (P.patens)*	
Rubiaceae	*Pentas*	*longiflora*	Dry wooded grassland
Rubiaceae	*Pentas*	*lanceolata*	Forest edges
	Polygala	*erioptera*	
	Polygala	*petitiana*	
	Polygala	*sphenoptera*	

Family	Genus	Species	Biogeographic affinities
	Protea	*gaguedi*	
Compositae	*Psiadia*	*punctulata*	Bushed grassland
	Pteridium	*aquilinum*	
Vitaceae	*Rhoicissus*	*tridentate*	Wooded grassland
Anacardiaceae	*Rhus*	*natalensis*	Bushland
Anacardiaceae	*Rhus*	*vulgaris*	Wooded grassland
	Rhynchosia	*ferruginea*	
	Rhynchosia	*minima*	
Euphorbiaceae	*Ricinus*	*communis*	Dry woodland edges
Rubiaceae	*Rubia*	*cordifolia*	Bushed grassland
Poligonaceae	*Rumex*	*usambarensis*	Rocky bushed grassland
	Satyrium	*macrophyllum*	
	Scadoxus	*multiflorus*	
Oleaceae	*Schrebera*	*alata*	Forest & grassland
	Senecio	*ruwenzoriensis*	
	Senna	*didymobotrya*	
Caesalpiniaceae	*Senra*	*didymobotyra*	Forest edges
Malvaceae	*Sida*	*ovate*	Dry grassland
Solanaceae	*Solanum*	*incanum*	Variable common wasteland
	Solanum	*terminale*	
Umbeliferae	*Steganotaenia*	*araliacea*	Dry stony hillsides
Scrophulariaceae	*Striga*	*asiatica*	Grassland
	Striga	*linearifolia*	
Compositae	*Tagetes*	*minata*	Weed in upland arable land
Compositae	*Tarchonanthus*	*camphorates*	Bushed grassland
	Themeda	*triandra*	
Labiatae	*Tinnea*	*aethiopica*	Bushland & Wooded grassland
Tiliaceae	*Triumfetta*	*rhomboidea*	Pathsides and disturbed place
Urticareae	*Urtica*	*massaica*	Forest edges
Rubiaceae	*Vangueria*	*madaascariensis*	Rocky bushland
Compositae	*Vernonia*	*brachycalyx*	Dry forest edges
Compositae	*Vernonia*	*lasiopus*	Grassland
	Vernonia	*gallamensis*	
Solanaceae	*Withania*	*somnifera*	Woodland
Cucurbitaceae	*Zehnesia*	*scabra*	Sand forest, Bushland
	Zornia	*setosa*	
Total	**121**		

Results show that the caldera floor is classified into eight plant communities. Plants species with the highest cover/abundance scale was used to name the community type. Bushed grasslands dominated the vegetation and comprised of *Tarconanthus camphorates* (leleshwa)*, Euphorbia canderabra, Acacia repanolobium Rhus natalensis, Grewici similes, Acacia tortilis, Cussonia arborea, Kleinia abyssinica,* and mixed bushland comprising of *Commelina bengalensis, Aspilia mossambicensis, Tinnea aethiopica, Justicia calyculata, Rhoicissus tridentate, Oxalis corniculata, Rhus vulgaris, Ozoroa insignis, Erythrinaabyssinica Celosia anthelmintica, Pentas longiflora, Dioscorea quartiniana, Heteromorpha trifoliate, Tetradenia riparia, Faurea saligna, Echinops amplexicaulis.*

Open grasslands are composed of various associations of *Chloris gayana, Digitaria abyssinica, Sporobolus sp, Hyparhenia, Fibristylis exilis (geothermal grass), Cynodon nlemfuensis, Cynodon dactylon,* and *Boma Rhode* grasses. Plants recorded in open grasslands include *Lantana trifolia, Tarchonanthus camphorates, Panicum maximum, Grewia fallax, Striga asiatica, Sida ovata, Rubia cordifolia, Helinus integrifolius, Cussonia holstii, Psiadia punctulata, Vernonia lasiopus, Acalypha volkensii, Dissotis senegambiensis, Hibiscus cannabinus, Hibiscus fuscus, Glycine wightii, Protea gaguedi, Lobelia fervens* and *Berkheya spekeana.*

The forest species include *Urtica massaica, Zehnesia scabra, Dracena steudneri, Senra didymobotyra, Ficus thonningii, Orobanche minor, Olea europaea, Pentas lanceolata, Cuscuta kilimanjari, Croton macrostachyus, Erythrococca bongensis, Solanum mauense, Monsonia angustifolia, Nuxia congesta, Agauria salicifolia, Acacia abyssinica* and *Acacia hockii.*

Orchidaceae, commonly referred to as the Orchid family, is a morphologically diverse and widespread family of monocots. The taxonomy of this family is in constant flux, as new studies continue to identify more classificatory elements. The Orchidaceae is currently placed in the order Asparagales by the APG III system of 2009. A majority of orchids are perennial epiphytes, which grow anchored to trees or shrubs. Other species are lithophytes, growing on rocks or very rocky soil. One orchid genus, Vanilla, is commercially important, used as a flavouring. The scent of orchids is frequently analysed by perfumists (using Gas-liquid chromatography) to identify potential fragrance chemicals. The other important use of orchids is their cultivation for the enjoyment of the flowers.

Results of the vegetation study in the show presence of 14 orchids. These include *Polystachya transvalansis* (yellow flowers), *Ansallia Africana* (spotted orchid), *Ranyaeris amaniansis* (tree orchid), *Brachyconyttis pubancans*.

Two ground orchids namely, *Satyrium cheirophorum* Rolfe (pink flowers and leaves) and *Pteroglossapis ruwenzoriensis* (Rendle) Rolfe (white flowers with violet centre "lip") have been described as rather unusual. Other orchid species include; *Foxglora spp.*, *Cremastill spp.*, *Gladioli spp.*, *Eurochila spp.*, *Tessolatta spp.*, *Straga spp.*, *Gollingansis simplex*, and *chamnangis spp.* (tree orchid).

4. CONCLUSION AND RECOMMENDATION

For any geothermal project, land is required for drill pads, access roads, steam lines, power plant and transmission lines. During such development, soil in these areas may compacted and changed hence impacts on vegetation may include loss of indigenous species and species diversity; increased risk of invasive species; increased risk of topsoil erosion and seed bank depletion; increased risk of fire; and alteration of water and seed dispersal. This study which is a baseline recommends for regular vegetation mapping and monitoring during implementation of Menengai Geothermal drilling project.

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DIRECT UTILISATION OF GEOTHERMAL ENERGY

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ABSTRACT

Direct use of geothermal energy is gaining popularity and the past decade has witnessed a tremendous growth in this technology. The biggest use of geothermal energy has been space heating especially in countries with cold climates. However, other direct uses such as drying, greenhouse heating and fish farming are also being practiced. Each of these direct use applications has its requirements in terms of the geothermal fluid temperature. The utilisation of geothermal energy requires the use of specific equipment which are discussed in this paper.

1. INTRODUCTION

The centre of the earth is made up of high temperature molten material called magma which is estimated to be between 5000 and 7000°C (Kubala et al., 1996). The magma sometimes gets trapped in chambers close to the surface of the earth, especially in tectonically active areas as it tries to find its way to the surface of the earth. The heat in the magma is transmitted to the surrounding rocks and conducted all the way to the surface of the earth.

The fractures in these rocks contain water, mainly of meteoric origin, which gets heated by the magma to very high temperatures. When the material overlying the hot subsurface rocks is a cap rock, the hot water gets pressurized and can sometimes find its way to the surface through cracks as hot springs, fumaroles or geysers. However with the advancement in technology, wells can now be drilled to more than 3 km to tap into the geothermal reservoirs and transport the energy in the water to the surface for utilisation. The energy in the hot fluid is referred to as geothermal energy since it is energy from the earth. This is shown in Figure 1 below.

Geothermal is a clean and renewable energy resource which can be found in many places in the world and especially in the tectonically active areas. This energy has been harnessed for both electricity generation and direct uses.

The worldwide direct use of geothermal as at 2010 according to IGA stood at 50583 MWt which is equivalent to 438071 TJ/yr. This was in 79 countries. The biggest users were China, USA, Iceland, Japan, Turkey, Norway, France and Germany.

Direct use refers to the utilisation of geothermal energy for any other application apart from electricity generation. The major direct use applications are in agriculture, aquaculture, swimming, bathing and balneology, space conditioning, industrial processes and heat pumps as shown in the Lindal diagram below (Figure 2).

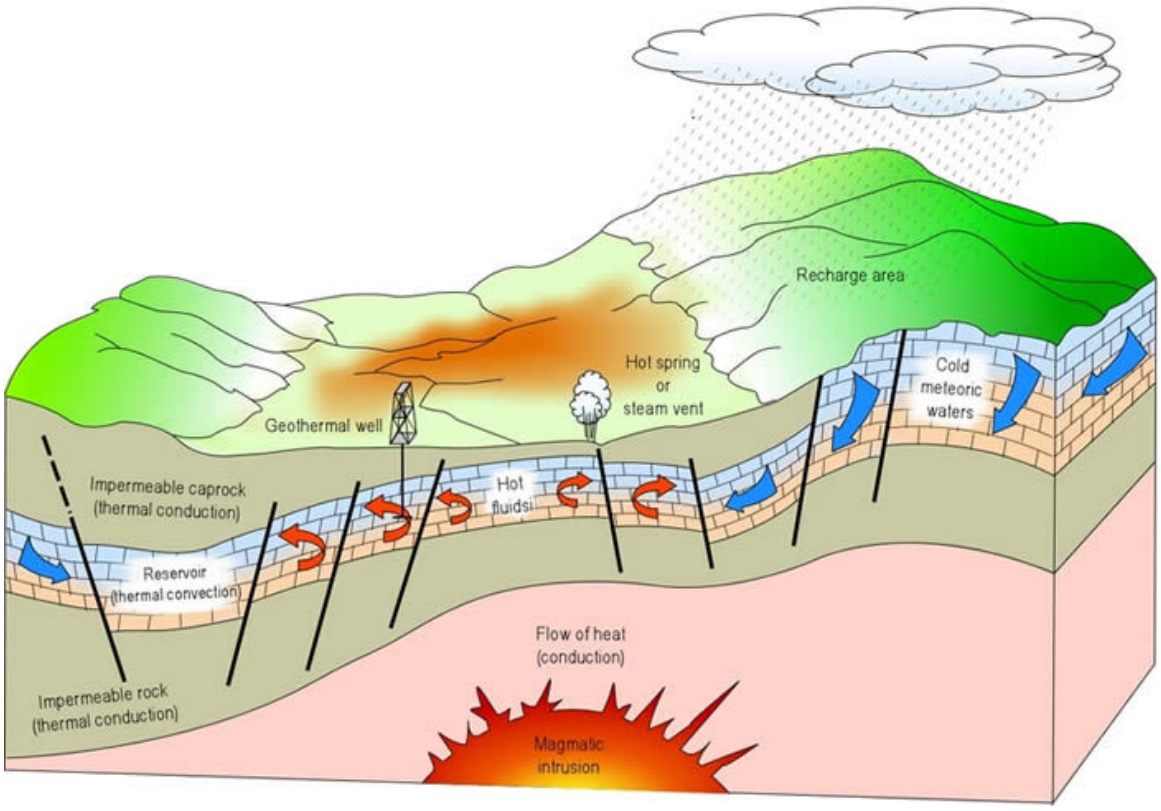

FIGURE 1: A geothermal conceptual model

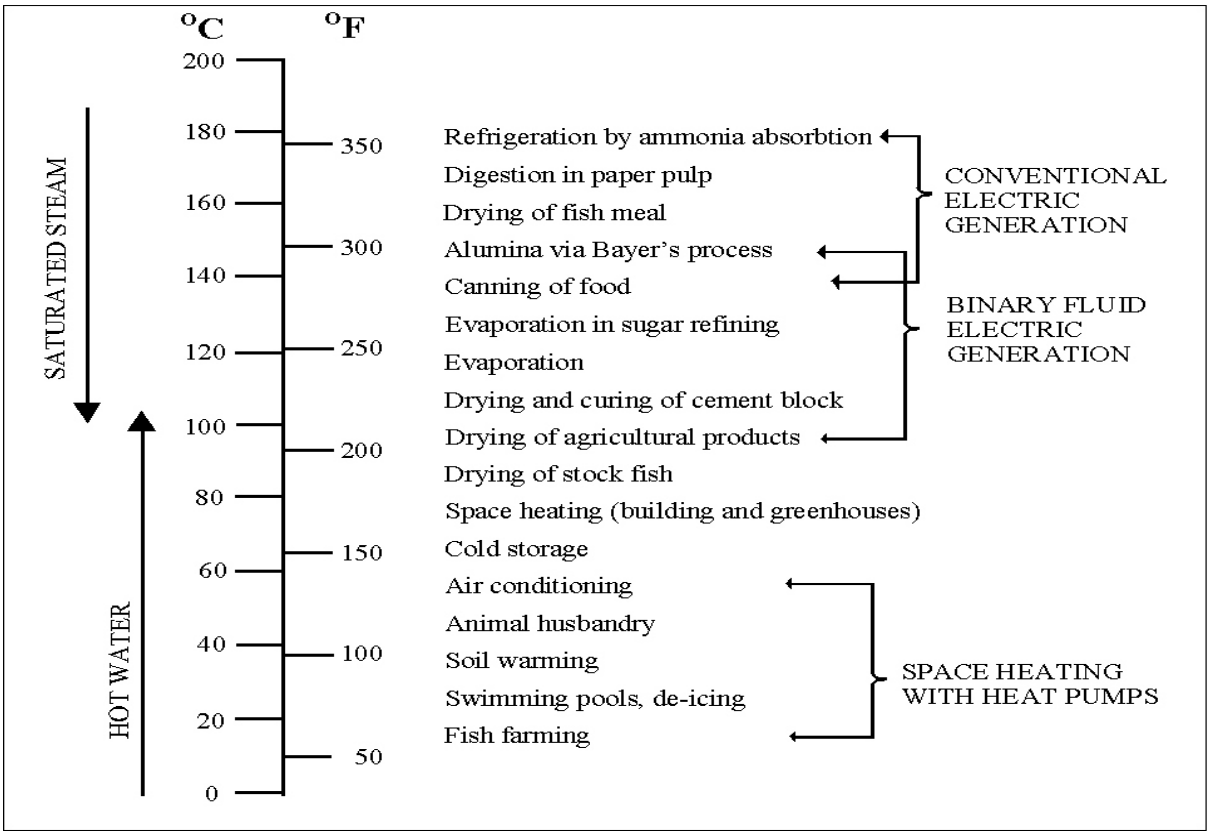

FIGURE 2: Lindal diagram

2. DIRECT USES OF GEOTHERMAL ENERGY

It can be observed from the Lindal diagram that fluids with temperature below 100°C are utilized mainly for space heating and agricultural applications while those above 100°C are for industrial applications.

2.1 Bathing, swimming and balneology

Bathing is one of the earliest known uses of geothermal energy. Ancient Romans, Turks and Japanese have bathed in geothermal water for over 1000 years. Not only is bathing in geothermal water a recreational activity even today, but also believed to have therapeutical effect on the human body. Some of the health benefits derived from bathing in geothermal water include treatment of high blood pressure, skin diseases, diseases of the nervous system and relieving the symptoms of rheumatism.

The use of geothermal energy to heat swimming pools is a common practice especially in the cold countries such as Iceland where almost all outdoor swimming pools are geothermally heated all year round. Lake Bogoria spa and hotel in Kenya is also using water from a nearby warm spring to heat its swimming pool.

Steam baths and saunas have also been designed to utilize geothermal fluids to provide steam and heat. Relaxing in these facilities is also associated with some health benefits such as

- improving blood circulation
- cleaning and rejuvenating the skin
- easing muscle tension
- promoting feelings of relaxation and well-being
- enhancing detoxification processes

2.2 Space conditioning

Space condition refers to the alteration of the climate in an enclosed space by either heating or cooling. The use of geothermal energy for space conditioning is popular in cold climates like Iceland where about 90% of the houses are heated using geothermal water (Lund et al., 2004). The heating of buildings is accompanied by the supply of hot water for domestic uses such as washing. In tropical climates, geothermal energy could be used to cool building for the comfort of the occupants. This is done by the use of vapour absorption machines, which use hot water as the source of energy in order to circulate a refrigerant medium within the system as shown in Figure 3.

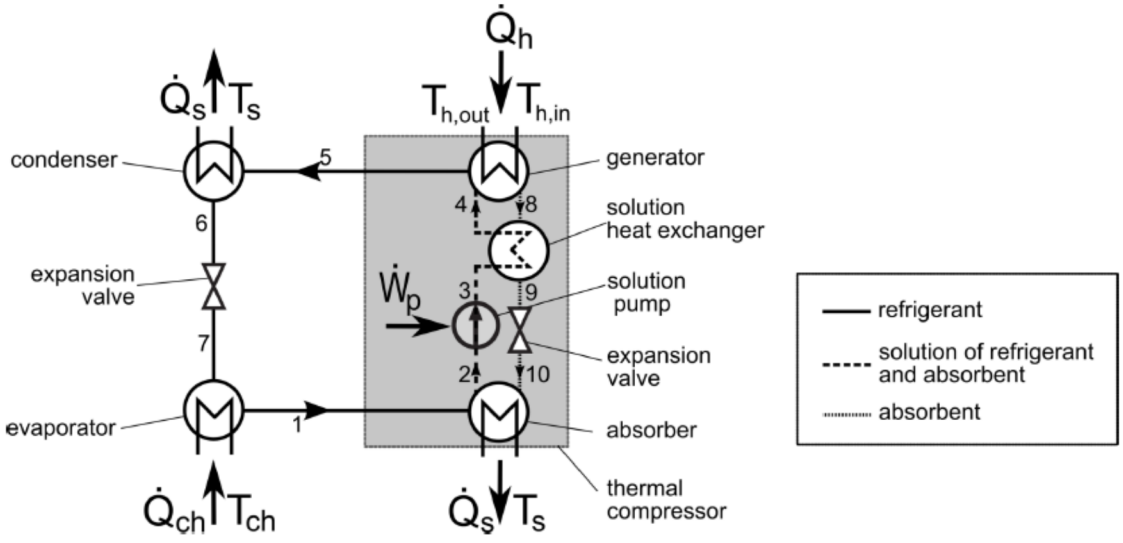

FIGURE 3: Vapour absorption system for space cooling

Vapour absorption systems are of two types: Lithium Bromide/water cycle, where water is the refrigerant while lithium bromide is the absorbent. This configuration is used mainly for air conditioning where temperatures do not go below 0°C as this would result in freezing of the refrigerant. The second configuration is the water/ammonia cycle where ammonia is the refrigerant. This is mainly used for refrigeration since it achieves temperatures below 0°C (Herold et al., 1996).

2.3 Agriculture

The major application of geothermal energy in agriculture is the heating of greenhouses in order to control the climate, mainly temperature and relative humidity. The temperature of the water supplied to the greenhouse depends on the heating demand and ranges from 40-100°C (Vasilevska, 2007). The water is distributed in steel pipes which could be placed under the soil, on the soil or on benches, between rows of plants or suspended in the greenhouse space (Panagiotou, 1996).

In order to produce fast maturing and high quality plants, certain growing conditions must be maintained as close as possible to the optimum. These include nutrients and climatic conditions such as temperature and humidity. It is for this reason that Oserian flower farm in Kenya utilizes thermal energy from one of its geothermal wells leased from KenGen to heat its greenhouses. Kenya is a tropical country in which annual temperatures remain relatively constant throughout the year. However during the cold months and at night, the temperatures could drop considerably. These temperatures may drop below the optimal value for growing flowers and result in formation of dew on the flowers and the leaves, a situation that could encourage the growth of fungi which destroy the quality of flowers.

Oserian has therefore put 50 hectares of rose flowers under the greenhouse heating project mainly to control the moisture content in the greenhouses especially at night and to maintain almost constant temperature throughout the growing life of the flowers. CO_2 gas from the geothermal wells is also separated from the geothermal fluids and used in the greenhouses to enhance photosynthesis in the flower. Irrigation water is also sterilized using the hot water to avoid infecting the flowers with diseases.

2.4 Industrial uses

The industrial uses of geothermal energy are numerous and involve mainly heating and cooling. They depend to a large extent on the economic activities around the geothermal resource. Drying or dehydration of agricultural produce is one of the major industrial applications of geothermal energy. The products that can be dried include grains, fruits, vegetables and pyrethrum as is the case at Eburru in Kenya where the local community uses steam from a shallow borehole for drying.

Dairy processing is yet another application of geothermal energy where fresh milk from the farmers can be pasteurised using hot geothermal water. A series of plate heat exchangers are used to keep the milk and heating water separated during pasteurisation. Concentration of milk, one of the stages in milk powder production, requires temperatures below 100°C. This is done in a falling film evaporator and the evaporation temperature can easily be obtained from geothermal water.

Animal products need to be processed immediately after production in order to preserve them for later use. Bee honey, which is a common product in Kenya, is heat treated after harvesting at about 60°C to prevent crystallisation. Skins and hides from goats and cows are treated by tawing and tanning at temperatures of about 40°C in order to produce high quality leather. Meat from livestock is preserved by refrigeration or canning. The use of a vapour absorption machine running on water/ammonia mixture as the working fluid, can provide the necessary refrigeration at about 0°C, which is sufficient for meat preservation. On the other hand, canning of beef entails precooking it and packing it in sterilised containers using hot water or steam at about 140°C. These processes require temperatures which can be supplied from a geothermal resource.

3. GEOTHERMAL FLUID

The utilisation of geothermal fluids for any purpose depends on the chemistry of the fluid and its thermodynamic properties. The most important of the thermodynamic properties is the enthalpy of the fluid. A fluid is classified as being low enthalpy (<90°C), medium enthalpy (90°C-150°C) or high enthalpy (>150°) depending on the nature of the geothermal system from which it originates (Muffler and Cataldi, 1978). Most direct uses utilize geothermal fluids in the low and medium enthalpy resource while fluids from high enthalpy resource are suitable for electricity generation. However, the waste brine from a high enthalpy resource is ideal for certain direct uses such as absorption cooling.

The common practice in many geothermal power stations including Olkaria in Kenya has been to re-inject the hot brine back into the ground immediately after separation from the steam. This is an inefficient way of utilizing geothermal energy because the brine is usually at a high temperature. At such a temperature, the brine has a lot of thermal energy which can be utilized for other applications such as hot water supply, greenhouse heating or space cooling.

It is clear that direct use is a way of diversifying utilization of geothermal resource.
The major problem associated with the use of brine is the presence of many dissolved solids such as silica, quartz and calcite. The solutes are usually in equilibrium with each other at high temperature and pressure in the reservoir. Upon change of these thermodynamic properties, deposition of amorphous silica in the pipeline and other equipment e.g. heat exchangers and valves normally occurs. To arrest silica deposition, heat exchange should be done at a temperature above the super saturation point of silica. Other factors such as pH and ion concentration also determine the rate of deposition. Therefore, pH reduction and dilution of the brine before utilization are options which can be used to inhibit deposition (Gudmundsson, 1983). Figure 3 and Figure 4 below shows the effect of pH alteration on the deposition rate of amorphous silica. It is also desirable that the level of reactive gases such as CO_2, H_2S, H_2, CH_4 and N_2 should be low so that corrosion is kept to a minimum.

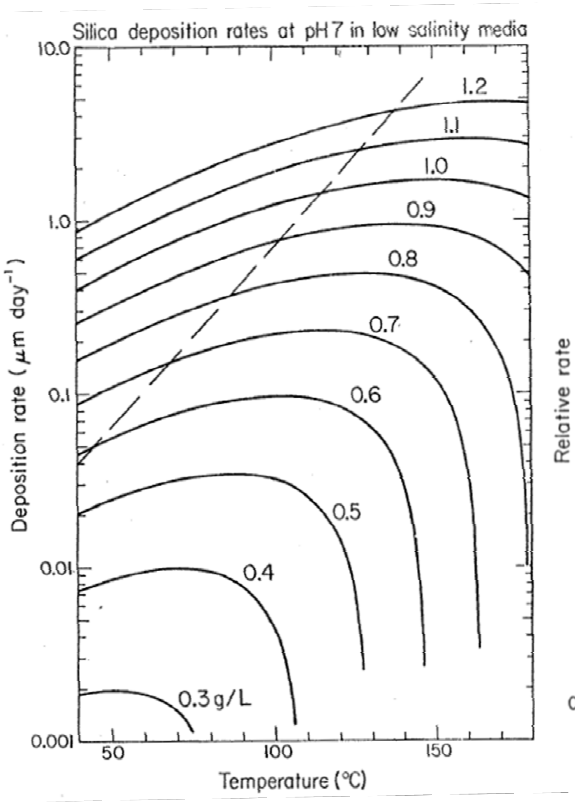

FIGURE 3: Rate of silica deposition at varying concentrations and pH = 7 (Kruger and Ramey, 1978)

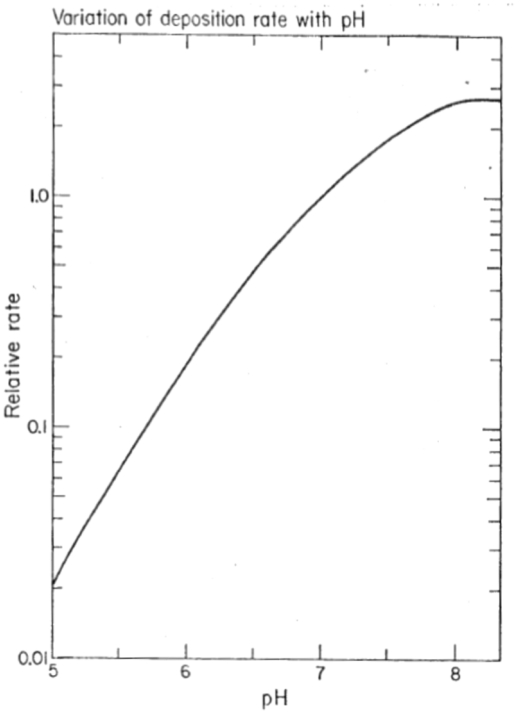

FIGURE 4: Rate of silica deposition at pH = x relative to rate of deposition at pH = 7, where x = 5, 6, 7, 8 (Kruger and Ramey, 1978)

A reduction in pH from 7 to 6 results in an 80% decrease in the rate of deposition (Figure 4). At such a rate, the deposition is likely not to be a major concern. In addition, heat exchange can be done at a much lower temperature and this will result in more energy being availed for utilization.

4. BENEFITS OF USING GEOTHERMAL ENERGY

Geothermal is a clean and renewable energy resource. It is classified as one of the green energy resources because it is friendly to the environment. Production of energy from geothermal is associated with the release of very little or no CO_2 to the atmosphere unlike the burning of fossil fuels. This means that industrial processes requiring temperatures in the range that geothermal fluids can provide such as milk pasteurization and food canning can replace the fossil fuel fired boilers with geothermal energy.

Over the past few years, the world has been experiencing ever rising fuel prices. This has placed a heavy financial burden on industries which rely on fossil fuels to run their daily operations. On the other hand, the prices of geothermal energy remains relatively unaltered for long periods of time once drilling has been completed. In some cases, savings of up to 80% on fossil fuels have been recorded with the use of geothermal energy directly (Lund, 2004). In addition, the maintenance of systems running on geothermal energy is very little as compared to other systems.

Direct use of geothermal energy is more efficient in the utilisation of energy as compared to other forms energy utilisation. At 50-70% efficiency, it stands much higher above geothermal electricity generation (12%) and internal combustion engines (54%) (EPA, 2006). In addition, with cascaded systems, the energy in geothermal fluids can be utilized down to very low values. Cascading is where a process which requires higher temperatures utilizes the energy in the geothermal fluids first, and then the fluid is utilized by yet another process requiring lower temperatures.

Finally, direct use of geothermal energy is a reliable source of energy. As longs as the associated equipment such as heat exchangers, valves and pumps are working well and the resource is utilized sustainably, a constant source of energy is assured. This is unlike other sources of energy such as hydro-power which rely heavily on the rainfall.

Before direct use of geothermal energy can be made a reality, there are a few requirements that should be in place. Firstly, there must be a geothermal resource which can be economically exploited. The thermodynamic properties of the geothermal fluid and its chemistry should be appropriate for direct utilisation.

Secondly, it is important that a market for the direct use application is within the locality of the geothermal resource. In most cases, the market is determined by the economic activities of the communities living close to the resource. For example, if the population living around the geothermal resource is made up of farmers, then the most appropriate direct uses should be geared towards the processing of agricultural produce. It is also worth noting that transporting the fluid over long distances is a costly affair because of the high cost of the equipment involved such as the transmission pipelines, valves and pumps. Fluid transportation is also associated with both temperature and pressure losses along the length of the pipeline which are not desirable.

5. COMPONENTS NECESSARY FOR GEOTHERMAL DIRECT UTILISATION

The geothermal fluid for utilisation in direct use applications should be transported from the geothermal reservoir to the surface. In some cases, this reservoir may not have outflow areas and therefore, a production well must be drilled to tap into the reservoir and bring the hot fluid to the

surface for utilisation. The depth of the production well varies widely but can range from about 1000 m to 3000 m.

In the medium and high temperature reservoirs, the geothermal fluid will in most cases flow to the surface under pressure but in the low temperature fields, the fluid must be pumped unless in situations where artesian flow is possible. Downhole pumps are used to pump the geothermal water to the surface especially where large scale applications are involved. The pumps used with geothermal fluids are the line shaft and submersible pumps. Line shaft pump is the preferred choice because of its longer mean time between failure and lower price (Lund, 1996).

5.1 Pump

The line shaft pump consists of a multi-stage downhole centrifugal pump, a surface mounted motor, a drive shaft connecting the pump and the motor, an enclosing tubing with water lubricated bearing and an outer column as shown in Figure 5

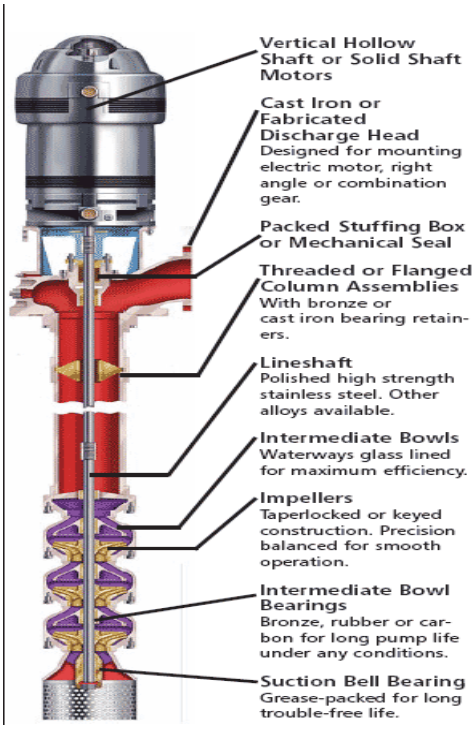

FIGURE 5: Line shaft pump

This pump has the following benefits:

- Proven pump reliability in diverse geothermal fluids.
- Mean time between failure is 7-15 years, depending mainly on water quality
- Water lubricated line shaft bearings which ensures there is no down-hole pollution of oil in water
- Depth range 0 to 300 m
- Fluid temperature range 4°C to 200°C

5.2 Heat exchangers

A heat exchanger is a partition that keeps the hot and the cold fluid separated during heat exchange. The heat exchangers used with geothermal fluids are made of stainless steel which has a good overall heat transfer coefficient and is relatively corrosion resistant. However, where highly corrosive fluids are involved, titanium could be used though it is expensive.

The driving force for heat transfer in a heat exchanger is the temperature difference between the heating medium and the product being heated. The bigger the temperature difference the bigger the quantity of heat transferred. Since this temperature difference varies within the heat exchanger, a logarithmic mean value is normally used and it is called Logarithmic mean temperature difference (LMTD).

In order to achieve efficient utilisation of energy during heat transfer, the two fluids should flow in opposite directions i.e. counter current flow, where the cold incoming fluid meets the cooled outgoing heating medium at the inlet, and a progressively warmer medium as it passes through the heat exchanger. During the passage the cold fluid is gradually heated so that the temperature is always only a few degrees below that of the heating medium at the corresponding point as shown in Figure 6.

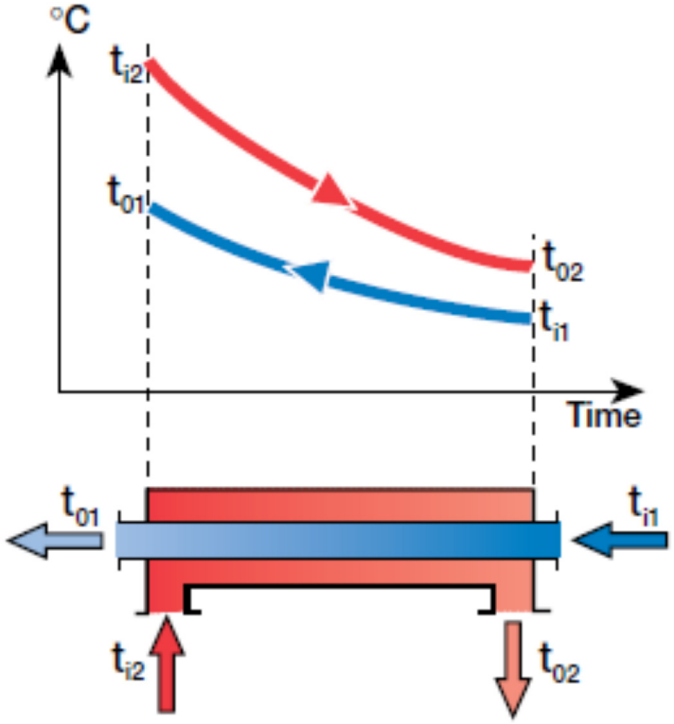

FIGURE 6: Counter current flow of fluids in a heat exchanger (Bylund, 1995)

There are three types of heat exchangers that are commonly used with geothermal fluids. These are plate, shell and tube and downhole heat exchanger. The most common of these is the plate heat exchanger.

In plate heat exchangers, the good overall heat transfer coefficient is made possible not only by the thinness and good thermal conductivity of stainless steel plates, but also by the design of the plates. The plates are corrugated to create turbulence in the flow of cold and hot media. Furthermore, the two fluids flow in opposite directions to enhance heat transfer as shown in Figure 7.

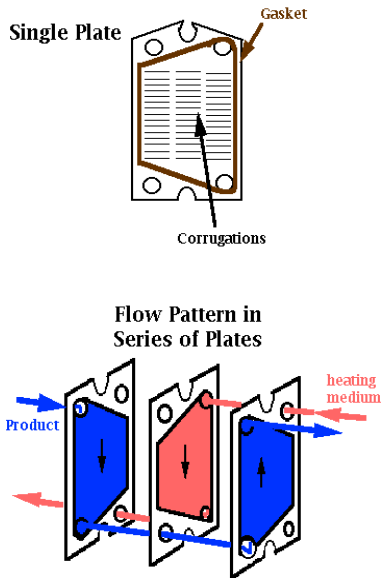

FIGURE 7: plate heat exchangers

As its name implies, shell and tube heat exchanger consists of a shell, which is a large pressure vessel, with a bundle of tubes inside it (Figure 8). One fluid runs through the tubes while the other fluid flows over the tubes to facilitate heat transfer between the two. The set of tubes is called a tube bundle. However, this heat exchanger is less commonly used with geothermal fluids because of fouling, big volume and high price of the device.

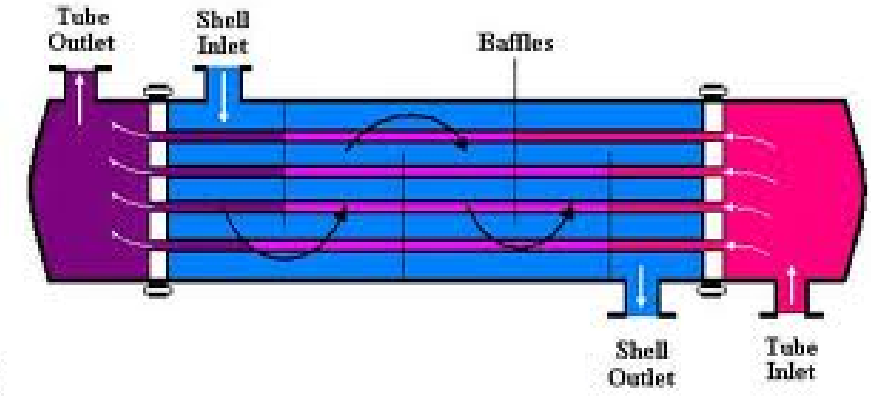

FIGURE 8: Shell and tube heat exchanger

5.3 Pipeline

Hot geothermal water should be transported from the source to the location where it is required for utilisation. A transmission pipeline is laid for this purpose, with provisions made to allow for thermal expansion when the pipe gets heated, with either expansion bellows or loops. The most common material for the transmission pipeline is carbon steel especially when the water temperature is above 100°C. Polyvinyl Chloride pipes (PVC) are used for water temperatures below 100°C. The pipes can be buried in the soil or installed above the ground (Lund, 1996).

In order to avoid heat loss in transmission pipelines, insulation with a watertight and waterproof material should be made. This is because moisture will conduct heat away and render the insulation ineffective. The most common insulation materials are rock wool, polyurethane foam and fiberglass. Burying the pipeline under the soil is also an insulation method though not as effective as with the use of insulation material. Apart from insulation, the other factors that affect heat loss are the pipe diameter and the flow rate (Ryan, 1981). Bigger diameters and higher flow rates lead to lower heat losses.

6. CONCLUSION

Geothermal direct use promises a wide range of applications such as space heating and refrigeration, drying and process heating. Though the installation of direct use systems is high, the running costs are very low and this makes the technology attractive in the long run. Apart from cost, the other important factor to consider before setting up a direct use system is to ensure reliability of the system. The major challenges associated with the utilisation of geothermal energy are scaling and corrosion. Scaling occurs due to the chemicals in the water such as silica and calcite. Corrosion is caused by the acidity of the water which wears out the equipment, especially the pipeline.

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DIRECT USE OF GEOTHERMAL ENERGY IN USA

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ABSTRACT

The state of Oregon, which is home to the Oregon Institute of Technology and the Geo-Heat Centre, is endowed with a geothermal resource which is mostly low-medium enthalpy. This resource is suitable mostly for direct use applications. Most of the direct uses in the USA are small scale. The applications highlighted in this paper are beer brewing, greenhouse heating, laundry, fish farming and onion dehydration. All the direct use applications covered in this paper are in Oregon apart from the Onion dehydration plant which is in Nevada.

1. INTRODUCTION

The United States has a large potential for geothermal energy spread across the country and especially in the mountainous western side of the country. USA is the largest producer of geothermal electricity with an installed capacity of 3,093 MWe and the second largest in direct uses at 12,612 MWt and 15,710GWh/yr, excluding geothermal heat pumps (IGA, 2010).

The most common direct uses of geothermal energy in the US are heating of individual houses, district heating, air conditioning, greenhouse heating, fish farming, industrial processing, agricultural drying, snow melting and swimming and bathing.

1.1 Oregon

The state of Oregon is located on the North Western part of the United States. The main direct use areas are Klamath Falls, Liskeys ranch, Oregon Institute of Technology and Lakeview which are located in southern Oregon as shown in Figure 1.

FIGURE 1: Map of the USA showing Oregon

2. HEATING OF BUILDINGS

2.1 Oregon Institute of Technology

The Oregon Institute of Technology (OIT) is constructed in an area known to have a geothermal reservoir underneath. The campus is 100% heated using geothermal energy and this has resulted in huge savings associated with heating cost. Within the campus is a 250kW binary power plant which utilises hot water at 85°C to provide some of the electric power needs of the campus.

2.2 The City of Klamath Falls.

The city of Klamath Falls has a population of about 20,000 (Klamath Falls demographics, 2012). The city has two geothermal wells with temperatures of 102°C and 108°C.

The geothermal water is pumped through a 1300m steel pipeline to the heat exchange building where it exchanges heat with city water as shown in Figure 2. The heated city water in a closed loop at 82°C is circulated in downtown Klamath while the geothermal water is injected back to the ground just outside the heat exchange building.

FIGURE 2: Klamath Falls heat exchange building. Some of the clients of the hot city water are 24 commercial and government buildings, greenhouses, sidewalk snow melt and a beer brewing company (Chiasson, 2006)

3. BREWERY

A brewery in downtown Klamath Falls utilises the heat in the city water to brew beer, melt snow on its sidewalks and heat the building which houses the brewery and a restaurant. City hot water at 82°C, exchanges heat with water in the brewery loop. The conversion of starch in malt to sugar takes place at 68°C in a process called mashing while lautering process, which marks the end of mashing takes place at 78°C. Figure 3 below shows some of the equipment used in geothermal brewing of beer. Use of geothermal energy by the brewery and the restaurant results in a 46% saving, on the price of gas, which would have been used to meet the energy requirements for heating and brewing.

FIGURE 3: Beer brewing equipment

4. GREENHOUSE HEATING

4.1 Tree Nursery heating

A tree nursery housed in a greenhouse in Klamath Falls uses heat from the city water to heat the greenhouse during the cold season. The tree seedlings are raised for up to 9 months and then sold for reforestation purposes. The tree nursery has its loop of water which exchanges heat with the city water. In addition, they also have a backup gas fired furnace which supplies the hot water when the city hot water supply system is not adequate. The heated water is used to heat air which is then circulated in the greenhouses to raise temperature. Figure 4 shows the seedlings inside the greenhouse.

FIGURE 4: Tree nursery greenhouse in Klamath Falls

4.2 Spider Mites Farming

Liskey's greenhouses are used to grow Lima beans and spider mites for their eggs. The leaves of the lima beans are rich in chlorophyll which provides food for the spider mites as shown in Figure 5. The spider mite eggs are harvested and then sold as food for predator mites which are used for biological control of bugs in crops. The greenhouses are heated using hot water from geothermal wells at a temperature of 88°C-93°C and a flow rate of 25.3litres/s. The hot water is carried in finned tubes inside the greenhouse to provide a temperature of 32°C through radiant heating.

FIGURE 5: Spider mite farming at Liskey's Ranch

5. AQUACULTURE

5.1 Gone Fishing

This farm rears tilapia and tropical fish from Lake Malawi in Southern Africa. The water in the ponds is of geothermal origin and considered suitable for fish farming as shown in Figure 6. It is introduced into the ponds at about 90°C but after mixing with the cooler water in the pond, its temperature drops quickly to 28°C ±2°C. However, this requires varying the flow rate from 3.15-18.9 Litre/s depending on the ambient temperature.

FIGURE 6: Geothermally heated fish ponds

5.2 Canby Tilapia Farm

The fish are grown in concrete fish ponds measuring 15 m in diameter and 2.5 m in depth as shown in Figure 7. This fish farm is the largest in the western side of the USA. The temperature of the water is kept at 29°C throughout the year by mixing water from a hot spring with cold water from a manmade lake. About 9100 kg of fish are harvested every week and transported to China Town in San Francisco where they are sold while they are still alive.

FIGURE 7: Tilapia farming tanks

6. ONION DEHYDRATION

FIGURE 8: Onion dehydration plant

An onion dehydration plant at Fernley, Nevada uses hot geothermal water from a nearby binary geothermal power plant to dehydrate onions, clean the onions, clean the processing equipment and heat the building and equipment to prevent freezing. Hot water at 140°C enters the dehydrators and hot air used in three stages to dehydrate the onions i.e. 120°C, 100°C and 70°C. Some of the water is then cooled to 110°C and used for cleaning equipment while the rest is discharged to a ditch and allowed to percolate into the ground. 6800 kg/hour of onions processed daily during the months of operation i.e. from May to December. Figure 8 shows the onion dehydration plant.

7. CANBY COMMUNITY PROJECT

A Christian community living in Canby owns geothermal wells that supply hot water for heating their buildings during the cold seasons, heating greenhouses for vegetable production and heating ponds for fish farming.

7.1 Aquaponics

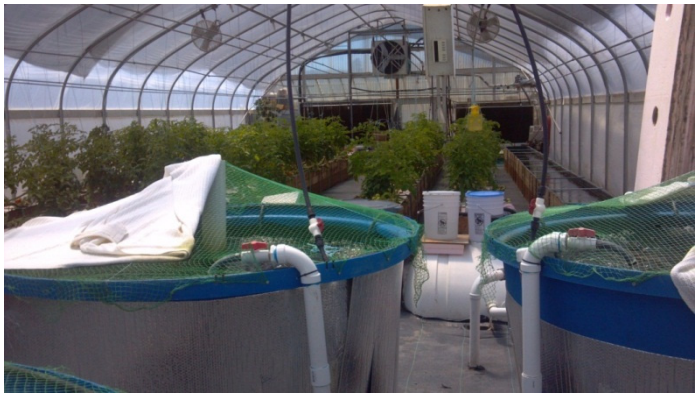

FIGURE 9: Canby Aquaponics Project

Aquaponics, a system of growing plants without using soil or fertilizer for the plants is employed. The spent water from the fish tanks, which is rich in ammonium, is filters and bacteria allowed to act on it so that ammonium is converted to nitrates, which in turn becomes food for the plants. The plants consume the nitrates and the resulting "clean water" is returned back to the fish ponds. Figure 9 shows the aquaponics

project inside a greenhouse.

7.2 Geothermal Laundry

The Canby community members have a common laundry where all the clothes for the members are washed using geothermally heated water as shown in Figure 9. Drying of the clothes is also done using geothermal energy. It is estimated that the community made up of 170 members saves about $16200/year from the use of geothermal in laundry as opposed to the use of propane.

FIGURE 9: Geothermal laundry

8. CONCLUSION

Though the United States has large energy consumption in terms of direct use of geothermal energy, the growth has been very slow due to limited funding. This is mainly because the Department of Energy is more interested in electricity generation. However, the persons who have direct use applications installed have nothing but praise for the technology especially due to the energy saving.

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DIRECT UTILISATION IN KENYA: A CASE OF A GEOTHERMAL SPA AND DEMONSTRATION CENTRE AT OLKARIA

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ABSTRACT

Geothermal energy is used in electricity generation and other direct uses like greenhouse heating, carbon dioxide enrichment in greenhouses, hot bathing, sauna or steam bathing, space heating and cooling, fruits or crops drying, and skin healing. Direct Uses of geothermal energy has been applied to a small extent in flower farms for heating green houses and carbon dioxide enrichment. Over the years, the Kenya Electricity Generating Company Ltd has utilised geothermal resources mainly for electricity generation. To this end, KenGen has constructed a Geothermal Health Spa and Demonstration Centre, the only one of its kind in Africa, to market and promote geothermal direct uses. The Centre is located in the Greater Olkaria Geothermal Area (GOGA) which is within the Hell's Gate National Park. It consists of three cascading blue lagoons, sauna and massage, steambath, restaurant, reception, Manager's office, geothermal museum and changing rooms. The museum will host artifacts, models, posters, and brochures to showcase the history of geothermal development in the country and other current developments in the technology worldwide Additional facilities that will be added include conference facility that can hold 200 people, cottages and ski lifts. After completion, the Centre will attract both domestic and foreign tourists because of its unique nature and more so because of the benefits that will be derived from patronizing the steam bath, sauna, massage, and the hot swimming pools or blue lagoons. There is sufficient evidence that the brine with its sulphur and silica content has balneological (healing and smoothening effects on the skin). In addition, as a result of the centre being established, the Hell's Gate National Park will be branded as the only park with a geothermal health spa in the world. This will in effect promote Hell's Gate National Park the world over and thus the number of tourists visiting the park is anticipated to increase spontaneously. This paper discusses direct uses of geothermal energy, the establishment of the geothermal health spa and Demonstration Centre, challenges and gives recommendations.

1. INTRODUCTION

Geothermal energy is used in electricity generation and other direct uses like greenhouse heating, carbon dioxide enrichment in greenhouses, hot bathing, sauna and massage, steam bathing, space heating and space cooling, fruits or crops drying, and skin healing.

2. DIRECT USES OF GEOTHERMAL ENERGY

Kenya is naturally endowed with enormous potential of geothermal energy that is a clean indigenous environmentally benign source of renewable energy used for electric and non-electric uses. Duffield and Sass (2003) attest that geothermal resources were limited to non-electrical applications before the development of high-temperature drilling and well completion technology. The non-electric uses of geothermal energy are also known as direct uses. Non-electric uses of geothermal resources exploit geothermal waters of temperatures ranging from 38^0 C to over 149^0C coming directly from the earth.

By the year 2000, global statistics on non-electric uses of geothermal energy showed Kenya has a capacity of 1.3 MWt with a capacity factor of 0.25. The annual heat produced then was 10 TJ/yr with 3 GWh/yr of utilization mainly from well OW-101 in the Olkaria field leased to Oserian Development Company Ltd (ODC) by the Kenya Electricity Generating Company Ltd (KenGen). Lagat (2003) has documented non-electric uses of hot water from well OW-101 at Olkaria Central field in green house heating, soil fumigation and addition of carbon dioxide to green houseplants at ODC. At the Lake Bogoria resort, water from a natural hot spring is used in the swimming pool. Duffield and Sass, 2003, cite lack of awareness of the direct uses of geothermal energy as the greatest impediment to the growth of enterprises in geothermal utilization. They further argue that extensive capital ventures in development of the warm water systems, most commonly found in volcanic areas but also in a few non-volcanic areas, would significantly improve the energy balance of the nation.

Direct uses of geothermal energy have been applied in the world where geothermal resources exist. The direct uses take the form of rudimentary traditional systems where communities living in the area have used geothermal energy for various uses like bathing, drying of crops, condensation of the steam to harvest portable water and boiling of eggs, to complex systems like district heating, greenhouse heating and refrigeration. In Kenya, traditional systems are evidenced at Eburru where the local community has been tapping the steam and condensing it for domestic uses and running hot pipes through pyrethrum driers. In Iceland, the "blue lagoon" located at Svartsengi power plant in Grindavik is an international tourist attraction facility where visitors and tourists patronage the sauna and hot water bathing. Gunnlaugsson et al, 2001, mentions that in Iceland, use of geothermal energy gained further momentum in the twentieth century when it was used to heat greenhouses and homes. 63% of geothermal energy is used for space heating but a significant 4% is used in swimming pools. (Lundi, Freeston, 2000) indicate that 55 countries reported direct uses of geothermal energy in 2000 compared to 28 in 1995 and 24 in 1985. They add that worldwide use of geothermal energy for bathing stood at 22.15 in 2000.

The Kenya Electricity Generating Company Ltd has identified and is implementing direct use applications of geothermal energy through constructing a Geothermal Health Spa and Demonstration Centre. Additional facilities as part of the Geothermal Health Spa and Demonstration Centre include conference facility, cottages, Fish farms and vegetable farms.

The Centre is located in the Greater Olkaria Geothermal Area (GOGA) which is within the Hell's Gate National Park. It consists of three cascading blue lagoons, sauna and massage parlour, geothermal museum, restaurant, reception, changing rooms, steambath and a conference facility. The museum will host artefacts, models, posters, and brochures to showcase the history of geothermal development in the country and other current developments in technology worldwide. After completion, the Centre will attract both domestic and foreign tourists because of its unique nature and more so because of the benefits that will be derived from patronizing the steam bath, sauna, and the hot swimming pools or blue lagoons. There is sufficient evidence that the brine with its sulphur and silica content has balneological (healing and smoothening effects on the skin. In addition, as a result of the centre being established, the Hell's Gate National Park will be branded as the only park with a geothermal spa in the world. This will in effect promote Hell's Gate National Park the world over and thus the number of tourists visiting the park is anticipated to increase spontaneously.

3. LOCATION

The Olkaria Geothermal field is located in the Rift Valley about 120km from Nairobi and within the Hell's Gate National Park (Figure 1). The proposed Geothermal Health Spa and Demonstration Centre will occupy an area of about 4.5 Ha and will be located in the Greater Olkaria Geothermal Area where the Kenya Electricity Generating Company Limited (KenGen) operates two geothermal power stations, Olkaria I and Olkaria II, generating 45 MWe and 105 MWe respectively.

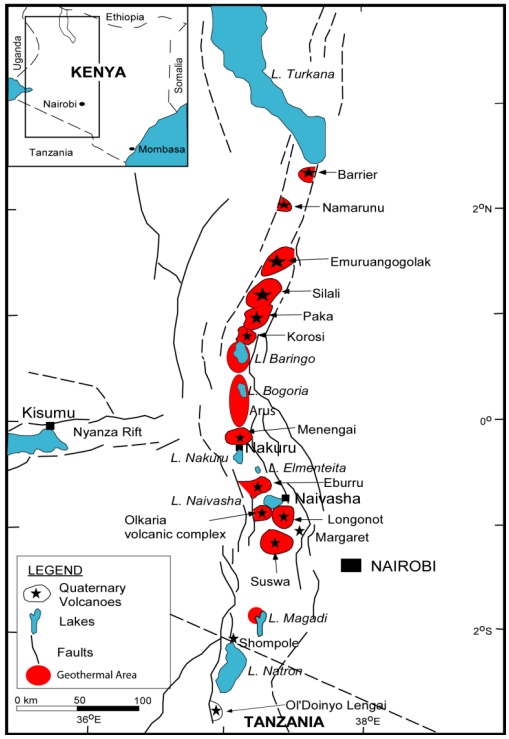

FIGURE 1: Location of Olkaria Geothermal field

4. USE OF GEOTHERMAL ENERGY

4.1 Geothermal Use in Kenya

To date, geothermal resources in Kenya have mainly been used for indirect uses, i.e., like generation of electricity with little application in direct uses. Figure 2, 3, 4 and 5 show KenGen's geothermal power plants.

FIGURE 2: Olkaria I power station (45 MW)

FIGURE 3: Olkaria II power station (105 MW)

FIGURE 4: Eburru wellhead plant (2.5 MW)

FIGURE 5: Olkaria wellhead plant (5 MW)

Most wells in Olkaria produce 75% water and 25% steam. The separated hot water from the wells is used at the Geothermal Health Spa and Demonstration Centre for sauna and massage, Spa and steambath.

4.2 Greenhouse heating

Green house applications use hot water from geothermal wells found in the relatively rural location, where most geothermal resources are located. Such locations offer advantages that include clean air, fewer diseases, clean water, a stable workforce, and often, low taxes. Savings of about 80% of fuel costs and 5% to 8% of total operating costs are realized when geothermal resources are compared to traditional energy sources (Duffield and Sass, 2003). Figure 6 shows greenhouse heating

FIGURE 6: Green house heating at Oserian Development Company, Naivasha, Kenya

by geothermal hot water through the white pipes at Oserian Development Company's greenhouses.

Oserian Development Company has championed greenhouse heating in Kenya. They have realized the benefits of low cost energy through direct cost heating using the geothermal brine; enrichment of carbon dioxide (CO_2) levels in the greenhouses and sterilisation of soils which is good for plant growth. More use of geothermal energy for greenhouse heating is evident in Mauritius.

5. AGRO- INDUSTRIAL APPLICATIONS

Agricultural - Industrial applications like timber and cereals drying, food dehydration, laundries, spas, milk pasteurizing can be done using heat from geothermal energy. The hot steam can be used to sterilize equipment and rooms without using drugs or chemicals. Geothermal energy can find use drying plants, making powders and concentrates that are used in food processing. At times, these substances can be used to add flavours or preserve foods without any unnatural additives. The food processing industry in Naivasha and in the other areas where geothermal energy abundantly exists can use geothermal steam to sterilize foods at an affordable cost. At Eburru, the local community uses geothermal heat to dry pyrethrum. With proper harnessing of the geothermal steam, the local community can greatly benefit from the drying of other plants like tobacco and maize. KenGen has designed a water harvesting and a drying unit on a commercial scale that is meant to benefit the community at Eburru. Figure 7 shows pyrethrum drying at using geothermal steam at Eburru.

FIGURE 7: Geothermal energy being used by the local community at Eburru for pyrethrum drying

5.1 Water harvesting

In water deficit areas where we have occurrences of fumaroles and hot grounds, some communities harvest water from geothermal steam. This water is used for irrigation, watering of animals and for domestic use, washing clothes, cleaning of floors and general cleanliness. At Olkaria, water from the steam is being harvested for use by the wild animals within the Hell's Gate National Park. Figure 8 shows water being harvested from fumaroles at Suswa.

FIGURE 8: Water harvesting by local a community at Suswa

5.2 Balneological and antibacterial uses

Balneology is a medical practice of soothing aching muscles practiced in hot springs and health spas. Health spas are good for recreation and for provision of health treatment. In Iceland, for example, the Blue Lagoon at Svartsengi power plant is one of the most visited attractions in Iceland. The steamy waters are part of a lava formation, just like the geothermal waters at Olkaria. Since the construction of the blue lagoons at Olkaria, many tourists now visit the park to enjoy the therapeutic brine waters

FIGURE 9: Panoramic view of the Geothermal Health Spa at Olkaria, KenGen, Kenya

FIGURE 10: Spa pool at Lake Bogoria Resort

Many locations in Kenya have potential for direct use application, e.g., Olkaria, Eburru, Homa hills, Nakuru Banita area, Lake Magadi, Kureshwa, Lake Bogoria, and Lake Baringo. Figure 10 shows the Lake Bogoria resort spa.

5.3 District and space heating and cooling

District and space heating is the dominant use of low-temperature geothermal resources in countries like Iceland where temperatures are low most of the time. Hydrothermal water is distributed from one or more geothermal wells through a series of pipes to several individual houses and buildings, or blocks of buildings in district systems. During hot weather, geothermal energy can be used to cool rooms and space by heating a refrigeration fluid that vaporizes to cool the rooms or space.

In Reno Nevada, USA, district heating is practiced in the south of the area. Industrial processes continue to grow and industrial geothermal heat pumps are an emerging market. A 1996 survey found that these applications were using nearly 5.8 billion megajoules of geothermal energy each year. Its energy equivalent is nearly 1.6 million barrels of oil. It has been estimated that geothermal district heating systems can save consumers 30 to 50% of the cost of natural gas heating, (US Department of Energy, 2010).

6. THE KENGEN GEOTHERMAL HEALTH SPA AND DEMONSTRATION CENTRE

6.1 Conceptual Design of the Geothermal Health Spa and Demonstration Centre

6.1.1 The Centre Components

The Geothermal Health Spa and Demonstration Centre consists of four interconnected “blue lagoons”, a reception area, a lobby and a parking area for about 20 vehicles, six changing rooms, an exhibition hall, a sauna, steam bath, a cafeteria and kitchen, a store, all constructed on a 45 000 m^2 piece of land on the west of Olkaria II power plant. The first, second and third lagoons have diameters of 30 m, 40 m and 70 metres respectively. The fourth lagoon, the children’s pond has a diameter of 10 metres. The

first and second lagoons have a maximum depth of 1.5 m while the third and largest lagoon has a deeper end of 1.5 m and shallow end of 1m depth. Temperatures in the largest lagoon designated for public use is between 35 and 30°C. The centre utilizes part of the brine from a hot reinjection brine pipe to establish the blue lagoons, sauna and a spa.

FIGURE 11: Swimming at the Olkaria Geothermal Health Spa at KenGen, Olkaria

6.1.2 Source of Brine

Brine is tapped from the main reinjection line to well OW-708. To tap the brine, a tee off on the brine line was prepared and an isolation valve installed.

At full flow, the three blue lagoons, assuming that they were empty at the start fills up in 23 hours. The brine flows at 300 tons/hr. on full flow rate.

6.1.3 Lagoon layout

The brine is flashed into the first lagoon through a pipe designed and constructed to collect the brine as it bubbles out. A silencer was designed that muffles the noise during the flashing out of the brine. The hot water pipe to the Geothermal Health Spa and Demonstration Centre has two valves for safety reasons. These valves are also used to control the flow of the brine. The brine flows into the first lagoon at about 91°C. When the first pond fills up, the brine overflows into the second lagoon at about 85°C. The brine in the second lagoon, which is slightly bigger, cools to about 84°C before exiting into the third and largest lagoon at about 69°C. The outlet temperature in the third and largest lagoon is 46°C. The valves on the pipe bringing brine from the reinjection lines are used to control the flow of the brine and therefore the temperatures. With this management, the inlet temperature at the third and largest lagoon is 35°C and outlet temperature is 30°C.

TABLE 1: Inlet and outlet temperatures (at full flow rate)

Pond	Inlet Temp., ˚C	Outlet Temp., ˚C
1	91	85
2	84	69
3	66	46

6.1.4 Sauna

Hot naked pipes carrying brine at 150°C will run in a room designated as the sauna. The heat radiated from the hot pipes will heat the room. Patrons will thus enjoy this overheat. The design of the sauna is complete and construction has started.

6.1.5 Steam bath

A steam bath is now being installed in the Geothermal Health Spa and Demonstration Centre. The brine will run through a heat exchanger that will vaporize steam into the steam room.

6.1.6 Reinjection system

The water from the third and largest lagoon is reinjected into the subsurface at well OW-R1 by gravity through a Victaulic pipe, running on the surface. Figure 12 is a schematic diagram of the flow system for the Geothermal Health Spa and Demonstration Centre.

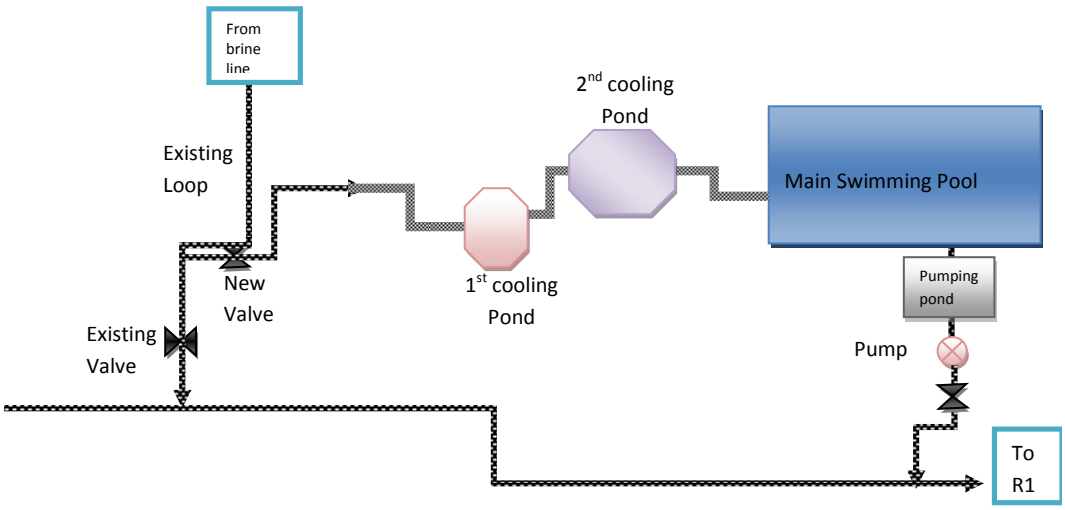

FIGURE 12: Schematic Diagram of the Flow System

6.2 Why centre was established

6.2.1 Tourist attraction

No such a centre exists in Africa. The centre acts as a tourist attraction as more tourists and visitors are now patronizing the Centre. The Geothermal Health Spa and Demonstration Centre has branded the

Hell's Gate National Park as the only national park in Africa where hot bathing for balneological effects can be obtained. This is thus expected to raise revenue to the Kenya Wildlife Service as more tourists come to see and also make use of the sauna and blue lagoon. In addition to the tourists, the number of students and Kenyans visiting the Park has now increased. In Iceland, for example, the Blue Lagoon is one of the most visited attractions in Iceland, Newsweek (2008).

6.2.2 Geothermal spa

A spa using geothermal waters (a hot spring) is currently operating at Lake Baringo hotel. Hotels within the vicinity of Olkaria may also adopt this concept and establish similar spas. The Company can assist these establishment to establishment similar facilities. This will improve attractions to their hotels and improve business performance. Individuals may also install spas in their homes for life enrichment.

6.2.3 Hot water heating in hotels and other entertainment joints for guests

Most of the hotels within the vicinity of Olkaria Geothermal Project use electricity to heat rooms and provide warm water for bathing at high power costs. Use of hot water from the wells would reduce electricity costs because the cost of the hot water is far much less. This will be demonstrated at the centre.

6.2.4 Greenhouse heating

Oserian Development Company in 2003 installed a green house heating system providing energy which amounts to 79.1TJ/yr from a well leased from KenGen. In addition to the heat from the geothermal water, carbon dioxide from separated steam is also used to provide carbon dioxide and hydrogen sulphide to improve the productivity of flowers.

We will establish a prototype greenhouse at the Geothermal Health Spa and Demonstration Centre that will showcase the use of geothermal energy in greenhouses. It is expected that more flower farms neighbouring Olkaria will start using geothermal water to heat their green houses. KenGen will sell separated hot water to these farms at a cost to be determined for consideration by the company

6.2.5 Steam bath

Steam bathing is believed to soften skin and reduce aging. Visitors will use steam bath from the hot brine that will be vented into the steam bath enclosure. In addition, this showcasing will market the use of hot brine among homes and hotels. This is expected to reduce dependence on electricity to heat water and thus reduce electricity costs. This saving in electricity will avail electricity to other industrial concerns that are located far from geothermal sources.

6.2.6 Sauna

The sauna that will be established will use brine running in naked pipes at 1500C. The heat from the naked pipes will raise temperature in the room which will then serve as the sauna. Patrons will use the sauna to heat their bodies which in turn is believed to soften skin, reduce cholesterol levels, remove toxins and waste and thus reduce ageing.

6.2.7 Cooling

Hot water can be used to heat a cooling agent which can then be used for space cooling when temperatures are high. Designing of a functioning system, akin to the refrigeration system is now underway.

6.2.8 Antibacterial and balneological effects

It is believed that due to the chemical content of the hot brine, the brine contains antibacterial chemicals that heal skin diseases and rushes like psoriasis. The brine contains sulphur either as a residue or as a compound in hydrogen sulphide gas or diluted sulphuric acid. The sulphur is otherwise referred to as the body's beautifying mineral. It is available in Keratin- chemical component of the body that keeps hair, skin, fingernails, skin, strong and healthy. It also enhances production of collagen that enhances skin elasticity. Sulphur also enhances cellular respiration and therefore promotes efficient utilization of oxygen in the body (Wikianswers; Newsweek, 2008).

6.2.9 Posterity

The Geothermal Health Spa and Demonstration Centre has geothermal museum and a conference facility. The museum will host murals, artefacts and models to show the history of geothermal development in the country and other current developments in technology in the industry worldwide. The Geothermal Health Spa and Demonstration Centre will thus act as a marketing centre for direct uses of geothermal energy in the region. Similar ventures will be replicated where geothermal resources exist.

6.2.10 Employment creation

The establishment of the centre will create employment to the citizens of the country. People will be employed to manage the centre and with additional facilities like cottages being included, more staff will be required. The cereals or crops drying facility will also employ several people. With the concept of fish farming and irrigation being adopted by farms/ firms in the vicinity, this will create additional employment to the population.

7. ADDITIONAL FACAILITIES

Additional facilities are planned as part of the centre. These include ski lifts that will carry patrons from the centre up to the view point (Figure 13).

Other facilities planned for development include cottages. We will also establish prototype fish farms, green houses, and irrigation farms to showcase direct uses of geothermal energy (Figures 14-16).

8. CONCLUSIONS & RECOMMENDATIONS

KenGen is the premier organization in harnessing of geothermal energy and therefore it has a social and corporate responsibility to promote geothermal energy in the region, for posterity.

The Geothermal Health Spa and Demonstration Centre will showcase direct uses of geothermal energy. In addition to promotion of geothermal energy as a renewable and cost saving source of energy, the centre has already become a major attraction to both tourists and visitors to the Park. This has increased revenue to the Kenya Wildlife Service. KenGen will establish such centres in all new geothermal fields. This will not only optimize utilization of the geothermal resources but will also enhance a good working relationship between the Company and immediate stakeholders.

FIGURE 13: Example of ski lift

FIGURE 14: Sample cottage

FIGURE 15: Fish farm

FIGURE 16: Vegetable farm

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organized by UNU-GTP, GDC and KenGen, at Lake Bogoria and Lake Naivasha, Kenya, Oct. 31 – Nov. 22, 2013.

GEOTHERMAL EXPLORATION IN KENYA

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ABSTRACT

The high temperature geothermal prospects in Kenya are located within and are associated with the development of the Kenya Rift. Kenya Rift is a continental scale volcano-tectonic feature that stretches from northern to southern Africa. Development of the Rift started during the Oligocene (30 million years ago) and activity has continued to recent times. The last 2 million years saw the development of large shield volcanoes within the axis of the rift. These centres are the most important geothermal prospects within the rift. Association between rifting and most of the occurrences of geothermal energy is mainly due to shallow magma chambers underneath the young volcanoes within the rift axis.

Detailed surface studies of most of the prospects in the central sector of the rift which comprises Suswa, Longonot, Olkaria, Eburru, Menengai, Lakes Bogoria and Baringo, Korosi and Paka volcanic fields have been studies and geothermal systems identified. Electric power is currently being generated at Olkaria with 209MWe installed while exploration drilling has been undertaken at Eburru and a 2.5MWe pilot plant is being developed by KenGen and due to be commissioned by 2011. Production drilling is in progress for 280MWe for Olkaria I unit 4 and Olkaria 4 developments due to be commissioned in 2013. The Geothermal Development Company (GDC) is currently undertaking detailed studies at Silali, Paka, Barrier and Korosi for siting of exploration wells. It is estimated that more than 7,000MWe can be generated from prospects in the Kenya rift.

1. INTRODUCTION

Geothermal is an indigenous and abundantly occurring resource in Kenya. Exploitation of Kenya's geothermal resources has environmental and social advantages over the other major sources of electricity generation options available for the country. Geothermal is the least cost source of electric power for base load in Kenya (Acres, 1987, 1994; 1997; KPLC, 1998, 2000). Currently, 209 MW_e of the installed interconnected generation of 1350MW_e is generated from geothermal sources at Olkaria. Geothermal is expected to contribute additional 5000MW_e by 2030. Current estimates indicate that generation potential of the Kenya Rift could exceed 7,000MW. In order to fast track development of geothermal resources in Kenya, the Government of Kenya incorporated GDC to explore all geothermal resources in the country, drill exploration and production wells and sell steam to power producers.

2. GEOLOGICAL SETTING

Kenya rift is part of the eastern arm of the East African rift system. The segment referred to as the Kenya rift extends from Lake Turkana in the north to northern Tanzania near Lake Natron (Figure 1). In this sector of the rift system, the activity began about 30 million years ago in the Lake Turkana area and then migrated southward being more intense about 14 million years ago.

Formation of the graben structure started about 5million years ago and was followed by fissure eruptions in the axis of the rift to form flood lavas by about 2 to 1 million years ago. During the last 2 million years ago, volcanic activities became more intense within the axis of the rift. During this time, large shield volcanoes, most of which are geothermal prospects, developed in the axis of the rift. The volcanoes include Suswa, Longonot, Olkaria, Eburru, Menengai, Korosi, Paka, Silali, Emuruangogolak, and Barrier Complex.

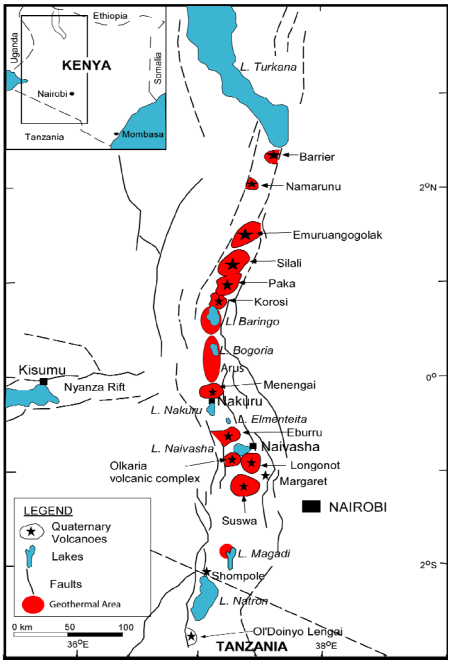

FIGURE 1: Map of the Kenya Rift showing the geothermal prospects

3. GEOTHERMAL DEVELOPMENT

Exploration for geothermal energy in Kenya started in the 1960's with surface exploration that culminated in two geothermal wells being drilled at Olkaria. In early 1970's more geological and geophysical work was carried out between Lake Bogoria and Olkaria. This survey identified several areas suitable for geothermal prospecting and by 1973, drilling of deep exploratory wells commenced and was funded by UNDP. Additional wells were thereafter, drilled to prove enough steam for the generation of electricity and in June 1981, the first 15 MW_e generating unit was commissioned. The second 15 MW_e unit was commissioned in November 1982 and the third unit in March 1985 which increased the total generation to 45 MW_e. This was the first geothermal power station in Africa and is owned and operated by KenGen. GDC is currently undertaking production drilling in the field to support an additional 140MW_e plant being developed by KenGen for commissioning in 2013.

In 2003, KenGen commissioned a 70MW_e Olkaria II power plant in the Northeast field and was further increased by 35MW in 2010 giving the station an installed capacity of 105MW_e. In the western sector of the greater Olkaria field is 55MW_e Orpower4 plant. The generator is currently undertaking production drilling to support a further 36MW_e in the field. GDC is also drilling production wells in the Olkaria IV area earmarked for 140MW_e plant being developed by KenGen. The plant is planned for commissioning in 2013. All the developments at Olkaria will result in a total installed capacity of 525MW by 2013 against a proven geothermal resource potential of well over 1,000MW_e.

The Government of Kenya and other parties have continued to explore for geothermal energy in the Kenya rift. British Geological Survey and the government of Kenya carried out studies in the Lake Magadi area (Allen at al., 1992), the area around Lake Naivasha including Longonot, Olkaria, Eburru, and Badlands (Clarke et al., 1990), and in the north rift (Dunkley et al., 1993). Geotermica Italiana also did some work in Longonot and Suswa calderas and also described geo-volcanological features important in geothermal exploration at Menengai (Geotermica Italiana Srl, 1987a, 1987b, and 1988).

4. GEOTHERMAL PROSPECTS

4.1 Eburru

Eburru volcanic complex is located to the north of Olkaria. The Government of Kenya carried out detailed surface studies between 1987-1990 that culminated in the drilling of six exploration wells in Eburru between 1989 and 1991. Further infill MT surveys done in 2006 revealed that the Eburru field can support up to 50-60MW$_e$ (Wameyo, 2006; Figure 3). The results from the exploration wells indicate that the field had experienced temperatures of over 300^{o}C possibly due to localized intrusive.

Discharge fluid chemistry from the wells indicates that the reservoir is non-boiling with moderate salinity brine and a high amount of non condensable gases (NCG). Despite the almost similar geology, the chloride level of EW-I (956 to 1976 ppm) is higher than the Olkaria average. As compared to Olkaria, the reservoir permeability is low (KPC, 1990).

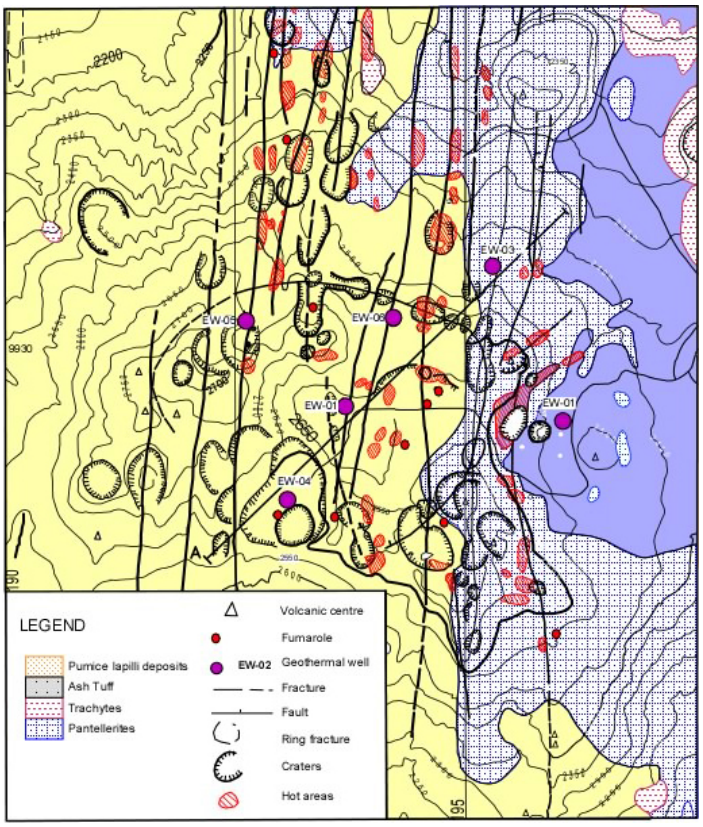

FIGURE 2: Geological map of Eburru Geothermal Field (Omenda and Karingithi, 1993)

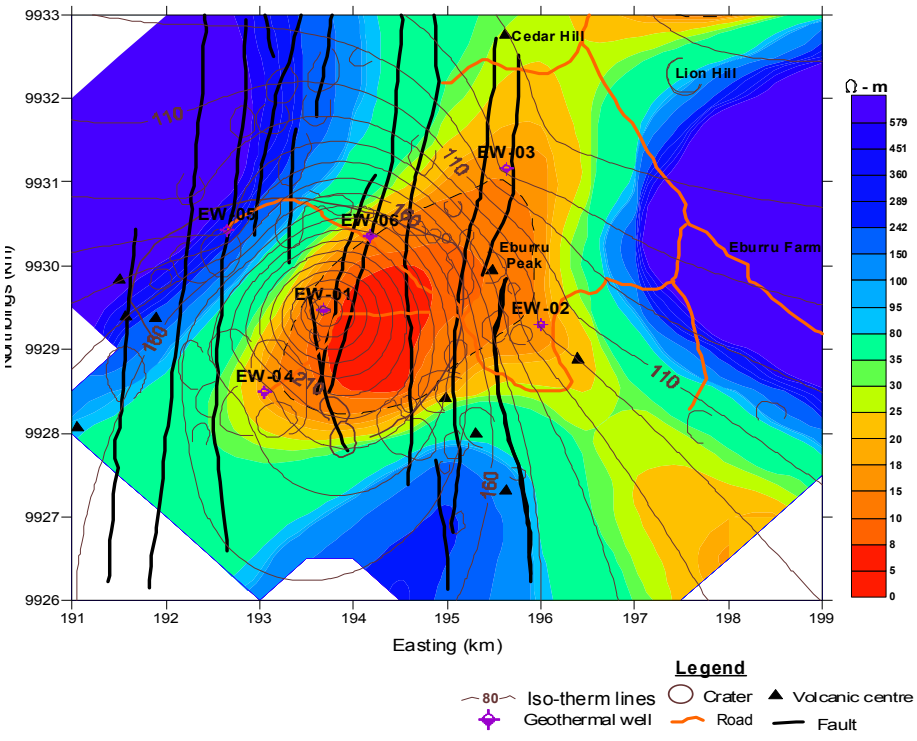

FIGURE 3: MT Resistivity distribution at 500 m a.s.l. (Wameyo, 2006)

The maximum discharge temperature was 285^{o}C and the total output from the two wells that discharged (EW-1 & EW-6) is 29 MWt (Ofwona, 1996). The estimated power potential of the field based on the data from the wells is about 50-60 MWe (Wameyo, 2006; Mburu, 2006; Omenda et al., 2000) and conceptualized as in Figure 4. The area has a fairly well established infrastructure and for this reason a 2.5 MWe binary pilot plant is planned for commissioning in 2011.

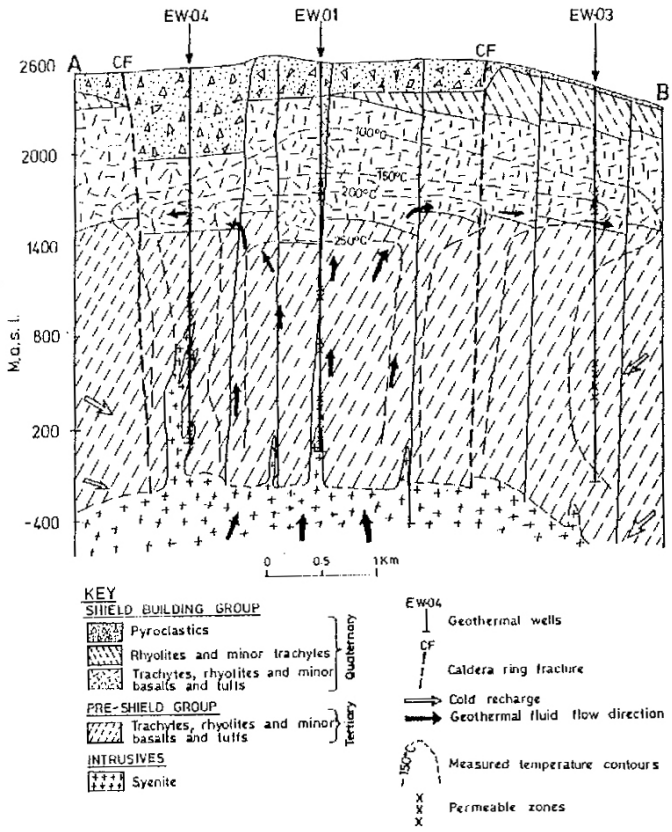

FIGURE 4: Conceptual model of the Eburru geothermal system (Omenda and Karingithi, 1993)

respectively suggesting the presence of magma bodies, which could be heat sources. Vp/Vs ratios of 1.6-1.7 suggest steam-dominated reservoir (Simiyu, 2003). Gravity modeling also shows the presence of dense bodies at about 4 km depth under the caldera floor.

Heat loss survey indicates that the prospect loses about 3,536 MWt naturally to the atmosphere with 2440 MWt being the convective component (Ofwona, 2004). Fumaroles are scarce in the prospect with the few strong ones occurring within the caldera floor. Fumaroles steam compositions have low contents of reactive gases (CO_2, H_2S, H_2, CH_4, and N_2). Gas geothermometry based on H_2S and CO_2 indicates that the reservoir temperatures are greater than 250°C.

The mapped potential area in Menengai is about 84 Km^2 translating to over 1650 MWe of electric power when conversion rate of 15MW per square kilometer is used (Figure 6 and 7). The reservoir rocks are expected to be trachyte as at Olkaria and therefore comparable permeability is postulated. Whereas Olkaria system has several discrete hot magmatic intrusions which are considered heat sources, Menengai has a centralized body under the caldera (Figure 7).

4.2 Menengai volcano

Menengai is a major Quaternary caldera volcano located within the axis of the central segment of the Kenya Rift. The volcano is located within an area characterized by a complex tectonic activity characterized by confluence of two tectono-volcanic axes (Molo and the Solai). The volcano has been active since about 0.8 Ma to present. The volcano is built of Trachyte lavas and associated intermediate pyroclastics. Most of the pyroclastics activity accompanied caldera collapse. Post caldera activity (<0.1 Ma) mainly centred on the caldera floor with eruption of thick piles of trachyte lavas from various centres (Figure 5).

MT resistivity distribution at 2km bsl shows a conductive body of less than 5ohm-m centred in the western caldera floor "lobe" and a smaller anomaly at the centre of the caldera (Figure 6). Seismology indicates seismic wave attenuation at 7-8km depths underneath Menengai caldera and Ol'banita,

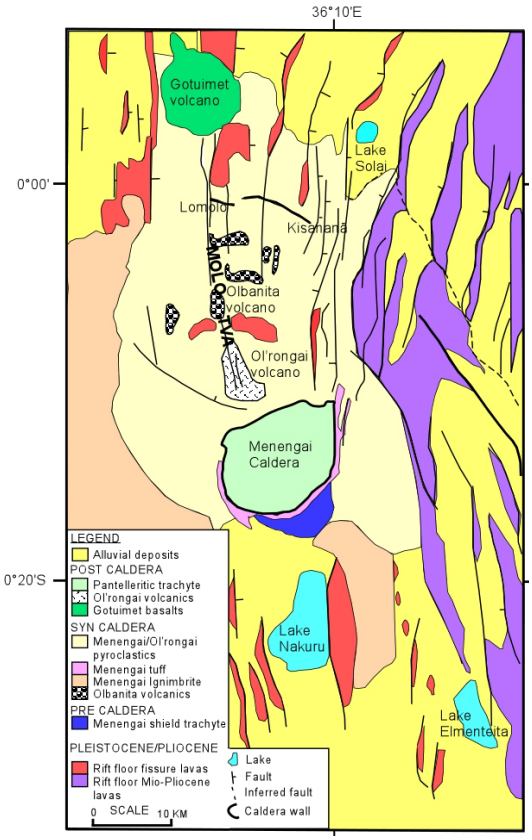

FIGURE 5: Geological map of Menengai caldera volcano

Environmental baseline studies conducted indicate that minimal impacts would occur from proposed drilling activities and future development of the resource (Mungania et al, 2004). Existing infrastructure also favor development of this resource. If developed, the resulting hot water could be used by the various Agro based industries which are close to the resource in Nakuru town. GDC plans to undertake drilling of exploratory wells in Menengai in February 2011.

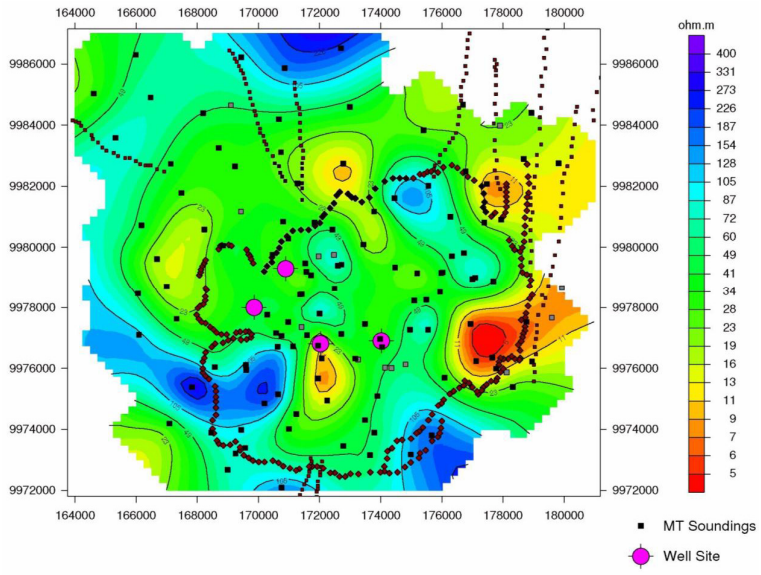

FIGURE 6: MT resistivity plot of Menengai at sea level

4.3 Longonot volcano

Longonot is a large caldera volcano within the floor of the southern Kenya Rift adjacent to Olkaria Geothermal field (Figure 1). The volcano comprises of a large trachyte caldera of about 11 km dia and a resurgent activity on the caldera floor that formed a central volcano with a crater at the summit. The caldera floor is filled, to a large extent, by trachytic ashes from the central volcano.

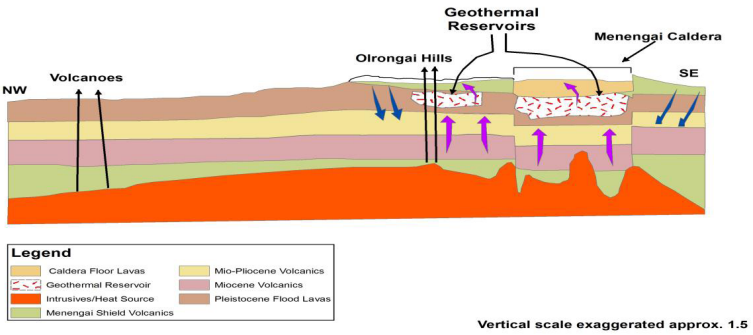

FIGURE 7: Geothermal model of Menengai volcano

The youngest activity (<300 yrs BP) at Longonot was of mixed Trachyte-basalt composition and erupted within the crater floor and on the northern flank of the central volcano (Figure 8).

Geothermal surface manifestations are mainly fumaroles and hot grounds within the central crater. The geochemical survey revealed high radon and CO_2 gas discharges. Gas geothermometry also indicate that geothermal reservoir temperatures could exceed 300 ^oC (KenGen, 1998).

MT resistivity distribution at 2 km bsl shows a conductive body of <11 ohm m in the southern slopes of the young central volcano and extending beyond the caldera boundary. It is postulated that the body could be of magmatic type and thus possibly the resource heat source (Figure 9). Preliminary results of micro seismic investigations show correspondence between seismics and MT. Shear wave splitting anisotropy directions were evidenced in the data suggesting fault control in the movement of pressurized fluids in the near subsurface (Onacha, 2006).

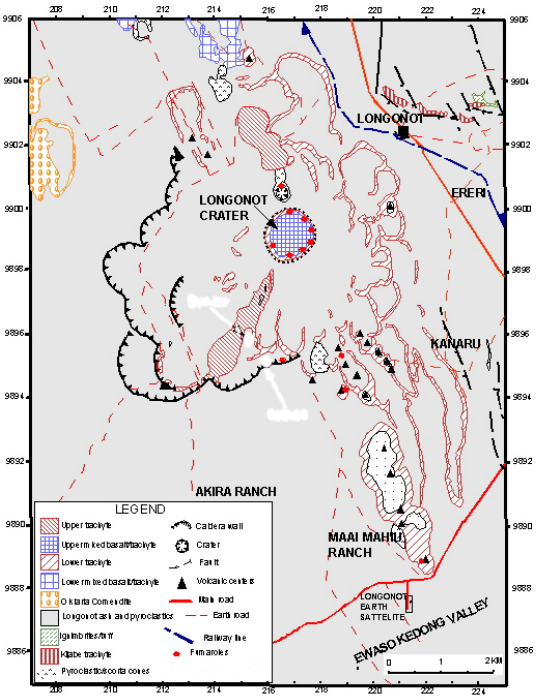

FIGURE 8: Geological map of Longonot geothermal area

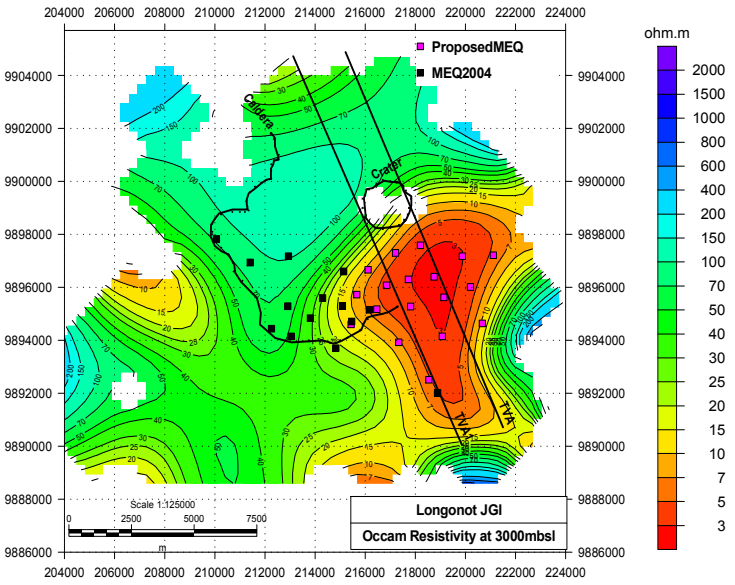

FIGURE 9: MT resistivity map of Longonot (Onacha, 2006)

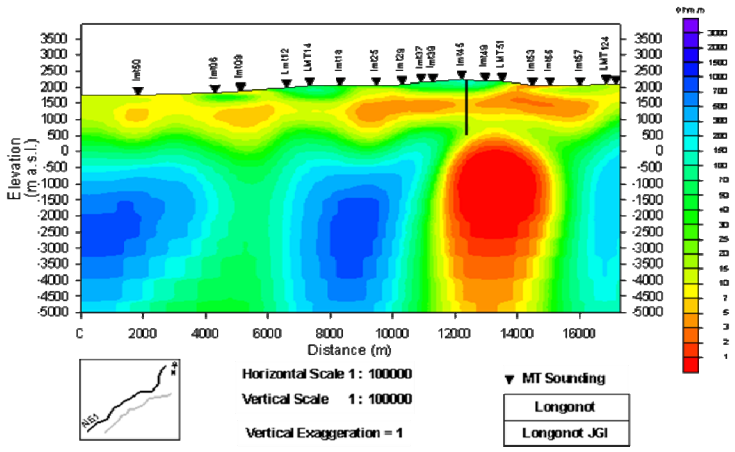

FIGURE 10: 2-D Resistivity model of Longonot volcano

Combined MT, gravity and seismics indicate that the heat source is at 6 km deep with the shallowest portion directly under the central volcano. Conceptual model indicates that the main upflow for the system is to the immediate south of the central crater extending beyond the SE margin of the caldera wall. The fluid then outflows southward (Figure 10). Recharge for the system is probably from the rift shoulders and also axially. The heat source for the main system is associated with the resurgent activity, which developed the central shield volcano within the caldera. The model indicates that a high temperature geothermal system >250°C is expected to exist under Longonot. The prospect has been licensed to Africa Geothermal Investment Limited (AGIL) which intends to undertake exploratory drilling in 2011.

4.4 Suswa

Suswa is the southernmost of a series of Quaternary caldera volcanoes in the Kenya rift. The volcano has two nested calderas: outer and inner with diameters of 10 and 4 km, respectively (Figure 11). Volcanism at Suswa that comprised trachytes and phonolites started about late Pleistocene and continued to less than 1,000 years ago (Omenda, 1997).

Results from detailed surface studies suggest reservoir temperatures of 250°C based on gas geothermometry. Seismic and gravity studies show that the heat source under the caldera is at about 6-8 km deep with a NE-SW bias. Resistivity (MT) at 500 m bsl indicates a low (15-20 ohm m) anomaly under the island block and extending to the north out of the inner caldera (Figure 12).

Conceptual model indicates that heat source for Suswa is a magmatic body centred under Ol Doinyo Nyoke volcano (Figure 13). The body is at a depth of more than 6-8 km and could be the heat source of the geothermal system. The geothermal system must have attained temperatures of more than 250°C as seen from the presence of hydrothermal epidote within the lithics. Gas geothermometry indicate that gases sampled in the prospect originated from sources having temperatures of more than 250°C. The prospect has a fairly good recharge from both the west and east rift escarpments. However, the water table in the rift floor is deep, probably more than 300 m, due to intense faulting of the pre-Suswa formations. The prospect is licensed to WalAm, Inc of Canada. However, it is not clear when the concessionaire may undertake exploratory drilling in the prospect.

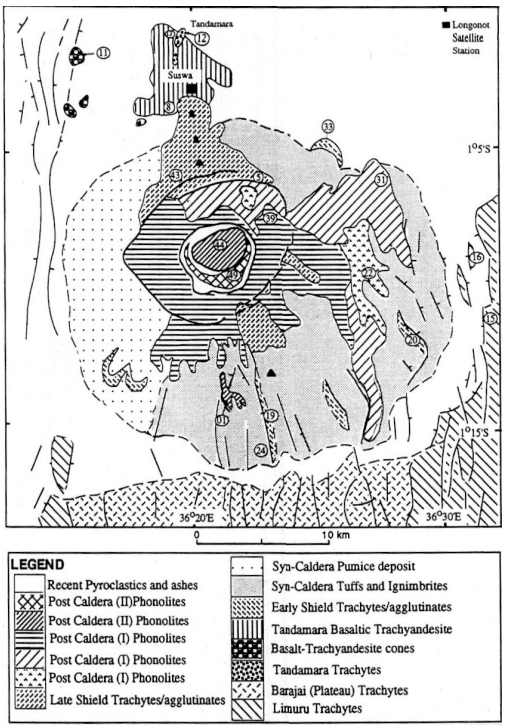

FIGURE 11: Geological map of Suswa volcano

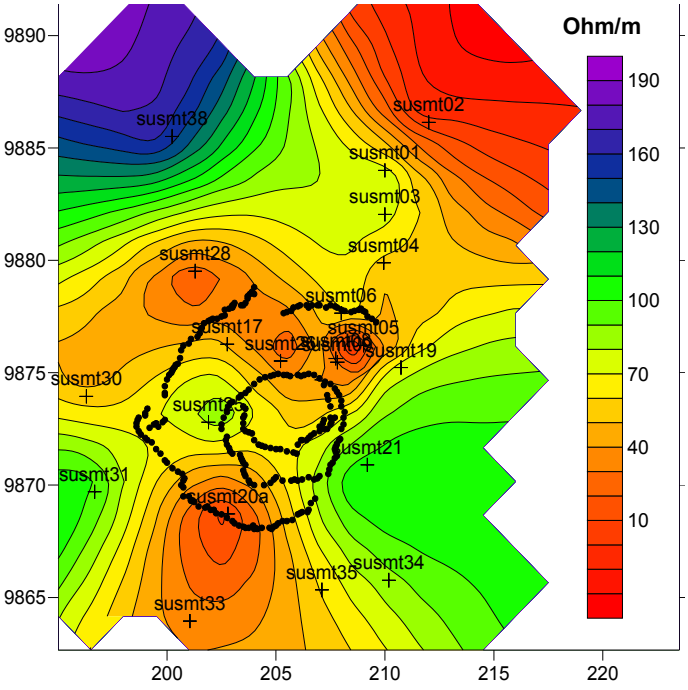

FIGURE 12: MT plot for Suswa at 500 mbsl

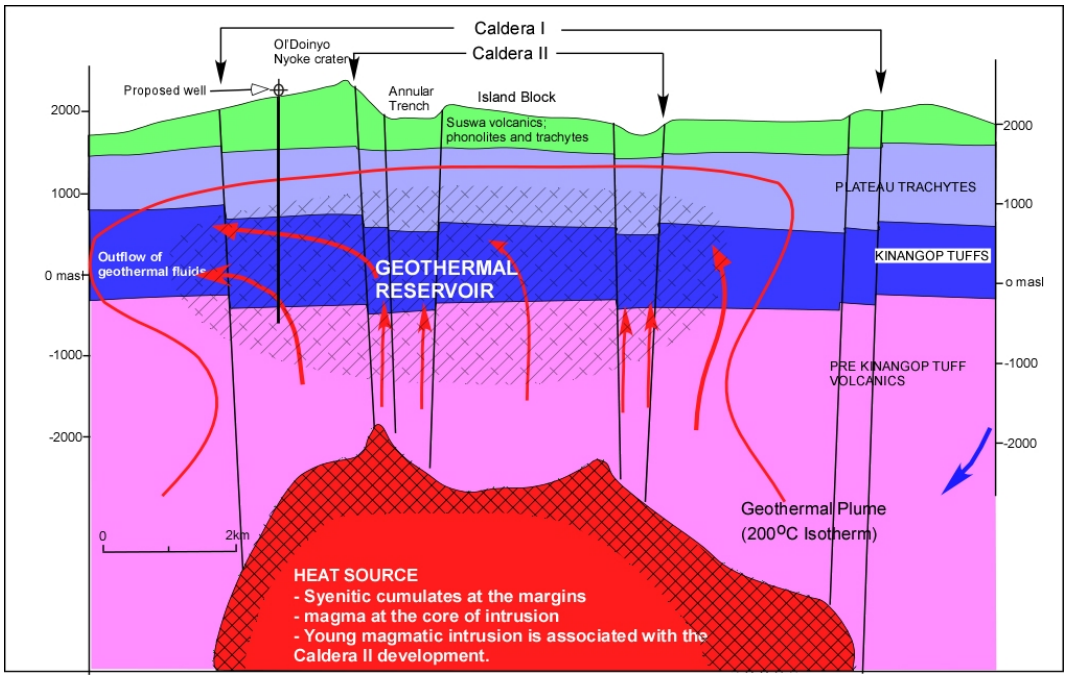

FIGURE 13: Geothermal model of Suswa volcano

4.5 Lake Bogoria and Arus

Arus – Lake Bogoria prospect is the area surrounding Lake Bogoria and extending about 50 km southward and westward (Figure 1). The upper Plio-Pleistocene volcanism of the rift floor in the area between Arus and Lake Bogoria is characterized by large volumes of evolved lavas that consist mostly of peralkaline trachyte, trachyphonolite and phonolite (Figure 14). Small outcrops of basaltic lavas

occur in isolated areas within the prospect. The northern sector south of Lake Baringo is, however, dominated by fluvial and alluvial deposits. There are no Quaternary central volcanoes in the prospect.

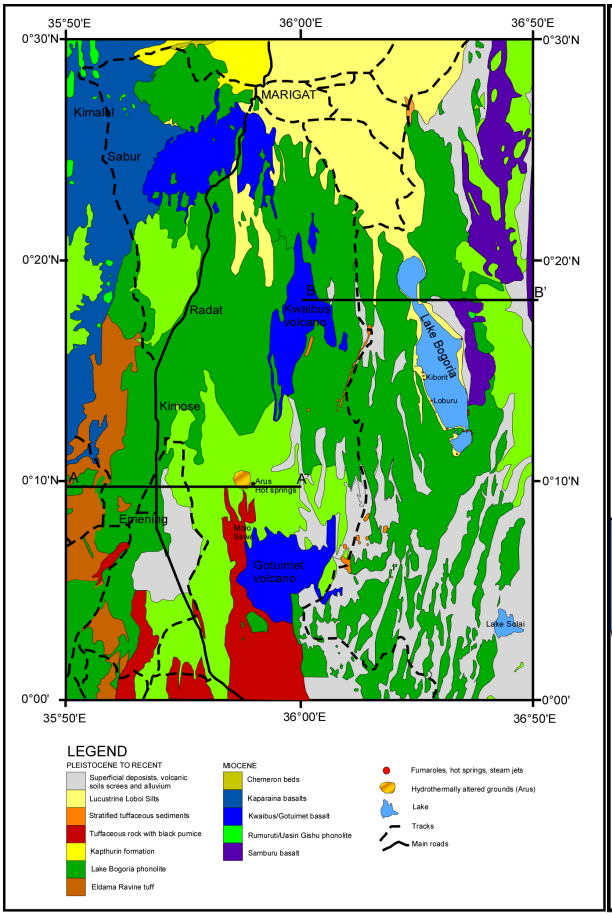

FIGURE 14: Geological map of the Lake Bogoria – Arus prospect

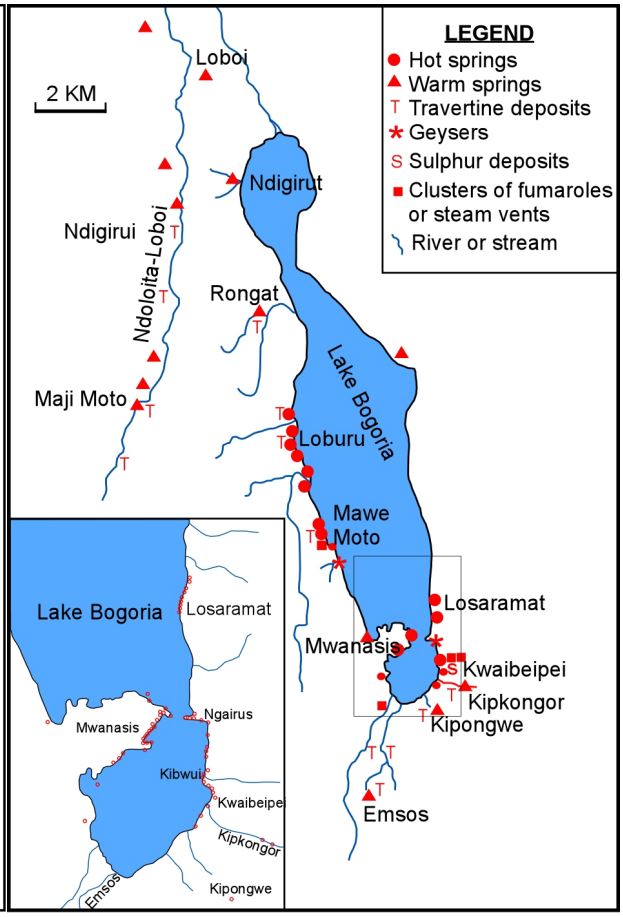

FIGURE 15: Locations of fumaroles and hot springs in the Lake Bogoria area

The geothermal manifestations occurring in the prospect include fumaroles, hot and steaming grounds, anomalous boreholes, hot springs, steam jets, altered grounds, sulphur, calcite and travertine deposits. Most o these manifestations occur along the shores of Lake Bogoria and at the Arus springs (Figure 15).

Fluid geothermometry indicates intermediate subsurface temperatures of more than 145-245°C for the Lake Bogoria springs while those at Arus are at 170-192°C. The low resistivity bodies (< 10 ohm-meter) occur mainly along and at the intersection of major faults and transverse zones (Figure 16). These intersection zones may be forming weak regions through which magmatic materials find their way to the shallow sub-surface. However, the resistivity data has not defined clear geothermal reservoirs in the field and more MT stations are planned by GDC in 2011.

The geothermal reservoirs in this field, therefore, could be assumed to follow the fault plane model where discrete small reservoirs are located along fault zones (Figure 17).

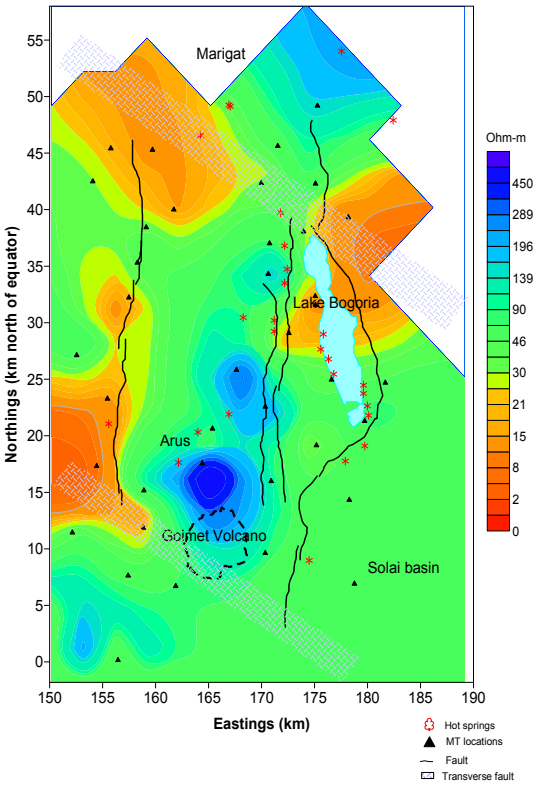

FIGURE 16: Arus-Bogoria MT resistivity distribution at 2,000 mbsl

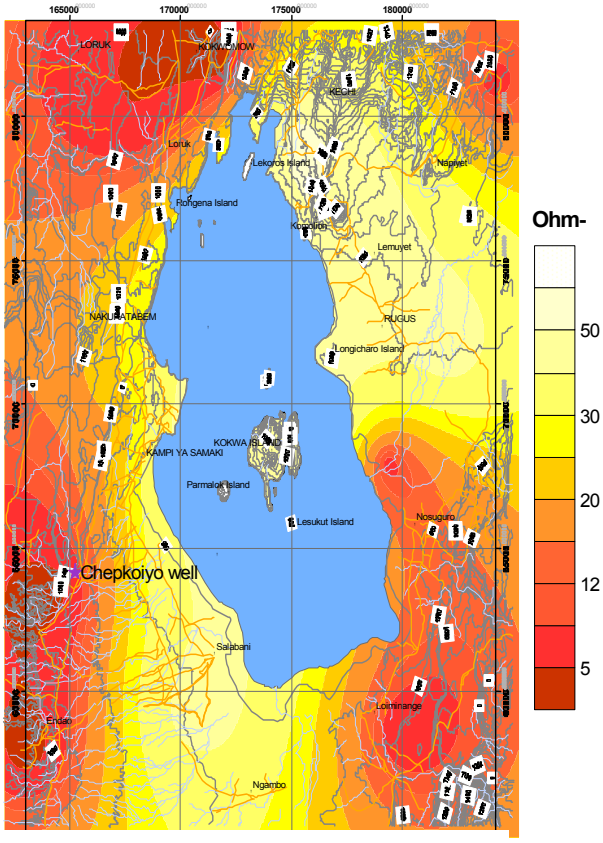

FIGURE 18: Resistivity at sea level at Lake Baringo prospect

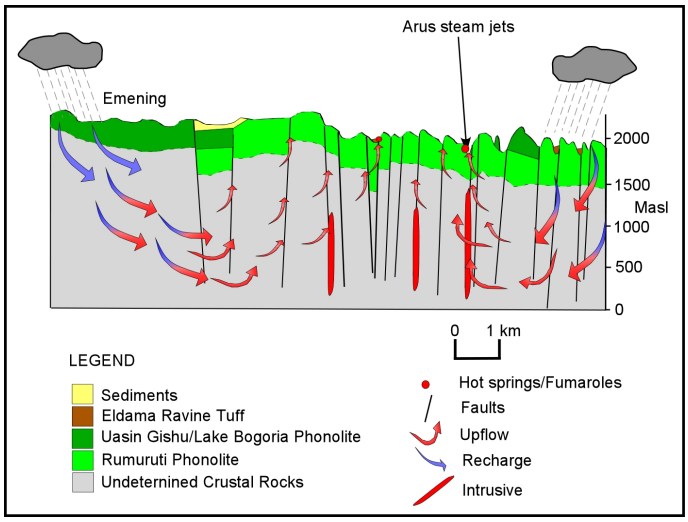

FIGURE 17: Regional geothermal model of Arus-Bogoria geothermal prospect

4.6 Lake Baringo

Lake Baringo geothermal prospect is in the northern part of the Kenyan rift and covers the area around Lake Baringo. Surface manifestations include fumaroles, hot springs, thermally altered hot grounds and anomalous ground water boreholes. The geology of the area is characterized by trachyte and trachy-phonolite to the east and west while basalts occur to the north and alluvial deposits to the south. Olkokwe Island in Lake Baringo is the only Quaternary volcanic complex which is associated with volcanic activity at Korosi to the north

Fumaroles and hot springs occur on Olkokwe Island while weak fumarolic areas occur in the western zone along fractures/faults. Gas geothermometry indicates reservoir temperatures of more than 120-200°C in the west near Chepkoiyo well and more than 170°C in the Olkokwe Island system.

Resistivity indicates potential occurrences of fault controlled, discrete reservoirs in areas west of the Lake, SE and north (Figure 18). Since a large portion of the prospect is not associated with a centralized Quaternary volcano, it is postulated that the heat sources are probably deep dike swarms along the faults. It can be concluded from the available information that the resource at Lake Baringo is low to intermediate temperature suitable for direct uses.

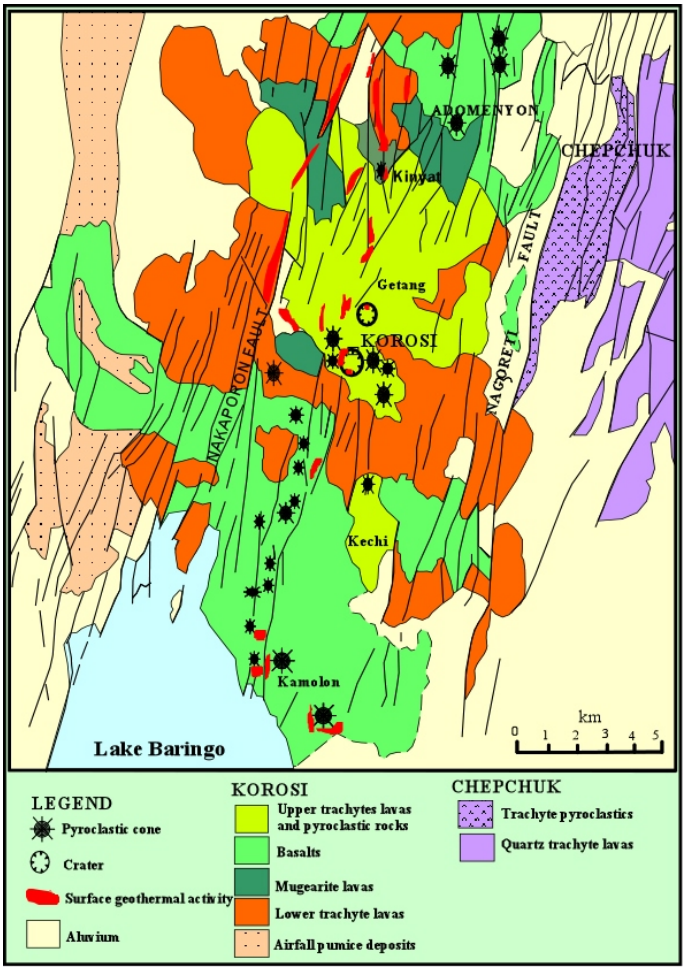

FIGURE 19: Geological map of Korosi volcano

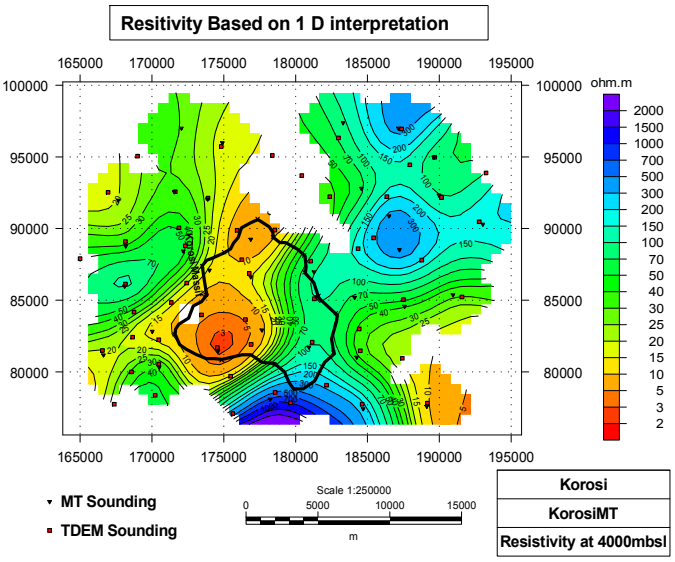

FIGURE 20: Resistivity distributions at 4000 m bsl in Korosi area

4.7 Korosi volcano

Korosi volcano is located in the north rift Valley and neighbours Lake Baringo to the south and Paka volcano to the north. KenGen and the Ministry of Energy undertook detailed surface studies in the prospect in 2005. The area is strongly faulted by a system of NNE trending faults, which extends northwards onto the flanks of Paka volcano (Figure 19). The latest volcanic activity associated with Korosi was of basaltic composition and occurred a few hundred years ago while the last trachytic volcanism occurred about 100ka.

Surface geothermal manifestations include hot steaming grounds and fumaroles. Surface temperatures ranging between 90 – 95°C have been recorded.

The MT resistivity map at 1500 mbsl shows low resistivity below the Korosi massif but is well defined in resistivity map at 4000 mbsl (Figure 20). The MT plot shows a well defined <10Ωm low resistivity below the Korosi Massif. The low resistivity below the massif is interpreted to mark the top of the heat source for the geothermal system.

Gas chemistry of five samples from Korosi using H_2S Gas geothermometry function indicates that temperatures of more than 250°C exist in the reservoir under the volcano. Conceptual model indicates that a viable geothermal system exists under the Korosi massif with the upflow within the micro-graben and outflow largely to the north.

4.8 Chepchuk volcanic field

The Chepchuk area was covered during the studies at Korosi which was done by KenGen and the Ministry of Energy in year 2005. The geology of Chepchuk is characterized by faulted Plio Pleistocene flood trachytes and younger basaltic flows occupying micro-grabens. The area is heavily faulted with half of the Chepchuk volcanic complex down faulted westward. It is postulated that the old Chepchuk volcano could be the dominant source but with contribution from Paka volcanic area. It is estimated that the resource is of intermediate temperature.

4.9 Paka volcano

Detailed surface studies of Paka volcano was undertaken in 2006/7. Paka shield volcano is constructed largely by trachyte lavas and pyroclastic deposits and located just to the north of Korosi volcanic complex (Figure 21). Volcanic activity commenced by 390 ka (Trachytes) and continued to within 10 ka (basalts).

The structure of Paka is dominated by a broad zone of normal faulting 7.5 km wide graben bound by the eastern and the western fault boundaries respectively. This zone shows a right stepping en echelon arrangement along the volcano and forms one of the regional fault pattern, which extends southwards to Chepchuk and northwards into the southern flanks of Silali.

Surface geothermal activity is widely developed at Paka particularly within the summit craters and the northern

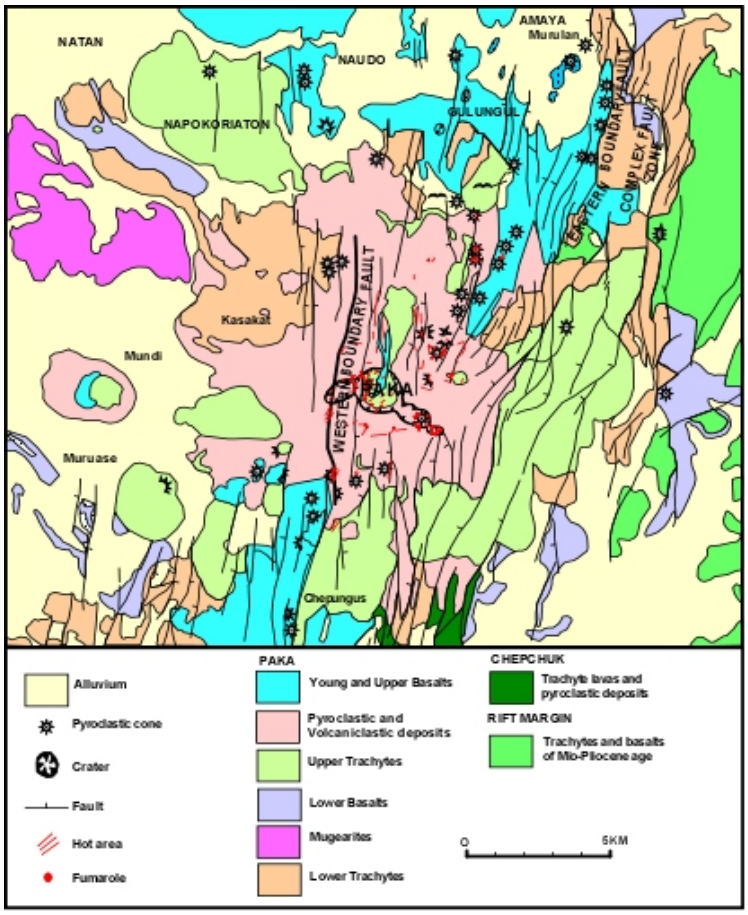

FIGURE 21: Geological map of Paka volcano

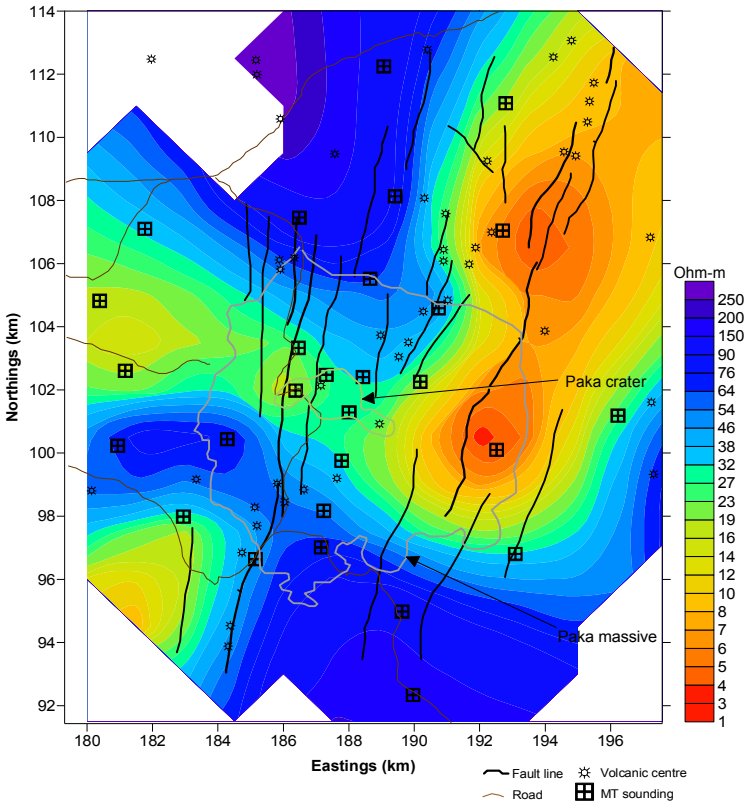

FIGURE 22: MT resistivity plot at 3000 m bsl

flanks where fumaroles at >97°C are common. Sulphur crystals are common for the fumaroles within the craters. Gas geothermometry of fluids from Paka indicate the reservoir system to be at more than 250°C.

MT resistivity at Paka prospect shows conductive bodies under the massif and on the eastern side at foot of fault scarp. The latter is not considered to be of geothermal interest (Figure 22).

The anomaly under Paka volcano could be imaging hot rocks. Seismic studies indicate shallow events directly under Paka suggesting that a hot body exists below about 2.5 – 5km depth. Heat loss studies of Paka volcano revealed that a total heat loss of 2,855 MW_t occurs within the prospect with a convective

component of 10 MWt. Most of the heat is lost within the Paka craters area.

Conceptual model developed for Paka indicates that the system is closely associated with the magmatic intrusion under the volcano. The model indicates that the low resistivity imaged by MT at the foot of the eastern scarps may not be of geothermal significance but further studies are required to characterize the anomaly. GDC plans to collect additional MT data in 2011 to assist in siting of exploration wells.

4.10 Silali volcano

Silali is the largest Quaternary caldera volcano on the floor of the northern Kenya rift. Previous studies of the volcano and the surrounding areas indicated occurrence of a hydrothermal system, indicating probable occurrence of a high temperature geothermal resource. These earlier studies recommended the prospect for further detailed surface investigations to determine its geothermal resource potential. Consequently, Geothermal Development Company Ltd (GDC) as part of its mandate to develop geothermal resources in the country carried out detailed surface exploration in 2010. The studies involved geological mapping, soil gas assessments, fumaroles and hot spring sampling, MT and TEM measurements and environmental baseline surveys.

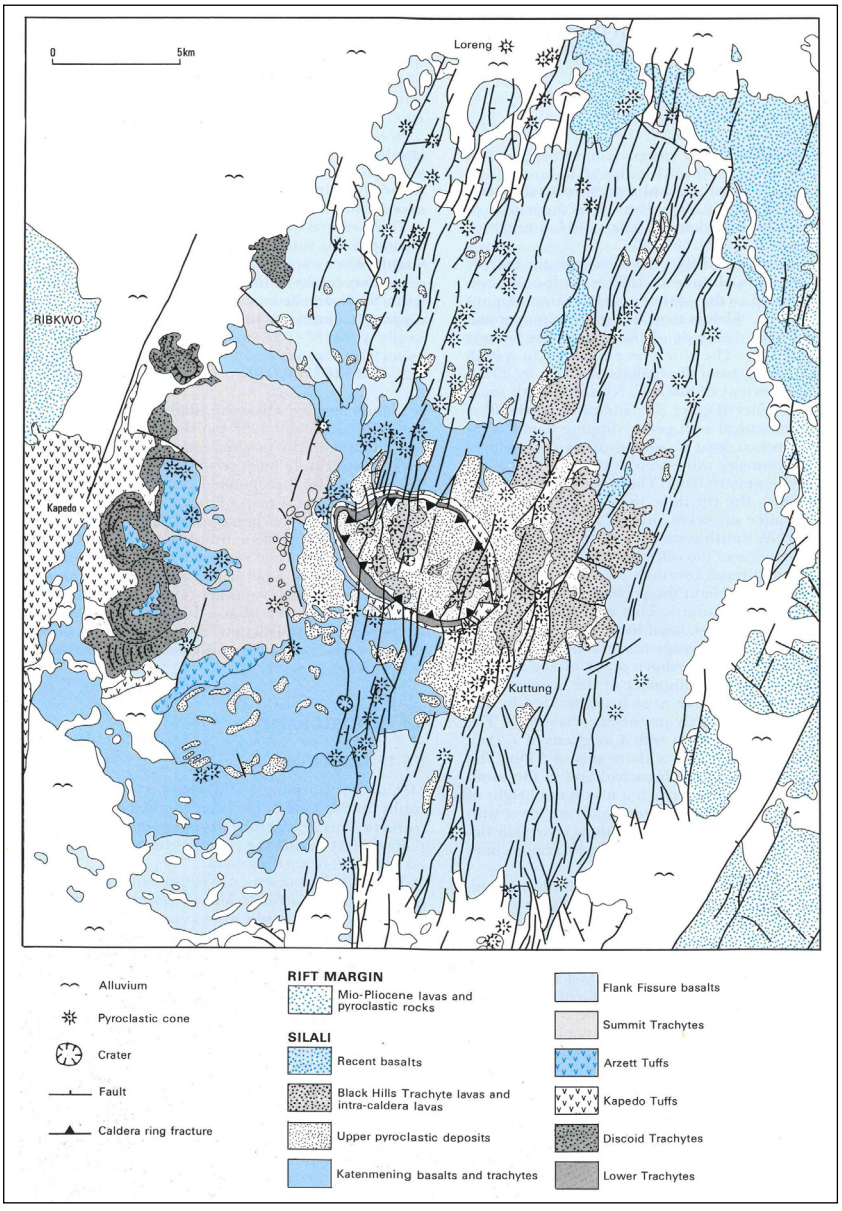

FIGURE 23: Simplified geological map of Silali volcano

Integrated results of the studies indicate the existence of a geothermal resource under Silali caldera that extends to the eastern flanks of the caldera (Figure 23). The heat source is associated with shallow magmatic intrusive under the caldera and extends to the eastern flanks. Estimated gas geothermometry from the prospect area gave temperatures of 238-287ºC. It is estimated that the high temperature anomaly from geophysical covers an area of about 81km^2. Using the worlds' average conversion rate of 15 MW$_e$/km^2, this translates to potential generation capacity of more than 1,200MW$_e$ (Lagat and Ngenoh, 2010). GDC plans to undertake exploratory drilling in the prospect in late 2011.

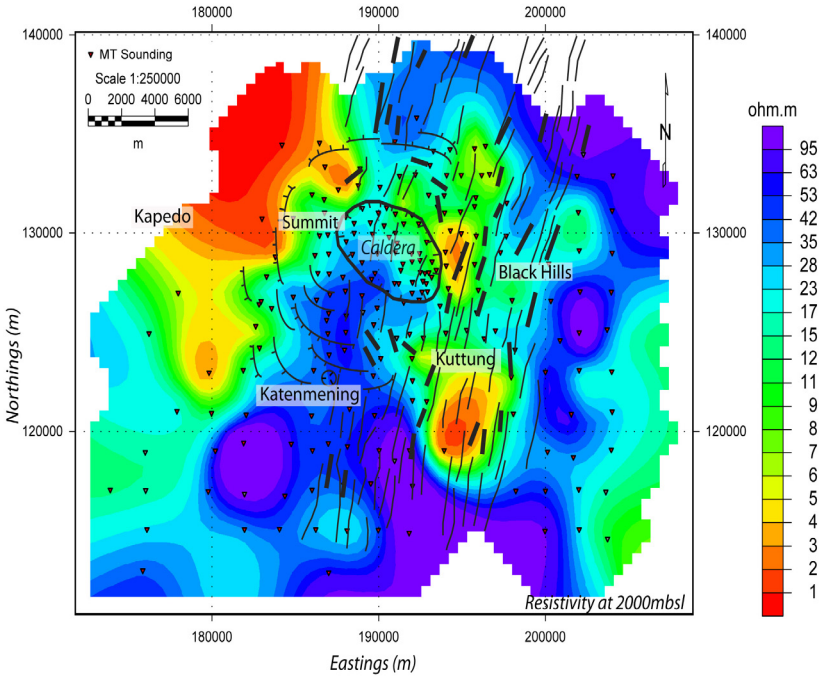

FIGURE 24: Resistivity distribution map at 2000 m bsl
(Lagat and Ngenoh, 2010)

4.11 Other geothermal prospects

The other potential geothermal prospects within the Kenya rift that have not been studied in details include Lake Magadi, Emuruangogolak, Namarunu, and Barrier volcanic complex. Preliminary information indicates that the Lake Magadi system could be of intermediate temperatures and suitable for binary power plant development and for direct applications (Allen et al., 1989). Magadi prospect is not in the immediate plans for detailed evaluation.

Most of the northern prospects are magmatically active and have been postulated to host high temperature geothermal systems (Dunkley et al., 1993). GDC is at advanced stages of planning to systematically investigate these prospects commencing with Barrier in early 2011. If successful, Barrier will be committed to exploratory drilling in 2013.

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Presented at *Short Course VIII on Exploration for Geothermal Resources,*
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GEOTHERMAL EXPLORATION AND DEVELOPMENT IN ETHIOPIA: STATUS AND FUTURE PLAN

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ABSTRACT

Ethiopia is located in the Horn of Africa between 3.5° and 14°N and 33° and 48°E. Access to energy is among the key elements for the economic and social developments of Ethiopia. The energy sector in Ethiopia can be generally categorized in to two major components: (i) traditional (biomass), and (ii) modern (such as electricity and petroleum). As more than 80 % of the country's population is engaged in the small-scale agricultural sector and live in rural areas, traditional energy sources represent the principal sources of energy in Ethiopia. The current total installed electrical capacity in Ethiopia has reached 2,178 MW. The medium and long term electrical generation development plan consists mainly of hydro projects. Generation from wind and geothermal power plants are foreseen to compliment the hydro.

The government's Energy Policy is an integral part of its overall development policy. It aims to facilitate the development of energy resources for economical supply to consumers. It seeks to achieve the accelerated development of indigenous energy resources and the promotion of private investment in the production and supply of energy.

Ethiopia started long-term geothermal exploration in 1969. About 120 localities within the rift system are believed to have independent heating and circulation systems. From these localities about two dozen are judged to have potential for high enthalpy resource development, including for electricity generation. Only two prospect areas have been subjected to exploration drilling to date. Currently geothermal exploration and resource assessment is being carried out in strategically selected prospect areas in the Ethiopian Rift Valley.

In the short term a total of 675 MW geothermal power is planned to be developed from six selected prospects by 2018 and in the long term 2000 MW is to be developed by 2030. In order to achieve the countries medium term plan in geothermal development both the public and the private sector participation is envisaged. Financial resources are secured or are on the process of being secured for the planned development under the public/private sector.

1. BACKGROUND INFORMATION

1.1 Physiography and Climate

Ethiopia is located in the Horn of Africa between 3.5° and 14°N and 33° and 48°E. The country has an area of 1.14 million km^2 made up of a broad plateau and low lands along its periphery. The highlands rise up to 4,600 m altitude while the most depressed lowlands reach 120 m below sea level. The Ethiopian sector of the Great East African Rift bisects the plateau from the northeast to the southwest of the country (Figure 1). The rift in Ethiopia has created a conducive environment for the existence of geothermal resources and covers an area of about 150,000 km^2 that is close to 12% of the total land area.

Several rivers drain the plateau flowing, radially outwards, into the peripheral lowlands and onwards into the neighboring countries. The average annual rainfall in the highlands is 1200 mm in the northern half of the country and 1800 mm in the southwest. The lowlands annually receive below 600 mm of rainfall. About 70-80% of the rain falls during mid-June to mid-September. In the highlands, the maximum monthly average temperature ranges between 23 and 27°C and the minimum between 10 and 13°C. In the lowlands, these temperatures range are higher.

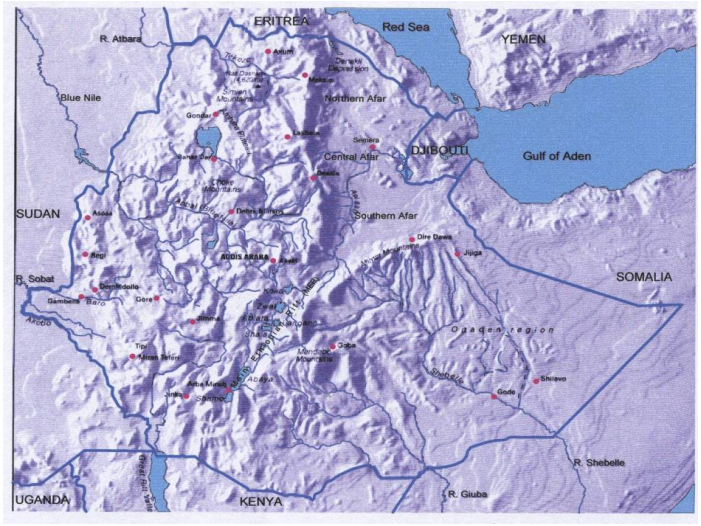

FIGURE 1: Physiography of Ethiopia

1.2 Energy Sector

Access to energy is among the key elements for the economic and social developments of Ethiopia. The energy sector in Ethiopia can be generally categorized in to two major components: (i) traditional (biomass), and (ii) modern (such as electricity and petroleum). As more than 80 % of the country's population is engaged in the small-scale agricultural sector and live in rural areas, traditional energy sources represent the principal sources of energy in Ethiopia.

Domestic energy requirements in rural and urban areas are mostly met from wood, animal dung and agricultural residues. At the national level, it is estimated that biomass fuels meet 88 % of total energy consumed in the country. In urban areas access to petroleum fuels and electricity has enabled a significant proportion of the population there to employ these for cooking and other domestic energy requirements.

1.2.1 Electricity Sector

The annual per-capita consumption of electricity stands at 100 kWh. The same figure for the Sub-Saharan Africa is 510 kWh. This reveals that most of the energy usage is still from traditional energy sources such as wood and animal waste. Moreover it also informs the fact that with the country's economic development and improvement of the per-capita income, there will be huge potential for consumption of electricity within the country.

The delivery of an adequate electricity service is essential. To fulfill the high growth rate of electricity demand which is 32%/ yr, the generation capacity will increase to over 10,000 MW at the end of

Growth and Transformation Plan (2014/15). The aim is to address both domestic demands while exporting surplus power to neighboring countries and beyond.

The current total installed electricity generation capacity has reached 2,178 MW, (Abayneh, 2013). Although Ethiopia is endowed with a variety of energy resources, many of these resources have not yet been exploited. Hydropower generates more than 90% of electricity in Ethiopia (Table 1). However, as the rainfall in Ethiopia varies considerably from year to year, the need to diversify the country's energy sources to ensure a stable supply is essential. It also implies that overdependence on hydropower makes energy supply unstable, resulting in heavy strains on the pace of the growth in every sector and the whole economy by extension.

Development of alternative energies from renewable sources such as hydro, wind, geothermal and biomass will be a key part of Ethiopia's energy mix during the existing 5-year Growth and Transformation Plan period (GTP) and integrated with the country's new Climate Resilient Green Economy (CRGE) Strategy, which has the ambitious objective of transforming Ethiopia into climate resilient green economy by 2025, EPA (2011).

TABLE 1: Current modes of generation and their contribution

	Thermal	**Hydro**	**Geothermal**	**Wind**	**Total**
MW	89	2000	7	82	2178
%	4	91.8	0.4	3.8	100

The medium and long term electrical generation development plan consists mainly of hydro projects. Generation from wind and geothermal power plants are foreseen to compliment the hydro. The GTP aims to increase the power generation capacity of the country from the present level of about 2041 MW to over 10,000 MW by the end of 2015. The CRGE foresees to develop up to about 25,000 MW of Ethiopia's generation potential by 2030. Of this hydro holds 22,000 MW, geothermal 1,000 MW and wind 2,000MW, (Table 2).

TABLE 2: Medium to long term power composition plan

Type	**2015**		**2030**	
	MW	**%**	**MW**	**%**
Thermal	89	0.8	89	0.3
Hydro	10640	91	21000	83.4
Wind	773	6.6	2000	8
Geothermal	77	0.7	2000	8
Bagass	103	0.9	103	0.3
Total	11682	100	25192	100

The country in its medium to long term power development plan aims to address both the domestic demand and the export of power to neighboring countries and beyond. On the bases of the domestic demand forecast, three fold increases from the current demand of 6000 GWH is expected by 2015 (Figure 2). The most notable factors that played a major role for the attainment of such a remarkable demands in recent years are: (i) GDP growth in double digits for the last ten consecutive years, (ii) population growth, (iii) aggressive expansion of the National grid to rural towns and villages, and (iv) implementation of customer service reform program.

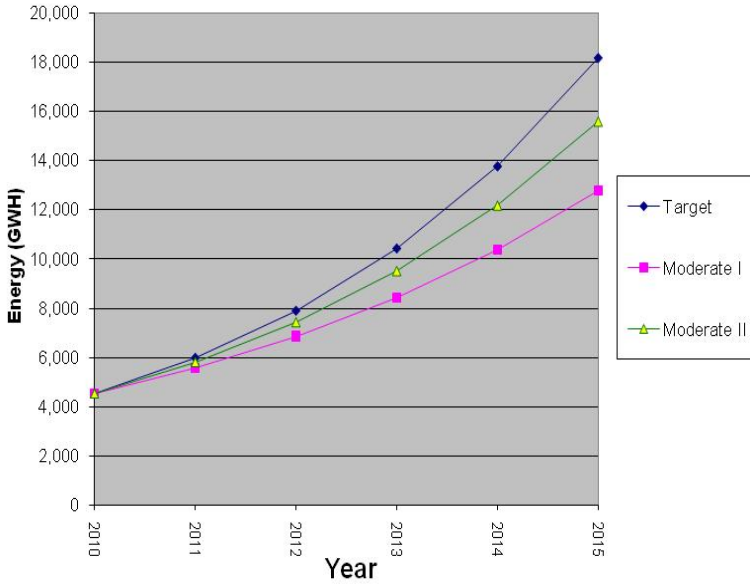

FIGURE 2: Energy demand forecast, (Lemma, 2012)

1.2.2 Energy Policy

The sector policy and regulatory framework supports IPP development. Subsequent to the National Economic Policy (NEP) of 1991 that encouraged private sector participation in the economic development of the country, a number of Proclamations and reforms have been made, aimed at enabling private participation within the electricity sector. Development of renewable energy resources for power generation is now being encouraged through the establishment of feed-in-tariffs (FIT) for such sources. A draft law and regulations supporting FIT is soon to be passed into law.

Due to rapid increase in demand for energy and through the poverty eradication program, the government devotes a lot of energy and resources to rural development for the purpose of enabling the large rural population to emerge out of subsistence production and become integrated within the national economy as surplus producers for trade and as a market for goods and services. The emphasis on agriculture aims at achieving food security, increased rural income, surplus generation and production for the agro-industry for export.

The government's Energy policy is an integral part of its overall development policy. It aims to facilitate the development of energy resources for economical supply to consumers. It seeks to achieve the accelerated development of indigenous energy resources and the promotion of private investment in the production and supply of energy. Electricity supply, as an element of the development infrastructure is being advanced in two fronts: (a) the building up of the grid based supply system to reach all administrative and market towns, and (b) rural electrification based on independent, privately owned supply systems in areas where the grid has not reached.

An independent power producer (IPP) may engage in power development for selling the generated electricity to the public utility, known as the single buyer model. The single buyer model does not exclude captive geothermal power generation, i.e. generation for own use in primary economic production or service industries owned by the developer. EPC turnkey contracts could be negotiated and signed between a private companies and the public utility, in which the private sector would have the role of not just as a project developer but also as a critical stakeholder that can bring financing to the table under the right circumstances.

To IPP's, the Government of Ethiopia is at present in the process of finalizing a Feed-in-Tariff proclamation, which is expected to pass into law shortly, aimed at facilitating the large scale deployment of geothermal and other renewable technologies, providing investment security and market stability for private investors in electricity generation from these resources, MoW&E (2011). Incentives such as, corporate income tax holidays, waiver of import duties, grant of tax holidays on dividend and interest incomes are on the table for negotiations. In addition to encouraging investment, such measures should contribute to lowering the cost of electricity supply, and allow affordable tariffs.

Initiated by the existing conducive environments for private sector participation, currently concessions are issued for private companies in about five geothermal prospect areas in the country. EPC contracts are also under pipeline in other prospect areas.

2. GEOTHERMAL EXPLORATIONS AND DEVELOPMENT IN ETHIOPIA

2.1 General

Ethiopia started long-term geothermal exploration in 1969. Over the years, an inventory of the possible resource areas within the Ethiopian sector of the East African Rift system, as reflected in surface hydrothermal manifestations has been built up. The inventory work in the highland regions of the country is not complete but the rift system has been well covered. Of the about 120 localities within the rift system that are believed to have independent heating and circulation systems, about two dozen are judged to have potential for high enthalpy resource development, including for electricity generation. A much larger number are capable of being developed for non-electricity generation applications such as in horticulture, animal breeding, aquaculture, agro-industry, health and recreation, mineral water bottling, mineral extraction, space cooling and heating, etc. (UNDP, 1973).

Since the late 1970's, geoscientific surveys mostly comprising geology, geochemistry, and geophysics, were carried out at, from south to north, the Abaya, Corbetti, Aluto-Langano, Tulu Moye and Tendaho prospects (Teklemariam and Beyene, 2005). In addition, a reconnaissance survey of ten sites in the central and southern Afar has been carried out, some of these being followed up by more detailed surface investigation. The prospects and fields discussed here are shown in Figure 2.

Due to various factors that determined where the first geothermal power plant would best be located, detailed exploration work was decided to commence in the Lakes area of the rift system during the 1970's. The ICS was already being extended into this region of load growth. The best prospect areas from the technical point of view were located in the Afar which had then been poorly endowed with essential infrastructure and local load demand to support power development. The present circumstances however favor resource development also in the Afar region.

Exploration work peaked during the early to mid 1980's when exploration drilling was carried out at Alutu. Eight exploratory wells were drilled with five of these proving productive. During 1993-98, exploration drilling was also carried out at Tendaho. Three deep and three shallow wells were drilled and geothermal fluids were encountered in the 200-600m-depth range.

Resource utilization was delayed until 1999. A 7.3 MWe net capacity pilot plant installed at Aluto has faced operational difficulties that are essentially due to the lack of the appropriate field and plant management and operation skills. In 2007 activities related to problem identification and putting the plant back into have been carried out at the Aluto-Langano geothermal field. The plant is partially rehabilitated and has been put back into an operation of about 4 MWe.

During the three decades that geothermal resource exploration work was carried out in Ethiopia, a good information base and a good degree of exploration capacity, in human, institutional and infrastructure terms, has accumulated, ensuring that selected prospects can be advanced to the resource development phase much more rapidly than before.

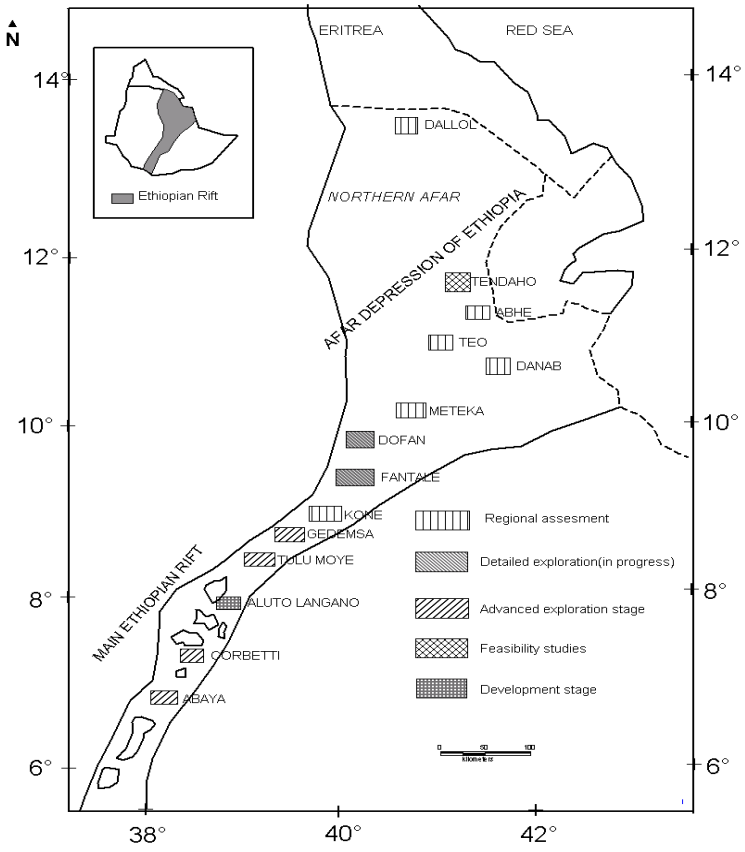

FIGURE 3: Location of geothermal prospects in Ethiopia

The exploration work to date has been carried out by the Geological Survey of Ethiopia (GSE) but has benefited from a number of technical cooperation programs. The most consistent over the long term had been support by UNDP, which also helped in creating other technical capacities of the GSE. The European Development Fund financed the overseas cost of the exploration-drilling project that resulted in the discovery of the Alutu resource. The development cooperation program of the Italian Ministry of Foreign Affairs provided the funding for the offshore costs of the surface and drilling exploration of the Tendaho prospect. The reconnaissance survey of the Afar was spawned by the Petroleum Exploration Promotion project financed by IDA during the 1980's. The IAEA is assisting the GSE in the isotope geochemical study of hydrothermal fluids and in the process is providing training and experience in the application of the technique in geothermal investigations. IAEA also provided technical advice and equipment. The German Geological Survey (BGR) assisted in geophysical investigations (MT) of the Tendaho deep geothermal reservoir during 2006-07. The specialized geothermal science and technology training programs in Japan, Italy, New Zealand, Iceland and Kenya (in cooperation with United Nations University- Geothermal Training Programme of Iceland) contributed in human resource training and development.

The explored prospects in the country are at various stages of exploration and include: (i) more advanced prospects where exploration drilling has been conducted (Aluto Langano and Tendaho), (ii) prospects where surface exploration is relatively at higher level (Abaya, Corbetti, Tulu Moye and Fentale and Dofan), and (iii) prospects where surface exploration is at lower level and warrant further exploration in the future (Kone, Meteka, Teo, Danab, L. Abe and Dallol).

2.2 The more advanced prospects

2.2.1 The Aluto-Langano geothermal field

Detailed geological, geochemical and geophysical surveys were carried out in the Langano area during the late 1970's and early 1980's. Results showed the existence of an underground fluid at high temperature with evidence of long time residence in zones occupied by high temperature rocks (ELC, 1986). The objective then was to locate an economically exploitable geothermal reservoir.

Two wells (LA3 and LA6) drilled on the Aluto volcano produced 36 and 45 t.p.h. geothermal fluid at greater than 300°C along a fault zone oriented in the NNE-SSW direction. Two wells drilled as offsets to the west (LA4) and east (LA8) of this zone respectively produced 100 and 50 t.p.h. fluid with a lower temperature. LA5, drilled in the far SE of the earlier two wells was abandoned at 1,867 m depth due to a fishing problem but however later showed a rise in temperature over an extended period of time. LA7 was drilled in the SW but could discharge only under stimulation, being subject to cold-water inflow at shallow depth. The earliest wells drilled in the prospect were drilled outside the present limits of the reservoir area, to the south (LA1) and west (LA2) of the area drilled later.

A 7.3 MWe pilot geothermal plant was installed in 1999 utilizing the production from the above exploration wells. The plant has not been fully operational due to reasons that have to do with the lack of operational experience. But since 2007 the plant has been partially rehabilitated and put back into an operation of about 4 MWe.

Ethiopia and Japan signed a memorandum of understanding in June 2009 to generate geoscientific and reservoir engineering data that can be used for expansion and further development of the Aluto Langano geothermal field. Under this framework, the main activities conducted in August 2009 are magneto telluric (MT) and Audio magneto telluric (AMT) survey on 40 selected stations. During this survey, while experts from Phoenix Company of Canada conducted the MT study under contract for West Jec consultants of Japan, Ethiopian geophysicists took part in the field survey with the aim of obtaining hands-on experience in MT data generation and processing.

From the various resistivity maps produced, the area around the central and southern portions of the resistivity discontinuity R1 and the central portion of the resistivity discontinuity R2 especially in the uplifted relatively high resistivity zone detected at depths between 1,000 m and 2,000 m, can be recommended as promising zones for future drilling targets for production wells (Figure 3).

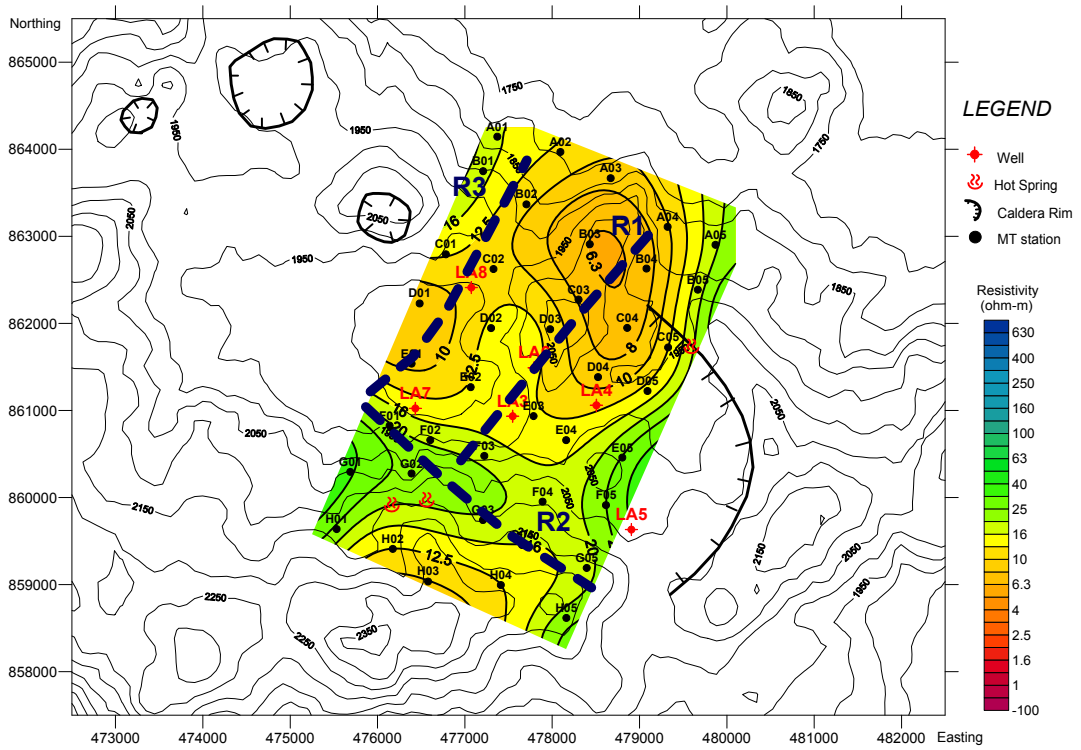

FIGURE 3: Resistivity map at a depth of 2,500 m at Aluto (3-D inversion results, West Jec, 2010)

The study outlined subsequent two phases for the expansion and power development, which include: (i) the drilling of four appraisal wells and resource assessment in the next phase, and (ii) the drilling of

production wells and step by step installation of 2 x 35 MW units in the final phase. Preparatory work for the drilling of the four wells is currently being conducted.

In 2011, additional magnetic and gravity surveys were carried out with the objective of identifying and locating subsurface faults, caldera structures that may host another reservoir if it exists. Thus the surveys were conducted to cover most Aluto volcanic complex including its surroundings.

From the various maps, a caldera within a caldera structures have been recognized with various vents and craters (Figure 4). Lineaments in NNE, NE, and NW are features identified and located as fault structures. Several ring fractures and domes were also located. The horizontal derivative and analytical signal maps based on high values plotting are found to be, specially, useful in identifying and locating these structures. Fault depth varies between 80 and 2100 meters (Bekele, 2012).

The NNE faults found within Aluto geothermal field are active sites of the present day extensions, continuously generating fractures to counteract the sealing effect of hydrothermal activity. This fault system divides the inner caldera, and most of the Aluto geothermal wells are found at and around this fault system. The open magnetotelluric resistivity anomaly found east of these structures could be the expression the second reservoir, probably deeper than the productive reservoir found in the central area.

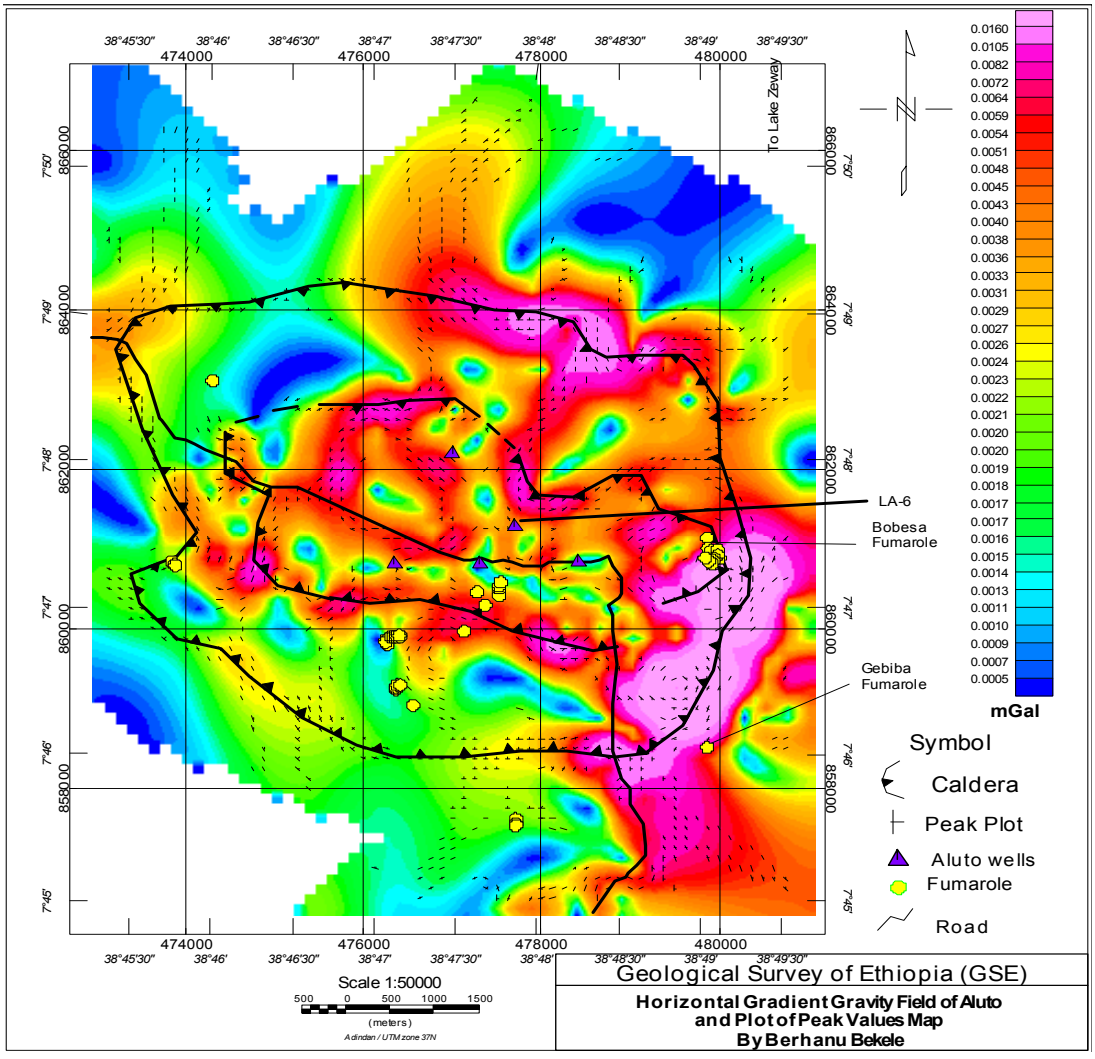

FIGURE 4: Map of Horizontal Gravity gradient Field of Aluto

2.2.2 The Tendaho geothermal field

Geothermal exploration was carried out in the Tendaho area with economic and technical support from Italy between 1979 and 1980. Between 1993 and 1998, three deep (about 2,100 m) and three shallow exploratory wells (about 500 m) were drilled and yielded a temperature of over 250ºC. The Italian and Ethiopian governments jointly financed the drilling operation in the geothermal field. A preliminary production test and techno-economic study indicated that the shallow productive wells could supply enough steam to operate a pilot power plant of about 5 MWe, and the potential of the deep reservoir was estimated to be about 20 MWe.

Based on this and further studies, the Ministry of Mines and Energy is currently working on Tendaho for progressing it towards development. The recent upgrade of a trunk highway through the Tendaho area will help facilitate such exploration and development. In addition, the Ethiopian government plans to extend the country's main 230KV transmission line to Semera, which is within ten km of the drilled wells at Dubti.

In the frame of the BGR GEOTHERM programme in 2007 to 2009, Magnetotelluric (MT) and Transient Electromagnetic (TEM) field surveys were conducted at the Tendaho prospect in Afar region of Ethiopia. The surveys covered Dubti and Ayobera areas, both north of the Awash River. Concurrent to the MT & TEM surveys, geochemical survey consisting of fluid (gas & water) sampling from wells, hot springs and rivers was carried out to check if there interference between wells. Processing, interpretation and analysis of MT data provided useful subsurface information and the results obtained from such endeavour are summarized here below.

The magnetotelluric soundings show in their 2-dimensional inverted resistivity sections regions with resistivity's as low as 2 Ohm-m, especially in near surface layers as well as at greater depth (below 7 km). Based on the inverted resistivity's, we get a good overview of the lateral resistivity structure as presented in figure 5 (a,b,c) for selected elevations.

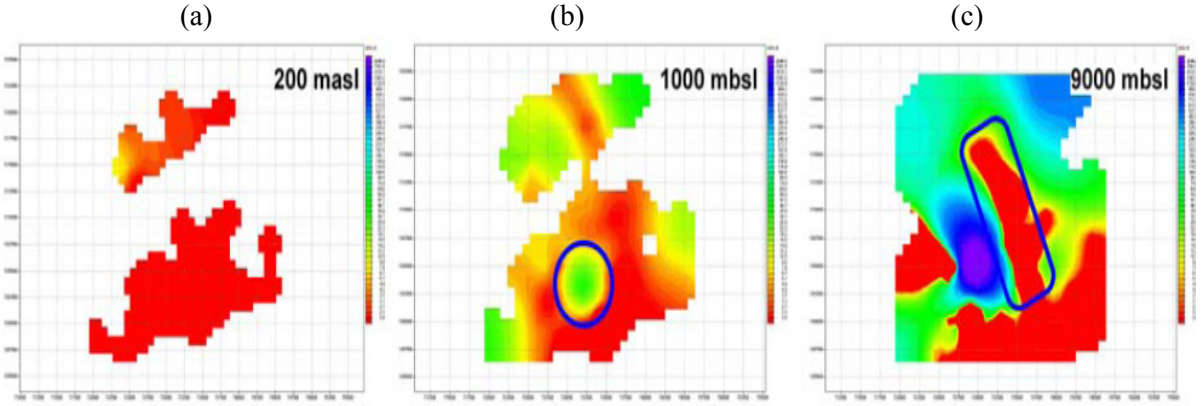

FIGURE 5: Lateral resistivity variations in selected profiles for various elevations

In Figure 5, Left*:* at 200 masl (150 m below surface). Shallow low resistive layer is (red) due to sedimentary infill. The sediments are up to 1 km thick. Centre: at 1000 mbsl (1350 m below surface). Slight increase of resistivity (> 10 Ω-m) possibly due to mixed layer clays and advancement towards deeper reservoir (blue circle). Right: at 9000 mbsl (9350 m below surface). Resistivity value that drops below 2Ω-m is along NW-SE trending feature (partly molten magma dyke?). This may form the deep heat source feeding the shallow geothermal reservoir.

A review and reinterpretation of geophysical data collected at Tendaho was performed in 2011 with the objectives of improving the understanding of the subsurface of Tendaho geothermal fields, delineate geothermal reservoirs, and locate exploration drilling sites. After correcting for the magnetic and gravity field variations that are unrelated to the earth's crust, several filters were applied to the

reduced data, so that anomalies of interest can be enhanced and displayed in a more interpretable manner.

Three high residual gravity ridges separated by gravity lows are reflection of subsurface rift configurations imprinted on Afar stratoid basalts. Computation of horizontal gravity gradients enabled to map the contact between masses of different densities. With such edge enhancement fault/contacts, calderas, craters, domes and vents are outlined. The magnetic method defined the axial region of the Tendaho rift which coincides with the central high gravity ridge. Estimates of vertical and horizontal positions have been made using Euler 3D deconvolution for fault, and sill/dyke models. Such models enabled to construct faults blocks constituting two half grabens separated by hinged high blocks with central depression (Bekele, 2012). Geologically mapped thermal manifestations and craters bear positional correlations with the geophysical interpreted faults, ring fractures, calderas, craters, and vents. Both gravity and magnetic data show that the Tendaho graben is severely affected by fault systems, trending NW, NE, EW, and NS

Based on the obtained results, it is highly recommended to drill a deep well at Ayrobera, where faults and ring fractures intersect and coincide with steaming grounds. Other highly recommended drilling site is at southeast position of the mud pools. But this has to be done after conducting high resolution MT survey at the recommended sites. Other recommended geothermal studies are Heat flow survey to estimate the resource and micro seismicity to locate fractures and monitor drilling activities.

A total of 129 MT sites were acquired from Tendaho high temperature field in 2011-2012. The main objective of the survey is to understand the deep geothermal reservoir of Tendaho. Geothermal Field using closely spaced MT stations and 1D and 2D inversions of MT data along ten profiles were performed. The 1D and 2D inversion of MT data from Tendaho high temperature field revealed three main resistivity structures down to a depth of 15 km: low resistivity surface layer underlain by a resistive layer followed by good conducting structure (Lemma et al, 2012).

The low resistivity surface layer shows areas with either sediments, lateral flow of geothermal fluids or Zeolite-clay alteration zone. Below the conductive layer is a high resistivity zone that can be correlated to Afar stratoid basalts or epidote alteration zone. The high resistivity structure can also be associated with the deep reservoir of the geothermal system. The deep good conductive body is associated with a probable heat source of the geothermal system.

The possible fracture zone inferred in the Afar stratoid basalts may give high temperature and high permeability. The 2D resistivity elevation slices showed possible up flow zone south east of the exploratory wells drilled in Dubti area. The high resistivity structure at depth of 2-3 km b.s.l and inferred fracture zones at this depth are possible targets for drilling at Dubti and Ayrobera area.

2.3 Prospects where surface exploration is at higher level

Over the years, a number of prospects have been subjected to surface investigation: geology, geochemistry and geophysics and the shallow subsurface has been investigated by drilling at a few of the prospects. They are mostly located in the MER, especially in its most recent zones of tectonic and magmatic activity, the different sectors of the discontinuous WFB. These prospects from south to north are: Abaya, Corbetti, Tulu Moye, Fentale and Dofan.

2.3.1 The Abaya geothermal prospect area

Abaya is located on the northwest shore of Lake Abaya, about 400 km south by road from Addis Ababa. The Abaya prospect exhibits a widespread thermal activity mainly characterized by hot springs, fumaroles and altered ground. Spring temperatures are as high as 96 °C with a high flow rate. Integrated geoscientific studies (geology, geochemistry, and geophysics) have identified the existence

of a potential geothermal reservoir with temperature in excess of 260°C (Ayele et al., 2002). Further geophysical studies including drilling of shallow temperature gradient wells are recommended here.

The 132 KV transmission line to Arba Minch to the south starts at the Wolayta Soddo substation located about 40 km distance to the NNW of the prospect. This raises the prospect for development of the resource once it is adequately explored, including by drilling.

2.3.2 The Corbetti geothermal prospect area

The Corbetti geothermal prospect area is located about 250 km south of Addis Ababa. Corbetti is a silicic volcano system within a 12 km wide caldera that contains widespread thermal activity such as fumaroles and steam vents. Detailed geological, geochemical and geophysical investigations conducted in the Corbetti area indicate the presence of potential geothermal reservoirs with temperatures exceeding 250°C. Six temperature gradient wells have been drilled to depths ranging from 93-178m (Kebede, 1986). A maximum temperature of 94°C was recorded. The data shows the probable existence of an economically exploitable deep geothermal reservoir.

A 132 KV power transmission line passes within 15 kms of the prospect and is the main trunk line to southern Ethiopia, to towns along the two branches of the highway to Kenya.

The Corbetti prospect has been given in concession for an Iceland based private company (Reykjavik Geothermal). In 2011-2012 the Compny has conducted MT/TEM surveys with supplementary other geoscientific studies and the results indicated the Corbetti the geothermal reservoir lateral extent and depth and a potential up to 1000 MW has been estimated, RG (2012)

2.3.3 The Tulu Moye geothermal prospect area

The area is characterized by volcanism dating from Recent (0.8 –0.08 Ma) to historical times. Volcanism involved the extrusion of per alkaline felsic lava associated with young tensional and transverse tectonic features dating from 0.1 to1.2 Ma, with abundant silicic per alkaline volcanic products (Di Paola, 1976) **.** This suggests the existence of a deep seated magma chamber with a long residence time. The area is highly affected by hydrothermal activity with the main hydrothermal manifestation being weak fumaroles, active steaming (60-80°C) and altered ground. The absence of hot springs is related to the relatively high altitude of the prospect area and the considerable depth to the ground water table. During 1998-2000, integrated geological, geochemical and geophysical studies including shallow temperature gradient surveys (150-200m) , confirmed the existence of potential geothermal reservoirs with a temperature of about 200°C (Ayele et al., 2002) and delineated target areas for further deep exploration wells.

This prospect area is located close to the koka and Awash II and III hydro-electric power stations and the associated 230 and 132 KV substations and transmission lines.

2.3.4 The Fentale geothermal prospect area

The Fentale geothermal prospect is characterized by a recent summit caldera collapse, felsic lava extrusions in the caldera floor and widespread fumarolic activity, suggesting the existence of a shallow magma chamber. Active tensional tectonics form fissures up to 2m wide near the volcanic complex. Ground water discharge to the system is assured by the proximity of the area to the western escarpment. The results of an integrated interpretation of previous data suggest that the area is potentially prospective for future detailed geothermal resource investigations. Therefore, due to the presence of an impervious cap rock, the western part of the prospect particularly deserves to be investigated during a more detailed geothermal exploration programme. In this view, the Geological Survey of Ethiopia has carried out detailed geological, geochemical and geophysical investigations in order to delineate and select target areas for deep exploration wells.

Semi-detail/semi-regional magnetic and gravity studies were conducted around the north-eastern periphery of Fantale volcanic mountain in 2011-2012. The survey was made along six NW-SE oriented profiles confined within an area of about 268 km^2 around the Filwoha hot springs.

The objectives of the study were to locate local/regional structures that could be associated with the circulation of thermal fluid, locate possible heat sources and alleviate the understanding of the geothermal field in the north-eastern portion of Fantale geothermal prospect area.

As a result the gravity and magnetic data revealed both local and regional structural and lithological units in the north-eastern Fantale volcanic mountain in great detail. E-W and NW-SE local structures and NNE-SSW, NE-SW and N-S lineaments related to traces of regional structures. The north-east south-west massive intrusion intersected by north-west south-east dyke is delineated in the vertical integral map of the gravity field. The heat source in the area could be the high velocity structure interpreted as maffic intrusion and/or the prevailing regional heat anomaly existing under the rift.

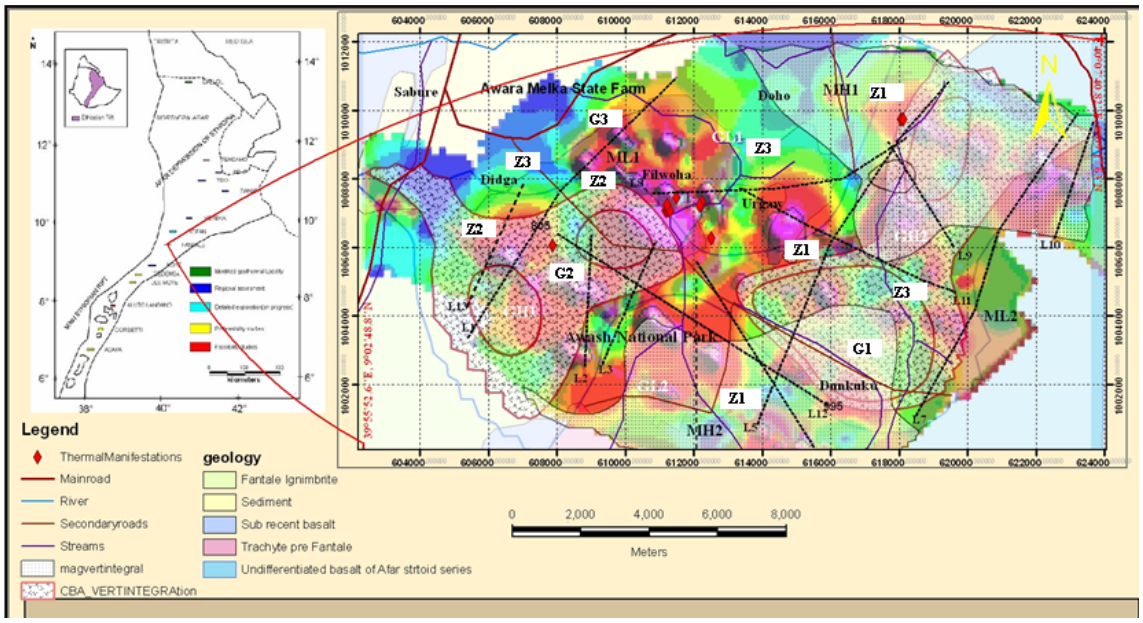

FIGURE 6: Geophysical compilation map at the North Eastern Fentale (Kebede et al., 2012)

Referring the geophysical compilation map, Figure 6, generally four types of magnetic anomaly signatures help delineate basic and acidic rocks in the area. High and intermediate magnetic zones.

2.3.5 The Dofan geothermal prospect area

Geological, geochemical, and geophysical investigations in the Dofan geothermal prospect show that the area is characterized by a complex volcanic edifice that erupted a considerable volume of pantelleritic lava from numerous eruptive centers between 0.5-0.2 Ma (Cherinet and Gebreegziabhier, 1983). The presence of several hydrothermal manifestations (fumaroles and hot springs) within the graben, together with an impervious cap, needs to be regarded with high priority for further detail exploration and development (Teclu, 2002/2003).

The area is located about 40 km from the high voltage substation in the Awash town.

2.4 Prospects where surface exploration is at lower level

During the 1980's, reconnaissance geological, geochemical and geophysical investigations have been conducted at Dallol, Kone, Meteka, Teo, Danab and L. Abe areas that are found in a zone extending between the southern and northern Afar geological provinces. Meteka and Teo hold promise for the discovery of economically exploitable geothermal resources at high temperature and warrant detailed surface investigation, to be followed by exploration drilling. The Lake Abe area warrants further investigation in a wider exploration context that encompasses areas in the eastern part of Tendaho graben and the Lake Abe prospect in Djibouti. These resource areas are not included in this proposal as their large distances from electricity load centers and the national grid accord them lower priority. With advancing economic activity in southern and central Afar as well as in the eastern part of the country, these prospect areas should prove useful for power supply both within the region and to the national grid in the longer-term.

The prospects that have been dealt with under reconnaissance stage are located to the north of 12°N latitude and comprise terrain that is at the most advanced stage of rift evolution in the eastern Africa region and holds a much greater potential for geothermal resources than any other region of equivalent size. This region should be considered as a prime target area for future exploration and development. With the improving availability of the economic development infrastructure in the region, the power-supply system in the load growth areas of northern Ethiopia would benefit from geothermal power generating facilities located in this part of the country.

From these long-term points of view, reconnaissance and preliminary surface evaluation works should commence in the not too distant future in the regions of southern and central Afar, North of 12°N latitude, in order to raise the available level of knowledge regarding the resource areas and to provide the necessary information that is required for long-term planning.

3. CURRENT GEOTHERMAL EXPLORATION AND DEVELOPMENT ACTIVITIES

Currently the following geothermal activities are being conducted in Ethiopia:

- A five year project entitled Strategic Geothermal Resource Assessment in the Ethiopian Rift Valley has started in 2009. The target areas of the assessment are Tendaho, Aluto Langano, Gedemsa, Dofan, Fentale, Meteka and Arabi, Geoscientific studies including: (i) geological, (ii) geochemical, (iii) geophysical (MT, TEM, Gravity and Magnetics) and (iv) Reservoir Engineering studies are being conducted in these areas. The objectives of the project are to locate and identify areas (sites) for deep drilling by acquiring data that can supplement the already available ones, and upgrade and synthesize all existing information in order to establish a geothermal exploration conceptual model for future feasibility studies. In 2013, MT and Soil geochemical surveys have been conducted at Doubti and Allalobeda of the Tendaho Geothermal Field.

- After Ethiopia and Japan conducted a feasibility study for the expansion development of the Aluto Langano Geothermal Field in 2010 which proved the expansion plan to be feasible, a project for resource evaluation by drilling of three appraisal deep wells and one reinjection well has been designed. The project is financed by the Government of Ethiopia, Japanese Government and the World Bank. In this project so far the following activities have being carried out: (i) Pre drilling preparation including well pad preparations, maintenance, testing and erection of an existing rig at the project site, and (ii) purchase of drilling consumables from overseas and training of local staff and capacity building required for the project. Commencement of the drilling of four wells has delayed due to traffic accident encountered while transporting a cementing unit from overseas to the project site. Currently a rental cementing unit has been obtained from Kenya and the drilling is scheduled to commence in early November, 2013.

Additional work to be conducted in parallel with the drilling has commenced, with the assistance of ICEIDA and the World Bank, which includes, production wells drilling site selection and purchase of Rigs and additional consumables.

- At Tendaho, a project proposal has been prepared to develop the geothermal resource to 100 MW at various phases. Additional surface studies indicated that, the previously drilled deep wells were not deep enough to encounter the main reservoir. In order to study the feasibility of utilizing the discovered shallow reservoir and further deep drilling, preparatory work has commenced. Currently early stage of work has commenced with assistance of ARGeo, AFD, and ICEIDA including: final preparations for surface investigations, review of previous data and feasibility study by international consultant and purchase of equipments and accessories.

- JICA and GSE have signed an agreement on June 2013, for geothermal Mater Plan studies in Ethiopia. The project is scheduled to conduct geoscientific, social and economic surveys in 16 prospects inorder to prioritize them. Currently, this eighteen months project has started with the review of previous data.
- Regarding the private sector participation, heads of term of power purchase agreement for Corbetti geothermal development has been signed in October, 2013 between EEPCo and Reykavik Geothermal for the development of Corbetti geothermal field. The agreement considers development of the Corbeti (including Abaya and Tulu Moye) prospectes to 1000 MW with estimated investment cost of 4 billion US$.

4. FUTURE GEOTHERMAL DEVELOPMENT PLANS

4.1 Work plan

Since recent times, the country has shifted its policy of relying in a single source of electric power (hydro) to secure energy in the country and thus geothermal sector development is receiving support. As a result a medium term and long term geothermal development plan has been established. According to the medium term plan, a total of 675 MW geothermal power is to be developed from six selected prospects by 2018 (Table 3) and in the long term 2000 MW will be developed by 2030.

TABLE 3: Medium term geothermal development plan

Prospect	Initial output (MW)	Commissioning
Aluto Langano	75	2016
Tendaho	100	2018
Corbetti	300	2018
Abaya	100	2020
Tulu Moye	40	2018
Dofan Fantale	60	2018
Total	675	

4.2 Financial plan

One of the major challenges in Ethiopia's energy sector development program is financing. Financing the projected electric power generation scale up has far proven to be very challenging in realizing the countries ambitious plan.

Inorder to achieve the countries medium term plan in geothermal development both the public, development partners and the private sector participation are envisaged.

The following financial resources are secured or are on the process of being secured under the public sector: (i) for the expansion of the Aluto Langano Geothermal field to 75MW, a 24.5 million US$ has been secured for the planned production drilling, from the Scaling Up Renewable Energy Program (SREP) of the Climate Investment Funds. Furthermore, finance for the planned expansion power plant is being looked for from the Japanese government and the World Bank, and (ii) The development of the Tendaho geothermal resources at various sites within Tendaho is scheduled with financing of the French Development Agency, African Rift Geothermal Development facility of the United Nations Environmental Program, Geothermal Risk Mitigation Facility of the German Development Bank and Africa Union, the World Bank and Ethio-Iceland bilateral cooperation.

Apart from Aluto and Tendaho the remaining four prospects of the six selected areas are expected to be developed by both the public and the private sector financial involvement.

4. CONCLUSIONS

Despite the long history of geothermal exploration in Ethiopia and an estimated 5000 MW potential, so far only a very little fraction of the total potential is harnessed. In order to avert possible shortfalls and also due to their added advantage in complementing the hydro generation during unfavorable periods of severe droughts, geothermal development in Ethiopia has been given more attention, since recent years.

Currently geothermal is: (i) integrated in the National Energy Development Plan, (ii) participation of international financial institutions, bilateral donors and development agencies to assist geothermal development projects has grown, and (iii) the private sector is being encouraged to participate in geothermal development projects and as a result activities in selected prospects by the private sector have started.

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GEOTHERMAL EXPLORATION IN TANZANIA – STATUS REPORT

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ABSTRACT

Tanzania is endowed with a huge geothermal potential which has not yet been used, and has only been explored to a limited extend. Geothermal power is a reliable, low-cost, environmental friendly, alternative energy supply and an indigenous, renewable energy source, suitable for electricity generation. Currently, the national power system is mostly relying on hydropower. A long period of drought between 2003 and 2006 lead to shortfalls in electricity supply from the hydropower stations; thus, the government of Tanzania intends to diversify the country's energy mix. In the energy sector roadmap has made geothermal development as one of its priorities. Most of the sites already identified with hot springs are located in areas transsected by the East African Rift System. Such areas include the northern volcanic province of Kilimanjaro, Meru and Natron and the Rungwe Volcanic province in southwest Tanzania. In addition, Utete and Luhoi in the eastern coastal area also show surface manifestations of geothermal resources.

In Tanzania, several reconnaissance surveys and a few detailed studies of hot springs and geothermal sites have been carried out since 1949; some of these early studies in geothermal sites include measurements of surface temperature, water and gas flow as well as water and gas analyses of the hot springs. These studies on geothermal energy provide basic information on planning current geothermal projects.

In 2006 and 2010, the Ministry of Energy and Minerals (MEM); the Division of Energy in collaboration with the Geological Survey Tanzania (GST) and the Federal Institute for Geosciences and Natural Resources (BGR) of Germany carried out geological, geochemical and geophysical investigation to assess the geothermal prospects as well as to locate a hydrothermal system and potential geothermal reservoirs. The results from the electromagnetic surveys (TEM, MT) conducted, show zones of low resistivity in the Ngozi area, which can possibly be correlated to alteration zones caused by geothermal activity and in turn indicate a potential geothermal reservoir (Geotherm, 2006).

1. INTRODUCTION

Tanzania is one of the East African countries with characteristics of geothermal energy resources. Most of the identified hot spring sites are located in areas transsected by the East African Rift System (Figure 1). Such areas include the northern volcanic province of Kilimanjaro, Meru and Ngorongoro and the Rungwe Volcanic province in southwest Tanzania (Figure 2). In addition, some coastal areas show geothermal surface manifestations. Hot springs have been mapped in the Rufiji basin, south of Dar -es - Salaam and to the north in the Tanga region. The hot springs in the coastal sedimentary basin are attributed to rifting and intrusions.

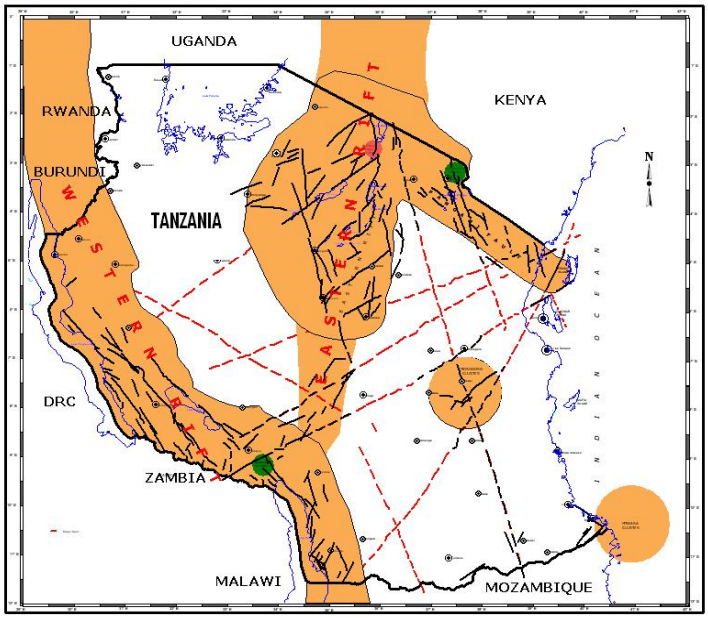

FIGURE 1: East African Rift System in Tanzania.

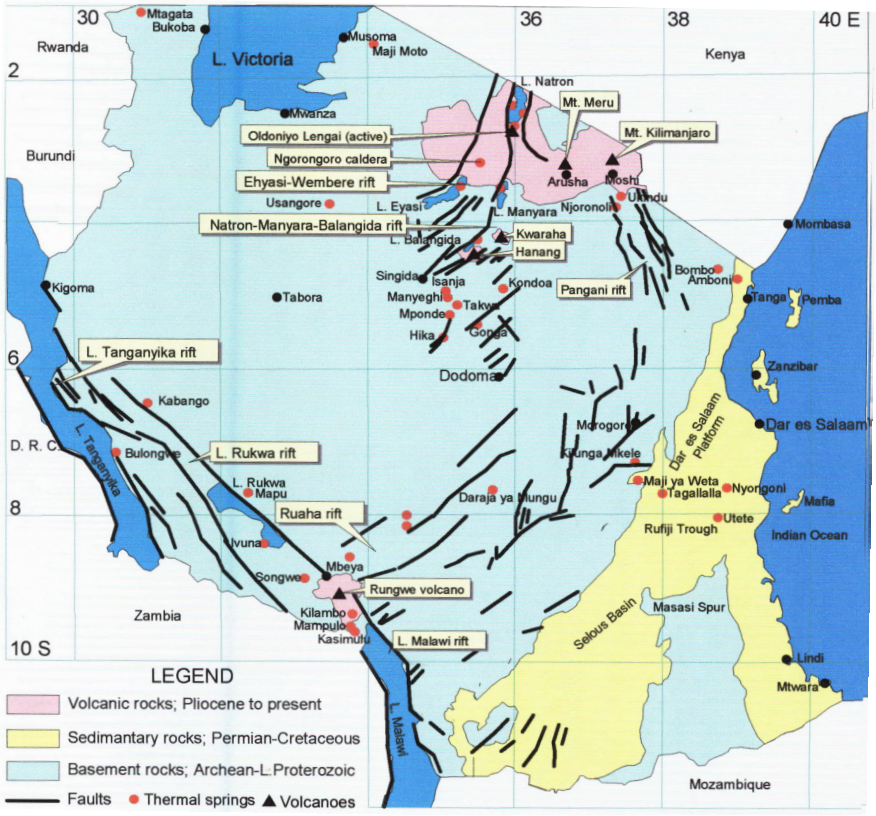

FIGURE 2: Geothermal sites in Tanzania

In Tanzania, several reconnaissance surveys and a few detailed studies on geothermal energy have provided basic information for planning current geothermal projects. Existence of thermal energy is indicated by the presence of hot springs, volcanic activities and geological structures. Hochstein et al. (2000) argue that the geothermal resources of Tanzania appear to be rather small and limited in terms of existing technology. Estimates by McNitt (1982), concluded by analogy method, the geothermal potential of Tanzania could be as high as 650 MW. Based on this result, the potential was refined to be

in the order of 140 to 380 MW. This value is based on the natural heatflow discharge from hot springs. Provided that geothermal reservoirs do exist, the potential could be even higher. The challenge is to locate the present reservoirs by integrating the geophysical, geochemical and geological techniques. Despite the fact that Tanzania has an estimated geothermal energy potential; it has not been given due attention in the energy policy of Tanzania until recently, (UNEP, 2003). The geothermal energy (as an alternative energy source for Tanzania) project conducted by MEM, GST and BGR in May and November 2006 give promising results for further surveys which might lead to the location of geothermal reservoirs.

The demand for electrical energy which is solely dependent on hydropower, gasoline and gas turbines has been increasing since its first production in 1908 by Germany for railway workshops in the Tanganyika territory. The country experiences long periods of droughts, rising imported oil prices and sedimentary infilling of dams, which hamper its energy security. While it is in an energy crisis, Tanzania is endowed with abundant, inexhaustible, and less polluting geothermal potential, which has not yet been explored.

In 2013, about 18% of 44.9 Million people had access to reliable electricity (The United Republic of Tanzania, 2013). The forecast of the energy peak demand is estimated to increase from 2,540 GWh in year 2000 to 11,548 GWh in year 2026 with a growth from 426 MW in year 2000 to 727 MW in year 2005 and to 1,994 MW in year 2026. In order to overcome the rate of increased demand, a total of 1,053 MW will be required between 2002 and 2021 (Mwihava et al, 2004). DECON, SWECO and Inter-Consult (2005) suggest that geothermal energy amongst others, as an indigenous, environmental friendly, renewable energy source, is suitable for future electricity supply.

2. GEOTHERMAL EXPLORATION

2.1 Geothermal studies in Tanzania.

In Tanzania, several reconnaissance surveys and a few detailed studies of hot springs and geothermal sites have been carried out since 1949. Some of these early studies are referenced in Walker (1969). A detailed overview and table including the location, temperature, water and gas flow as well as water and gas analyses of the hot springs in Tanzania has been given in the studies carried out. However, the geothermal resource assessment in Tanzania is still limited to preliminary surface studies. These studies on geothermal energy provide basic information on planning current geothermal projects.

In the years 1976 to 1979 geothermal exploration was carried out under the direction of SWECO, a Swedish consultant group, in cooperation with VIRKIR, Iceland. Financial support was provided by the Swedish International Development Cooperation Agency (SIDA). The objective of the reconnaissance studies was to study the possibility of exploiting geothermal recourses in Tanzania. For this purpose, 50 hot springs mainly in northern Tanzania and in the Mbeya region have been investigated and terms of reference for future investigations have been elaborated (SWECO, 1978). The study included measurement of surface temperatures of hot springs. Tests conducted have indicated high temperature sources in Lake Manyara, Lake Natron, Ngorongoro Crater and the Mbeya region, while lower temperatures were recorded around Lake Eyasi, and the Musoma area (Maji Moto). Based on this study, SWECO recommended further studies on hot springs occurring in the Rungwe Volcanic Province in the Mbeya region, Ngorongoro, and Manyara which appeared to have higher subsurface temperatures compared to the others. The results of the reconnaissance survey carried out by the Swedish Consultant Group (SWECO, 1978) were favourable, indicating good possibility of encountering high, intermediate and low temperature reservoirs, in northern and southern Tanzania within the Neogine volcanic areas in the East African rift system.

In 1995, Hochstein et al. (2000) made a reconnaissance study of the major geothermal prospects in Tanzania to assess their geothermal potential and the natural discharge rate, under financial support

from TANESCO. Since all the water samples were lost in transit, the authors had to use chemical analyses from SWECO (1978) for their study. From this study it was concluded that the geothermal resources of Tanzania appear to be rather small.

The First Energy Company Limited (FEC, Dar es Salaam) has the license for detailed geothermal exploration and development of the geothermal prospect Luhoi in the Lower Rufiji Basin. FEC compiled studies, which are mainly based on results and data from petroleum exploration, to assess the prospect. FEC estimated the geothermal potential at Luhoi to be in the order of 100 MW. The reports and data of the studies are not available yet.

In 2004 and 2005, the Tanzanian Rural Electrification Study (TRES) was conducted by Deutsche Energie-Consult Ingenieurgesellschaft mbH (DECON), a German company, SWECO and Inter-Consult. TANESCO was the implementing institution on the client's side. The African Development Bank (ADB) was the funding organisation of the TRES. In the study, geothermal energy, among others, was regarded as an indigenous, renewable energy source suitable for future electricity supply in Tanzania. In addition to the SWECO study, a number of other studies have been conducted as shown in Table 1.

TABLE 1: Studies conducted during the period 1976-2012

Year	Institution	Study	Results	Area
1976 - 1979	SWECO through Sida	Reconnaissance exploration	50 hot springs sampled	Lake Natron, Manyara, Utete, Mbeya, Musoma
1983	UNDP funded geothermal mission	Reconnaissance exploration	Mbeya considered a good prospect	South Mbeya
1997 - 2004	First Energy Company Ltd	Reconnaissance Exploration, Power project pre feasibility study	Samples collected and analyzed, good results, (promising site)	Luhoi - Coast region
2004 - 2005	DECON through African Development Bank (ADB)	Rural electrification study Magnetometric, gravity and resistivity surveys	Recommended detailed assessment of Mbeya area.	Lake Natron, Manyara and Mbeya (Songwe, Kasumulo, Mampulo)
2004 - 2005	Regional Consultant for Geothermal in East Africa	Status of geothermal resource development in Tanzania	Recommended further studies on Songwe, Luhoi and Lake Natron	Lake Natron, Songwe river, Luhoi (Coast region)
2006 – 2009	MEM collaboration with Geological Survey of Tanzania and Federal Institute for Geosciences and Natural Resources (BGR) German	Reconnaissance study on geophysics method of exploration by using Transient Electro Magnetic (TEM) and Vertical Electric Sounding (VES)	One site for detailed assessment identified	Songwe river in Mbeya region
2009 – 2012	GoT in collaboration with Federal Institute for Geosciences and Natural Resources (BGR) German; GEOTHERM phase 2	Pre-feasibility study by using (TEM) and Magnetotellurics (MT).	Low resistive layers encountered in the subsurface (report not yet out)	Lake Ngozi area in Mbeya region

In June, 2006 the Ministry of Energy and Minerals; the Division of Energy in collaboration with the Geological Survey Tanzania (GST) and the Federal Institute for Geosciences and Natural Resources (BGR) of German conducted a project on "Geothermal as an alternative Source of Energy for Tanzania". The project is part of the GEOTHERM programme; which is a technical cooperation programme of the German government. It promotes the use of geothermal energy in partner countries by kicking off development at promising sites. Songwe in the Mbeya region has been selected as a project site (Figure 2). The project's aim is to initiate a successive expansion of the geothermal sector in the country.

The objective of the GEOTHERM project in Tanzania is that "Tanzanian institutions move further on evaluating the country's geothermal potential". One project component is planned to prove the existence of a hydrothermal system and to recommend potential locations for a geothermal exploration borehole on the basis of modern geothermal exploration methods in the project area. Other project components include; training Tanzanian experts in acquiring, analysing and interpreting exploration data, thus enabling MEM and GST to continue with geothermal exploration works, dissemination of information about possibilities of geothermal energy use in Tanzania among decision makers and search for funds for shallow drilling in Songwe.

2.2 Methods employed in exploration

Geothermal resource assessment in Tanzania is still limited to preliminary surface studies; that is, geological and geochemical surveys. In 2006 and 2007, MEM, GST and BGR carried out geological, geochemical and geophysical investigation to assess the geothermal prospect as well as to locate a hydrothermal system and potential geothermal reservoirs.

Field visits to Songwe (November, 2006) involved the following activities:-

- Sampling of rocks; collecting water samples for analysing cations, anions; noble gases (helium) and carbon dioxide;
- Measuring Total Dissolved Solids, water temperature and conductivity;
- Analysing geological structures, these are fracture, fault and tectonic fissures;
- Exploration by using geophysics methods Transient Electro Magnetic and Vertical Electric Sounding; and
- Finding new geothermal manifestations in the Rungwe area.

Geo-electric Soundings (VES – Schlumberger array) and Transient Electromagnetic (TEM) were the geophysical methods selected. Low resistive layers encountered in the subsurface, together with promising geochemical results indicated possible geothermal activity encouraging further surveys. Due to these first results, later in June/July 2007, additional integrated surveys were carried out and the results have encouraged the project to move further to locate a potential geothermal reservoir. Transient Electromagnetics (TEM) and additional Magnetotellurics (MT) were applied this time. The same geophysical methods were applied in the zoomed area around Lake Ngozi during2009 – 2010 field work.

2.3 Results

The principal objective of geochemical surveys during geothermal exploration is to predict subsurface temperatures, to obtain information on the origin of the geothermal fluid and to understand subsurface flow directions (Arnórsson, 2000). The conditions for high-enthalpy resources are principally favourable in the Mbeya region due to the presence of active faults allowing fluid flow, a young volcanic heat source which is sparse in other parts of the western branch of East African Rift System, and surface manifestations of hot springs indicating geothermal activity in the subsurface. The geochemical study of hot spring waters in the Mbeya geothermal sites essentially involved three steps; namely, sampling, analysis and data interpretation.

Geophysical signatures were studied in order to demarcate the extent and depth to the reservoir; to ascertain stored anomalous heat, potential usable heat, heat loss and power potential of the study area and to develop a model, which will form a basis for the prospect model to be refined during drilling and exploitation

2.3.1 Geochemical data

The interpretation of thermal fluids is supported by the presentation of data in triangular diagrams, binary plots, and modelling plots.

The interpretation of chemical data obtained in the November 2006 field campaign shows waters with low B/Cl ratios, which suggest that they belong to the old hydrothermal system. Some hot springs plots in areas of immature water and others in areas of partially equilibrated water. The detailed information on chemical and geological investigation which comprises the findings of assessment of geothermal sites in Mbeya, including results for fields where investigations were conducted by GEOTHERM during June/July 2007, and 2009 characterize the Lake Ngozi water to near geothermal waters.

2.3.2 Geophysical data

The results from the electromagnetic surveys (TEM, MT) conducted, show zones of low resistivity in the Ngozi area, which can possibly be correlated to alteration zones formed by geothermal activity. This might be an indication of a potential geothermal reservoir (GEOTHERM.,2006). The results and findings from the geophysical surveys of the GEOTHREM project indicate Low resistive layers in the subsurface north west of Lake Ngozi area in Mbeya region.

3. BARRIERS TO GEOTHERMAL DEVELOPMENT

The main barriers of geothermal development in Tanzania are as follows:

- Inadequate awareness to most stakeholders including decision makers and land planners;
- Inadequate capacity to develop geothermal, few staff in the Ministry of Energy and Minerals have the knowledge (trained) on geothermal energy; and
- High cost of geothermal exploration and inadequate private sector interests in exploring geothermal. One exploratory well can cost up to US$ 5 million.

In order to address the barriers indicated above:

- More Tanzanians need to undergo training in various fields relevant to geothermal development i.e. in borehole geology and geophysics, surface geophysics and geochemistry and reservoir engineering.
- There is need for awareness creation amongst decision makers, planners and politicians on the importance of geothermal energy as a clean renewable energy source;
- More funds need to be mobilized for detailed geothermal resources assessment; and
- There is need for geothermal resource remapping. This will involve the preparation of a new geothermal map for Tanzania showing areas of geothermal potential by collecting new data for soil (surface) temperature, hot springs, hot and warm ground, steam vent, cold springs, faults and tectonic fissures. With appropriate support, the Geological Survey of Tanzania could produce a geothermal map. The map will serve as a tool for attracting research and potential geothermal developers.
- Tanzania should participate actively to the regional geothermal development initiatives including the African Rift Geothermal Development Facility (ARGEO).

4. RECOMMENDATIONS

- Additional measurements at sites with promising results have to be performed in order to narrow down the potential location of the geothermal reservoir. Nevertheless, no one method can stand alone. Geology, geochemistry, geophysics and later on drilling must be integrated in a single model to resolve the nature of the subsurface geothermal system.

- A more detailed study should be carried out to prove the commercial viability of geothermal energy, and; to identify and remove the barriers to the widespread commercial development of geothermal energy in Tanzania.

- To develop a comprehensive project management organizational framework that identifies individuals, and roles and responsibilities of those individuals. Provide CV's of all key staff at both the managerial and project levels. Identify the need for consultancy services and identify the roles of those consultants relative to staff.

- Let this report stimulate discussion and suggestions to improve our approach in exploration projects, in the potential geothermal sites in Tanzania and eventually come up with production wells for power supply from geothermal energy sources for future electricity generation.

5. CONCLUSIONS

- A detailed exploration plan and associated budget is needed for further assessment of the geothermal site(s) with the greatest potential for the near term development of an economically viable power generation project and by doing so to become eligible for risk mitigation programs designed to minimize the financial risk of exploratory drilling.

- Tanzania, among East African countries, has a large potential of geothermal energy, which is significant for exploration and exploitation. Electricity can be produced domestically, thus providing jobs for rural communities and reducing security concerns associated with dependence on firewood or foreign sources of oil.

- The large size of the resources creates significant market opportunities for geothermal technology companies.

- So far from the data available, the highest potential for geothermal power exploration is in south-western Tanzania (the Rungwe volcanics and the Rukwa basin); the second highest is at the northern zone (Lake Natron and Arusha –Kilimanjaro area), developing geothermal renewable energy resources will contribute to a stable and reliable supply of energy and also stable tariffs.

- Training is needed in different kinds of geothermal disciplines to build geothermal capacity building in Tanzania and to create awareness on geothermal in the country.

- There is need to facilitate international cooperation in geothermal development.

- Appraisal studies and field development should be initialized for more promising sites.

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organized by UNU-GTP, GDC and KenGen, at Lake Bogoria and Lake Naivasha, Kenya, Oct. 31 – Nov. 22, 2013.

GEOTHERMAL EXPLORATION IN UGANDA STATUS REPORT

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ABSTRACT

One of the greatest challenges of the 21st century is the production of sufficient energy to power the economies of both the developed and developing world. Declining reserves of fossil fuel, increased demand and environmental constraints will challenge human ingenuity in providing alternative sources of energy like geothermal.

Uganda is located in a geological setting of tectonically active rift system and characterized by recent volcanism. This is ideal geology for geothermal resources and evidence of geothermal resources include hot springs, warm springs, gaseous emission, travertine, hydrothermally altered rocks, mineral precipitates and thermophyllic grass. Preliminary surveys for geothermal resources in Uganda dates way back in 1920 when Geological Survey of Uganda was established. Three holes were drilled around Buranga in 1954 after preliminary geophysical surveying. However, serious exploration efforts were undertaken between 1993-1994 funded by United Nations Development Programme (UNDP), Iceland Government, OPEC and Government of Uganda. The International Atomic Energy Agency (IAEA) funded a programme "Isotope hydrology for exploring geothermal resources" from 1999-2002. IAEA also funded another programme from 2005-2006.

African Development Bank (ADB) and Government of Uganda funded a renewable energy project which included geological and geophysical surveying in Katwe from 2004 to 2005. In 2004, Iceland International Development Agency (ICEIDA) together with Government of Uganda funded geophysical surveys (TEM, gravity and magnetics), geochemical surveying and geological mapping in Kibiro and Katwe. Thermal Gradient Holes were drilled on the indicated anomalies in both Katwe and Kibiro in 2007 funded by World Bank Power 4 and ICEIDA. Reconnaissance survey of other geothermal sites all over Uganda was undertaken funded by ICEIDA and World Bank Power 4. Between 2005 and 2007, BGR carried out geophysical surveys, geochemical surveys, geological mapping of Buranga geothermal resource site. Between 2010 and 2011, IAEA funded another programme RAF/8/047 for exploring geothermal resources using isotope hydrology.

The timeline for geothermal exploration has stretched longer than expected. Breakthrough technology and techniques, finances and policy (Government strong will) are needed to develop Uganda's geothermal resources. The Government of

Uganda has committed public funds and manpower under the Uganda Geothermal Resources Development Project (1199). Under this programme geophysical surveys, geochemical surveys, geological mapping and environment baseline surveys have been undertaken in Kibiro, Katwe-Kikorongo, Panyimur and Buranga. Preliminary results indicate that these systems are larger than previously known. Under the Sustainable Management of Mineral Resources Project (SMMRP) airborne magnetic data was acquired and this has been processed, analyzed and interpreted to aid geothermal exploration. Airborne radiometric data is also being used to locate high heat producing granites important in geothermal industry. Japan International Cooperation Agency (JICA) is funding a preliminary survey of other geothermal sites in South and South West. JICA Studies included geochemical surveys, remote sensing (Landsat, Aster and SRTM) and environment studies. Not-technical data relevant to geothermal industry was also collected like nearness to the national grid, conservation area, accessibility, etc.

During the last Regional Integration Project Summit held in Kigali, Rwanda on October 26-28, 2013, the Heads Of State directed that an MoU between the Governments of Uganda, Rwanda and Kenya for exploration and development of geothermal resources be finalised and signed before the next Summit. This is yet to be signed and will fast track geothermal development in the region.

Uganda government has submitted a project proposal to African Rift Geothermal Development Facility ARGeo-UNEP for technical assistance to undertake surface studies at Kibiro Geothermal Resource Site.

The Ministry of Energy and Mineral Development has been restructured and a Department of Geothermal Resources will be created. The Department awaits a certificate of financial implication from Ministry of Finance, Planning and Economic Development. Human capital development is on-going and procuring survey equipment (Magneto-telluric, TEM, Gravity Meter, and Magnetometer) has been initiated to create a standalone state-run institution to steer and fast track geothermal development in Uganda.

The Government sought Private Sector Funding and granted 10 geothermal exploration licences to private sector investors. Due to high risks and costs associated with geothermal exploration, it is difficult to attract funds from private sector investors and most of them have not fulfilled their working obligations. Government has opted for public sector funding, undertaking exploration and de-risk its geothermal prospects.

Uganda is at the exploration stage of geothermal development aiming at test drilling in the near future. Geophysical methods so far applied have been structural in nature. A combined MT / TEM surveys planned in the near future will aid in locating conductive reservoir and image the sub-surfaces to locate reservoir.

Existence of geothermal resources is not enough for successful development. It is only a prerequisite. Geothermal development needs nation's comprehensive development ability such as technology, finance and policy and a strong will from the Government.

1. INTRODUCTION

One of the greatest challenges of the 21st century is the production of sufficient energy to power the economies of both the developed and developing world. Declining reserves of fossil fuel, increased demand and environmental constraints will challenge human ingenuity in providing alternative sources of energy like geothermal.

Uganda is located in a geological setting of tectonically active rift system and characterized by recent volcanism. This is ideal geology for geothermal resources and evidence of geothermal resources include hot springs, warm springs, gaseous emission, travertine, hydrothermally altered rocks, mineral precipitates and thermophyllic grass (Figure 1). Preliminary surveys for geothermal resources in Uganda dates way back in 1920 when Geological Survey of Uganda was established.

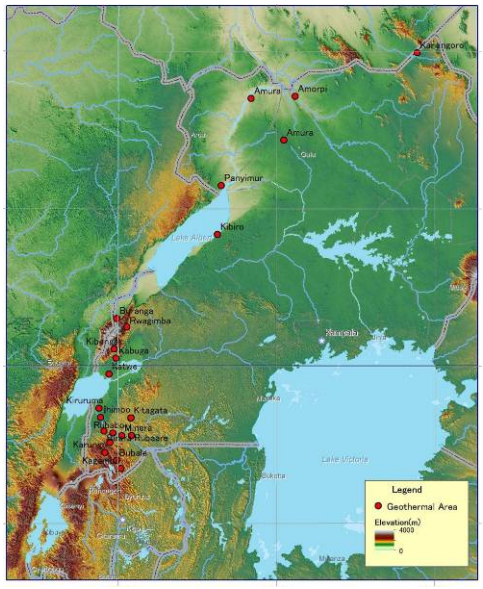


FIGURE 1: Location of geothermal resource sites in Uganda (Source: West Jec)

The existence of geothermal resources in not enough for its successful development. It is only a prerequisite. Geothermal development needs nation's comprehensive development ability such as technology, finance and policy (Government Strong Will).

Geothermal exploration and development is an acknowledged high-risk investment. Due to high risks and costs associated with geothermal exploration, it often difficult to attract sufficient funds from private sector equity investors. Therefore, the public sector has to play an important role in financing exploration. Government has to de-risk investment in the geothermal industry. Historically, governments have undertaken the earliest phase of geothermal exploration in those countries that now have established geothermal industries. Examples include Kenya (KenGen), Ethiopia, Costa Rica.

This successful business model can apply in Uganda. The timeline for geothermal exploration in Uganda has stretched too far and strategies have to be applied involving breakthrough techniques and technology to fast track geothermal development. There is need to put in place a stand-alone state institution to steer geothermal development, a policy, legal and regulatory framework.

There are seven recognised phase of developing geothermal projects; preliminary survey, exploration, test drilling, project review and planning, field development, power plant construction, commissioning and operation. Uganda is on the second phase of project development and the timeline has stretched too far. Historically, many large (50 MW or larger) geothermal projects have taken close to 10 years to develop.

2. GEOTHERMAL EXPLORATION HISTORY IN UGANDA

2.1 Geothermal projects in Uganda

Geothermal energy is hardly playing any role in the Uganda's energy mix despite its potential to do so, with a huge geothermal resource potential. Several exploration efforts have been undertaken in Uganda but drill targets have not been located.

In 1885, Emin Pasha an explorer described Kibiro hot springs issuing up the escarpment. E.J. Wayland (1920, 1921, and 1935) described hot springs in Uganda. Others included Simons (1921), A.J. Stevens (1948), Brown (1954), McConnell and Brown, (1954), C.G Dixon (1967), W.H. Morton (1967), D.V Sharma (1972). In 1954 four exploration wells were drilled in Buranga (Figure 2).

2.1.1 Geothermal Energy Exploration Programme phase 1 (1993-1994)

This was the first serious geothermal exploration carried out on the three highly ranked prospects. The project was funded by the Government of Uganda, United Nations Development Programme (UNDP), Organization of Petroleum Exporting Countries (OPEC), and Government of Iceland. It was implemented by DGSM and executed by Department of Development Support and Management Services of United Nations (UNDDSMS). Work included geological, geochemical and isotopic surveys, in Kibiro, Katwe-Kikorongo and Buranga. The results warranted more field investigations to up-grade the working model to a pre-feasibility status.

FIGURE 2: An old well drilled in Buranga in 1954

2.1.2 Isotope Hydrology for Exploring Geothermal Resources phase-1 (1999-2003)

IAEA together with MEMD funded this project with the aim of refining the conceptual working models of Kibiro, Buranga and Katwe-Kikrongo prospects, using isotopes. This was a follow up of the UNDP-ICEIDA project of 1993-1994.

2.1.3 Katwe-Kikorongo Prospect Exploration (2003)

ADB funded geothermal investigations were carried out in Katwe-Kikorongo in 2003, under the "Uganda Alternative Energy Resource Assessment and Utilisation Study (UAERAUS). This was to upgrade the working model of Katwe-Kikorongo to pre-feasibility status. The heaping up of volcanic materials around Kyamatumu-Lake Kitagata axis resulted in topographic heights (1250 m above sea level), possibly with a higher precipitation than the surrounding and a relatively high water table diverting the flow outwards. Such a high relief zone can have a relatively high groundwater table and an outward directed hydraulic gradient favouring the flow of hot fluids (through faults and permeable strata) to topographically lower areas like Katwe (895 m), Kikorongo (925 m), Kasenyi (895 m), Mahega (925 m) and Nyamunuka (884 m). This correlates well with earlier interpretation of having these outward areas as outflow of this system.

Travertine deposits typically precipitate from CO_2 rich thermal fluids, which are cooling at *marginal* and *shallow* subsurface zones. This possibly could cause to tentatively believe that *Lake Katwe, Lake Kikorongo, Lake Kasenyi* and *Lake Nyamunuka* where travertine deposits occur, represent out flow or marginal zones of this geothermal system. This would mean tentatively that the *up-flow zone* should be traced from around Lake Kitagata-Kyemengo-Kyamatumu area, assuming this is a single geothermal system. Such a high hilly zone can have a relatively high groundwater table and an *outward directed hydraulic gradient* favouring the flow of hot fluids (through faults and permeable strata) to topographically lower areas like Katwe (895 m), Kikorongo (925 m) and Nyamunuka (884 m). This correlates well with earlier interpretation of having these outward areas as outflow of this system. The spring around Kitagata gives a subsurface temperature above 200^{o}C, which is quite impressive.

2.1.4 Kibiro Prospect Exploration (2004)

Kibiro prospect investigations were carried out by ICEIDA experts and DGSM counter parts with the aim of advancing the geothermal pre-feasibility survey initiated by DGSM. This work included geophysical studies (TEM, gravity and magnetic survey), geochemical surveys and geological mapping (Figure 3). Geothermal investigations identified some open geophysical anomalies. These open-ended anomalies warranted further work to close them.

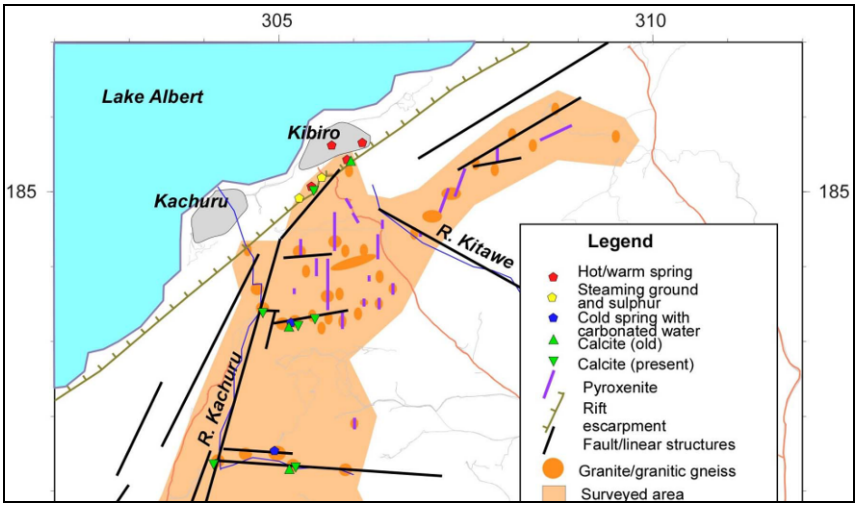


FIGURE 3: Geology map of Kibiro (ISOR)

A total of 70 TEM soundings were collected (Figures 4-8). A low resistivity anomaly was located in the sediments and a low resistivity trench was traced into the crystalline basement rocks. Magnetic surveys did not indicate any evidence of buried intrusive body. Anomalies were related to bedrock topography and do not reveal any structure. Similarly gravity surveys did not reveal any distinct density variation.

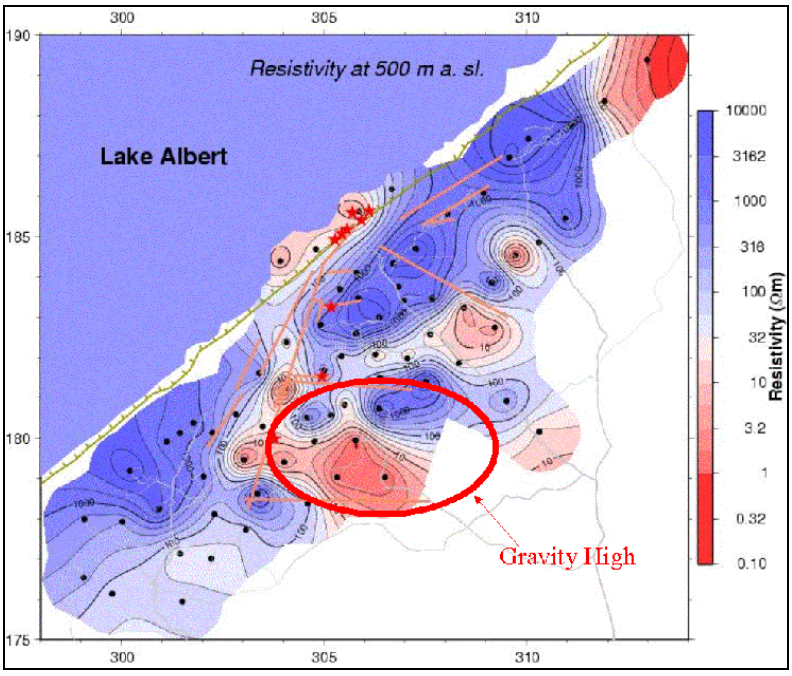


FIGURE 4: Kibiro resistivity maps (ISOR)

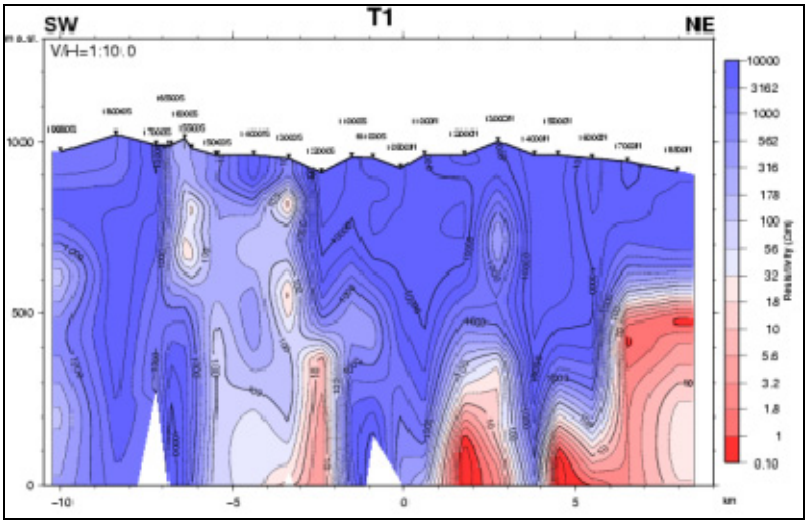


FIGURE 5: Kibiro resistivity maps (ISOR)

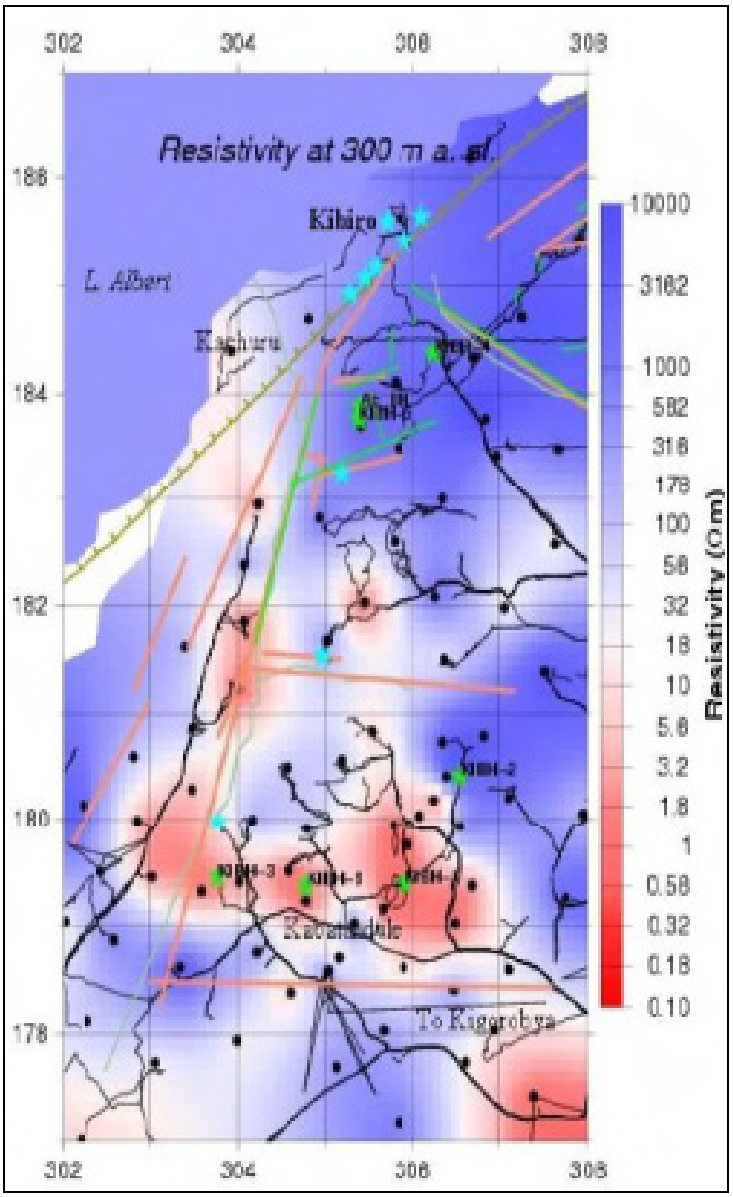


FIGURE 6: Kibiro resistivity maps (ISOR)

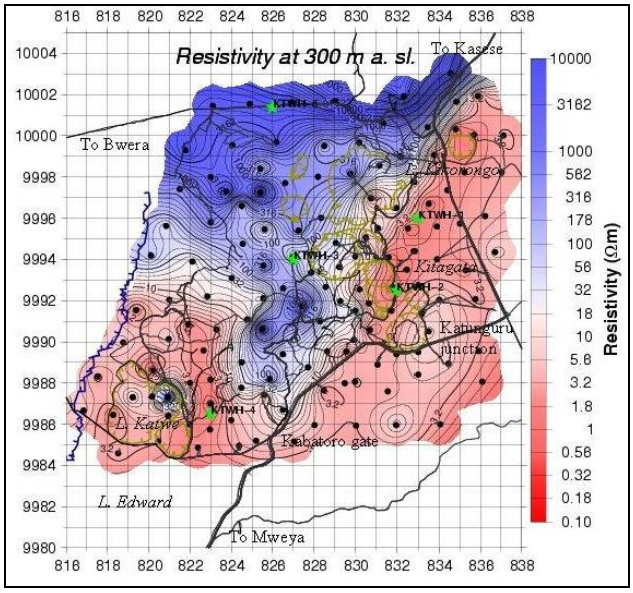


FIGURE 7: Katwe resistivity map (ISOR)

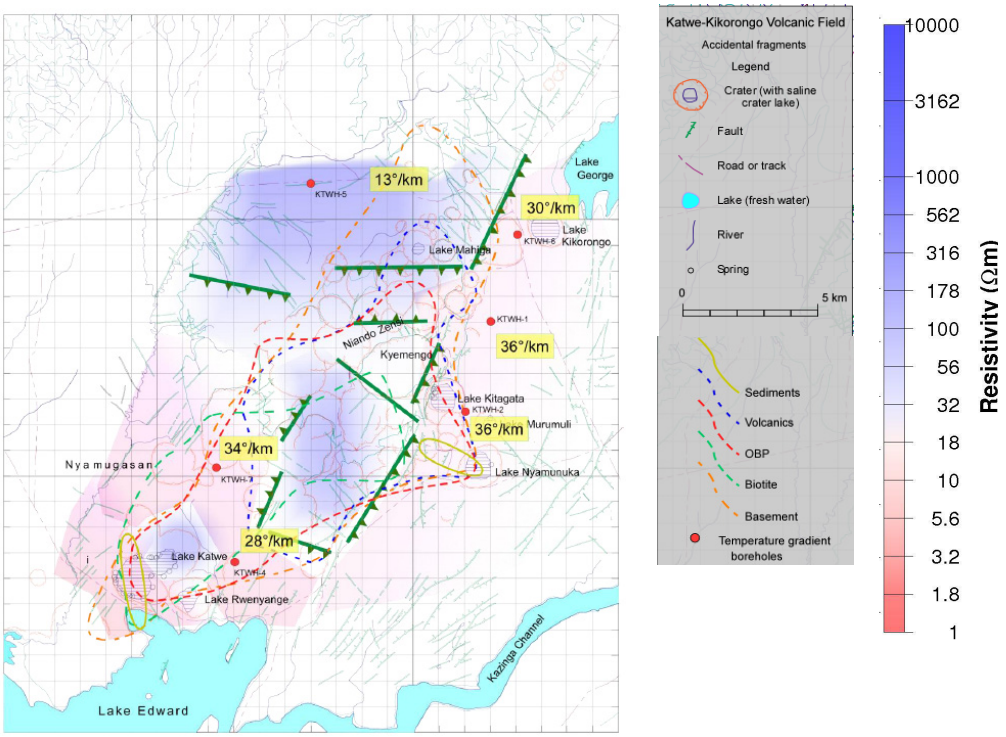


FIGURE 8: Thermal gradient map of Katwe (ISOR)

Low resistivity anomalies were subjected to drilling (thermal gradient holes) but the results were not encouraging.

2.1.5 Geotherm Project

Germany Federal Institute for Geosciences and Natural Resources (BGR) together with Ministry of Energy and Mineral Development carried out geothermal exploration in Buranga starting in 2003. The

GEOTHERM programme, was aimed at promoting the utilization of geothermal energy in developing countries. Studies included geochemical and geophysical surveys (TEM, and Schulmberger sounding). Seismometers (for micro-earthquakes) were installed in Buranga to aid in mapping active geological structures and rock types (Figure 9). A buried magma body was indicated beneath Rwenzori Mountains and the several micro earthquakes could be related to magma plumbing / diking (Figure 10). The geothermal system is recharged from the ice / glaciers from top of Rwenzori Mountain since waters from here have the same Deterium values as the hot springs. All springs around the Rwenzori are correlated pointing to a common origin.

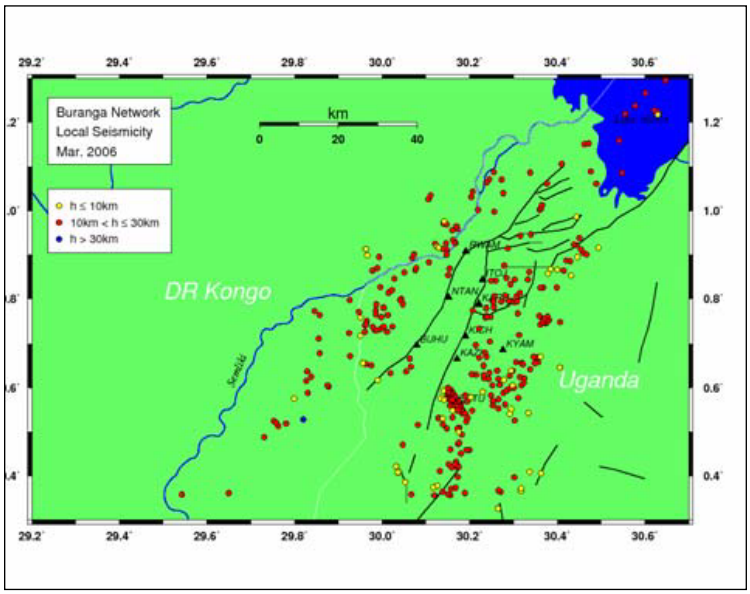


FIGURE 9: Buranga Network Local Seismicity map

2.1.6 ICEIDA-WB project.

Icelandic International development Agency (ICEIDA) together with Ministry of Energy and Mineral Development undertook exploration in Kibiro and Katwe-Kikorongo. This work included geophysical studies (TEM, gravity, magnetics, and temperature gradient measurements), geological and geochemical survey is intended to up-grade conceptual working models of these areas to pre-feasibility level. The local counterparts and their logistics were funded under Power IV. Under this programme a national geothermal reconnaissance was carried out to rank all other prospects for more future detailed investigations. Panyimur hot spring was ranked better and it was added on the list of best ranked. Swallow gradient wells were drilled in Kibiro and Katwe-Kikorongo but results were not encouraging.

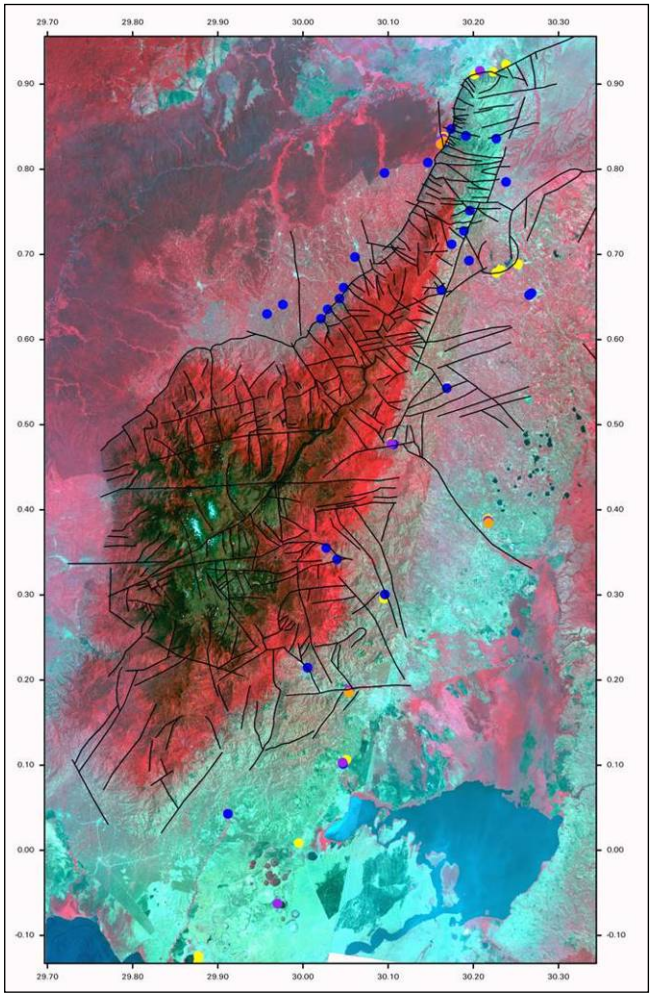


FIGURE 10: Sampling points of Rwenzori system

2.1.7 UGA/8/005 – Isotope Hydrology for Exploration Geothermal Resources- phase 2

The International Atomic Energy Agency (IAEA) funded a project "UGA/8/005 – Isotope Hydrology for Exploration Geothermal Resources- phase 2". This project was intended to refine conceptual working hydrological models for Kibiro, Buranga and

Katwe-Kikorongo prospects using isotopes. It will provide answer to questions still pending on these models.

2.1.8 Introducing Isotope Hydrology for exploration and management of geothermal resources, RAF/8/047

This project was funded by IAEA together with GoU to improve the conceptual models of the geothermal systems in Uganda.

2.2 Uganda Geothermal Resources Development Project (1199)

This project is solely funded by the Government of Uganda using public funds. The main objective was to carry out pre-feasibility study of Katwe-Kikorongo, Kibiro, Panyimur and Buranga and Feasibility study on one best ranked prospect. Under this project ground geophysical surveys (gravity and magnetics) have been undertaken in Kibiro, Panyimur and Buranga. Geological mapping has been undertaken all the four sites. Aero magnetic data was acquired, processed, analysed and interpreted. Geochemical surveys and Environmental baseline surveys have been undertaken as well.

2.2.1 Kibiro Geothermal Resource Site

Ground geophysical surveys were undertaken to define and refine the low magnetic anomalies indicated on the airborne magnetic map (Figure 11). These were believed to be related to thermal de-magnetisation of these rocks. A low magnetic signature was identified north-westwards and ground verification confirmed hydrothermally altered rocks

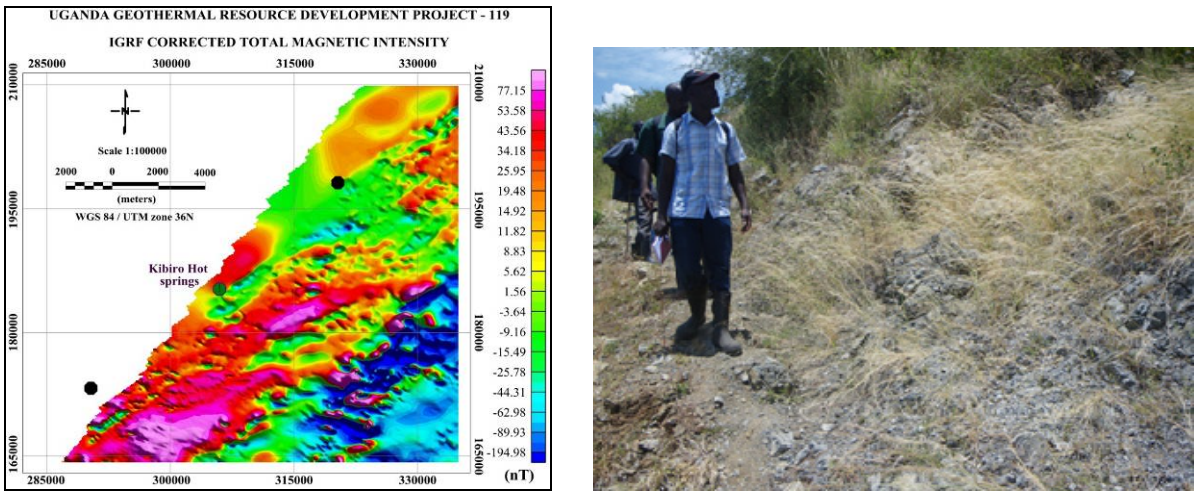


FIGURE 11: Processed and interpreted airborne magnetic map of Kibiro (left) and hydrothermally altered rocks (right)

Digital Elevation Models were prepared to aid in structural mapping. Other studies included XRD analysis of hydrothermally altered clays at Kibiro. Geological mapping was extended northwards and southwards (Figure 12). New Surface manifestations were discovered which included gypsum flakes, hydrothermally altered clays and volcanic remnants (Figure 13).

Environmental baseline survey was carried out in Kibiro. Description of natural, social and economic environment considered local community, land-use, proximity to infrastructure and housing, amenity, noise, dust, air quality, topography, landscape, climate, geo-hazards, hydrology, groundwater, flora, fauna, topsoil, subsoil, heritage (geological, cultural), proximity to conservation areas, pre-existing site contamination and previous disturbance.

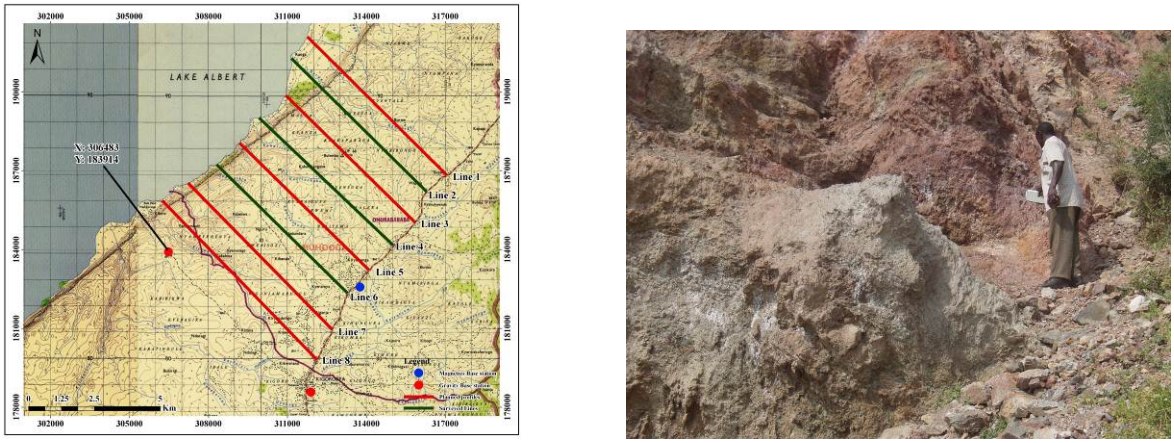
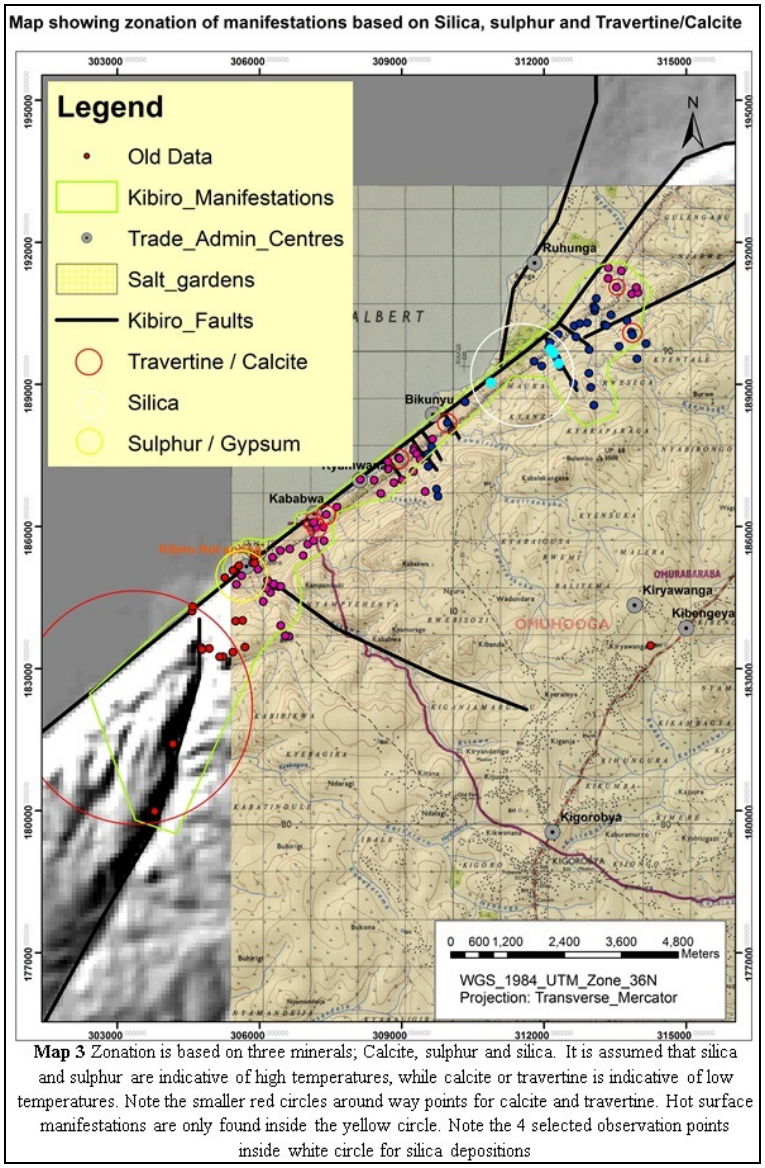


FIGURE 12: Area covered by ground geophysical surveys (magnetics & gravity) (left) and hydrothermally altered rocks (right)



Map 3 Zonation is based on three minerals; Calcite, sulphur and silica. It is assumed that silica and sulphur are indicative of high temperatures, while calcite or travertine is indicative of low temperatures. Note the smaller red circles around way points for calcite and travertine. Hot surface manifestations are only found inside the yellow circle. Note the 4 selected observation points inside white circle for silica depositions

FIGURE 13: Geology map of Kibiro

The occurrence of geothermal evidence at widely scattered localities from one end to the other is highly suggestive of the existence of large geothermal system than previously known. Planned work

includes soil gas sampling, MT and TEM surveys. Additional structural mapping and micro-seismic are planned.

There is no evidence of volcanism in this area and it is not yet clear what the source of the heat is whether it is from buried high heat producing granites or it is a swallow buried magma body. This can be confirmed by studying helium isotopes from gases or carbon-13 isotopes of the travertine at Kibiro.

2.2.2 Panyimur Geothermal Resource Site

It was discovered that diatomite are structurally controlled along *fault traces* (Figure 14 and 15). The source of silica for the diatoms is presumed to be high silica laden fluids more probably geothermal fluids. The diatoms had to flourish in a stable environment which produced *high silica laden fluids*. In the same area swelling clays were mapped interlayered with diatomite. *Diatomite* is not extensive but it is fault controlled by NE trending faults. One has to note that diatomite is more predominant in NE than in south west where the hot springs are located. This might imply that *diatomite* deposits are more proximal to the up-flow zone than the hot springs.

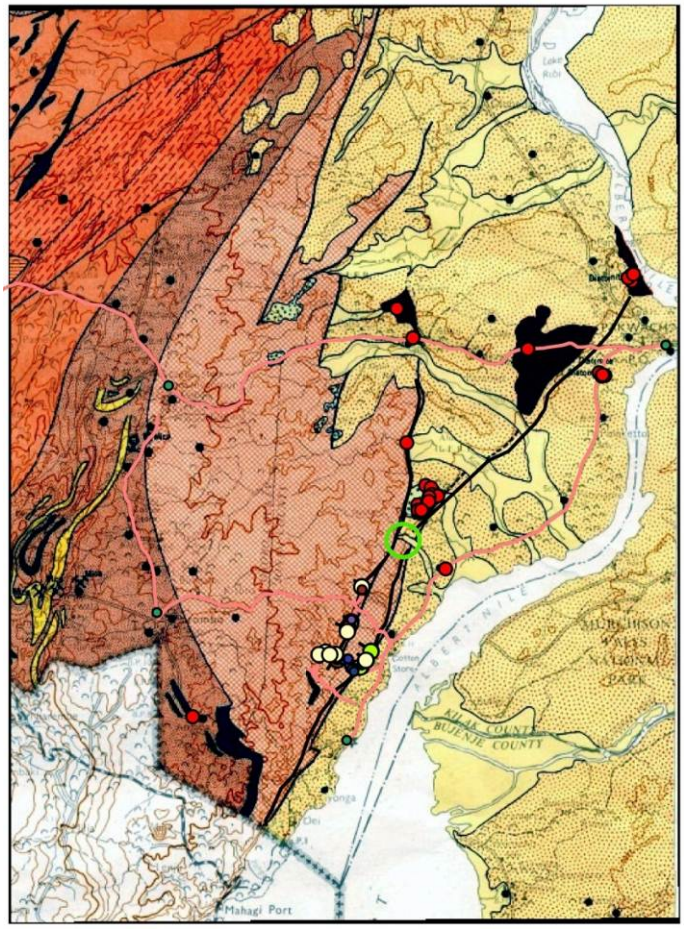


FIGURE 14: Geology map of Panyimur showing diatomite (brown colour) along fault traces

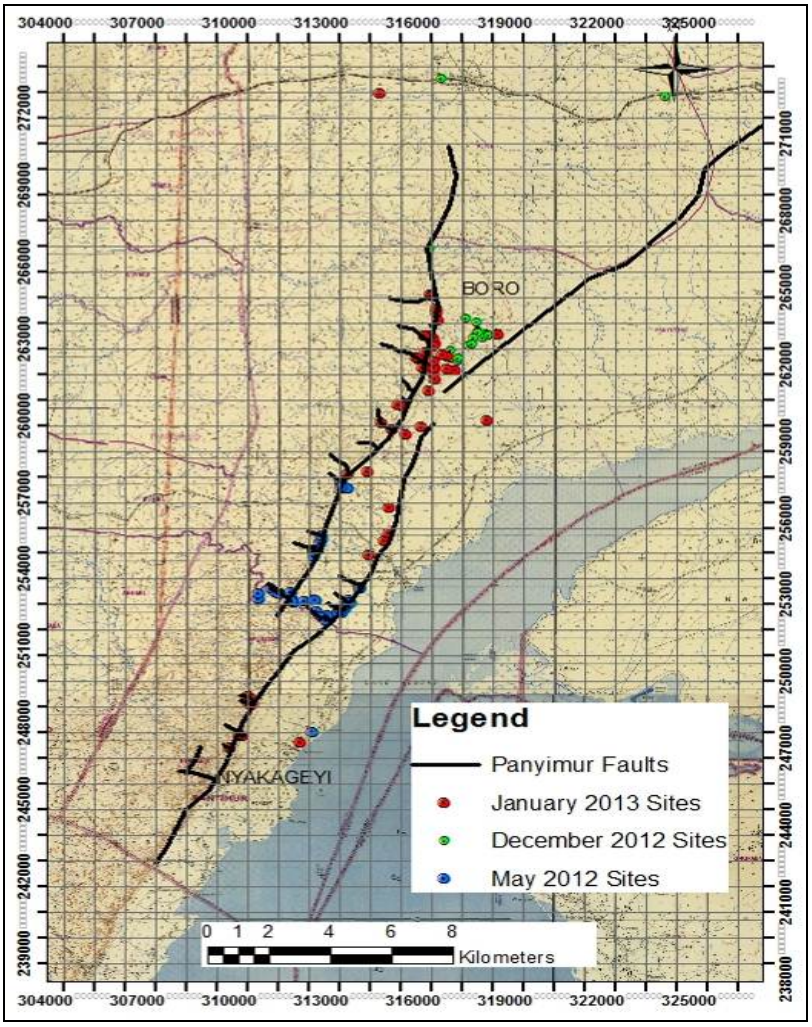


FIGURE 15: Faults acted as conduits / pathways for geothermal fluids which deposited silica rich fluids for the diatoms. These *diatomites* have elevated levels of *Zirconium* and indication of magmatic origin of these fluids

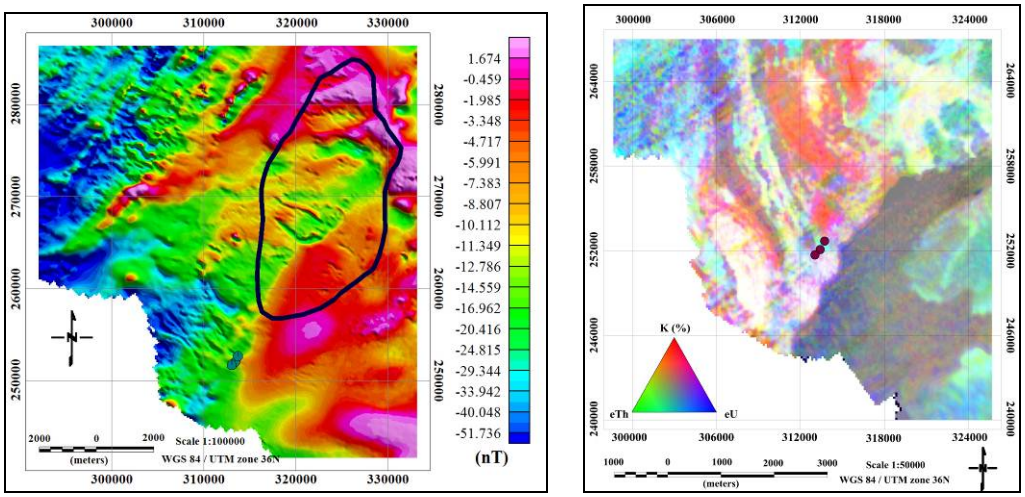


FIGURE 16: Airborne magnetic map (left) and radiometric map (right) of Panyimur

On the magnetic map, warm colours (red and purple) indicates areas with high magnetic signatures and cool colours (green and blue) indicate areas with low magnetic signatures probably related to demagnetisation by hydrothermal fluids. The linear magnetic lows are interpreted to represent fault zones. Temperatures from neighbouring oil wells indicate elevated values (Figure 16).

Digital elevation model of the area shows well marked NW-SE transverse faults cross cutting the SW-NE major fault in areas where diotomite is located (Figure 17). This increases or enhances permeability for fluids flow. Geologically, this is highly prospective area judged on the inter-play between faults and diatomite occurences which indicate existence of high silica fluids. Various maps were made for the area (Figures 18-21).

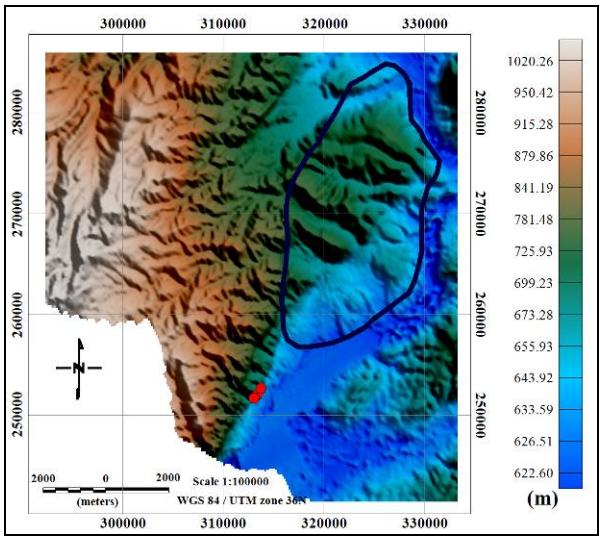


FIGURE 17: DEM map of the area showing cross cutting structures.
Red dot indicates hot springs location

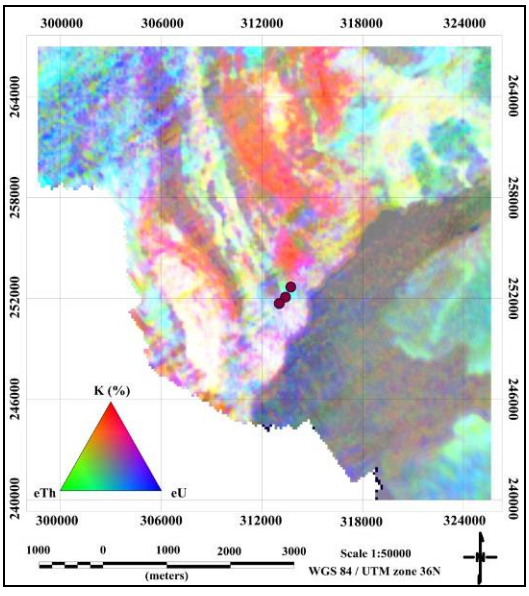


FIGURE 18: Radiometric map of the area

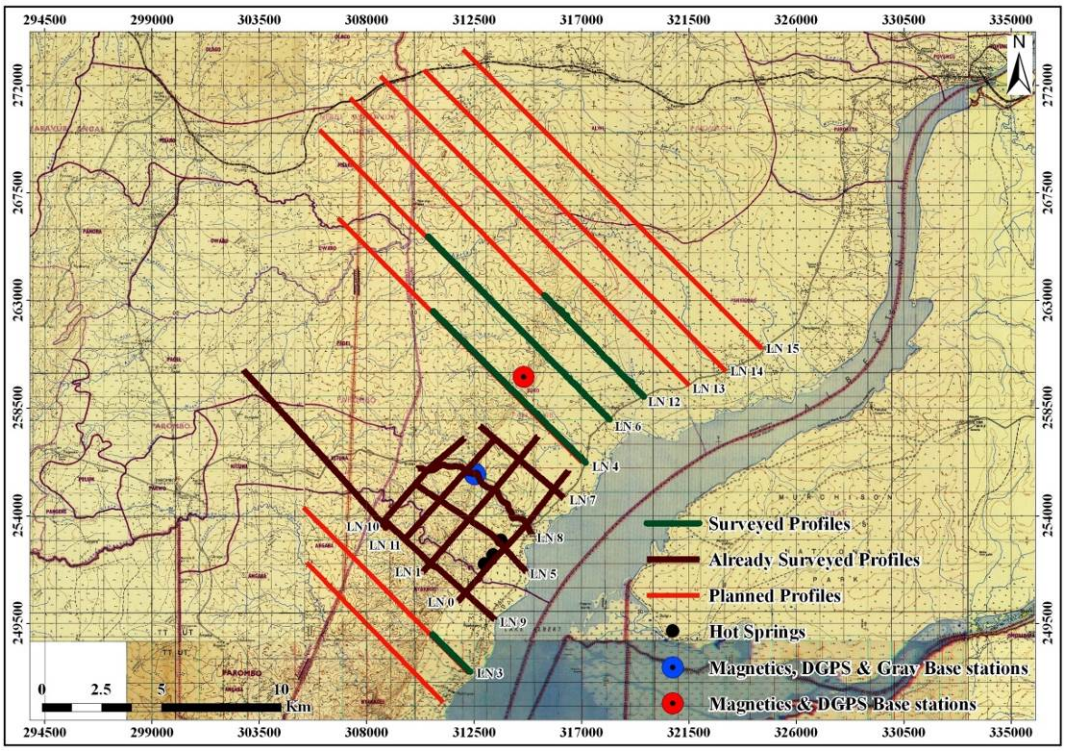


FIGURE 19: Traverse for geophysical surveying

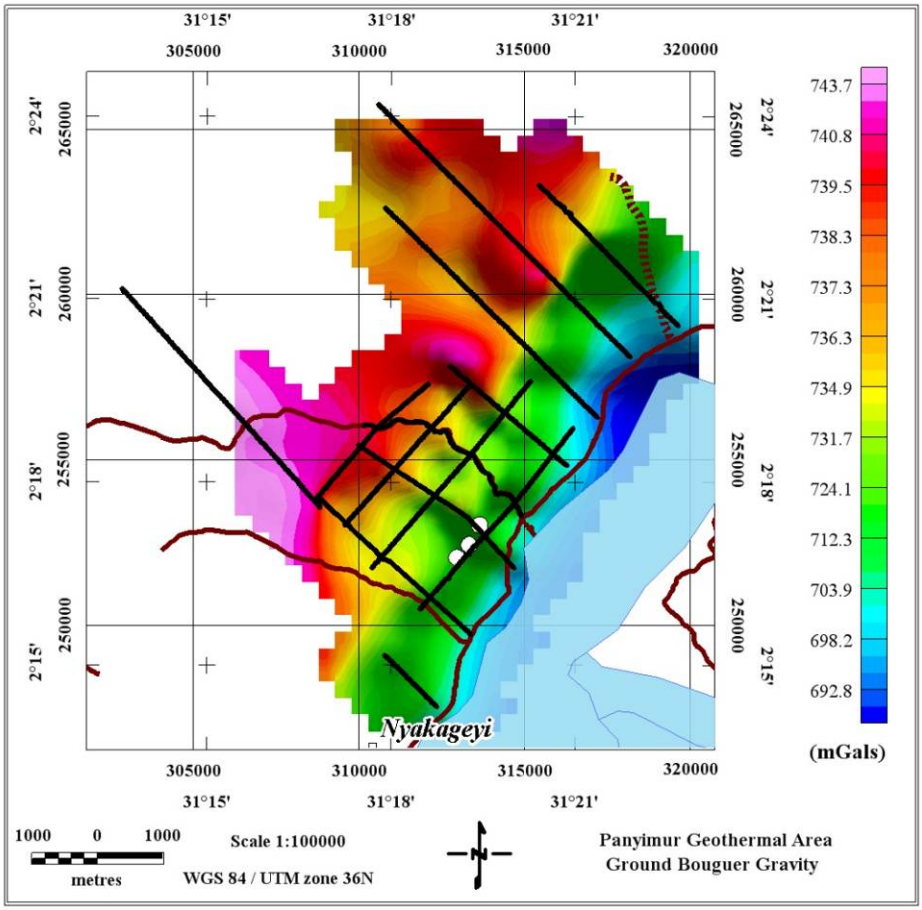


FIGURE 20: Bouguer gravity anomaly map of Panyimur geothermal prospect, brown lines denote roads and white dots are hot springs

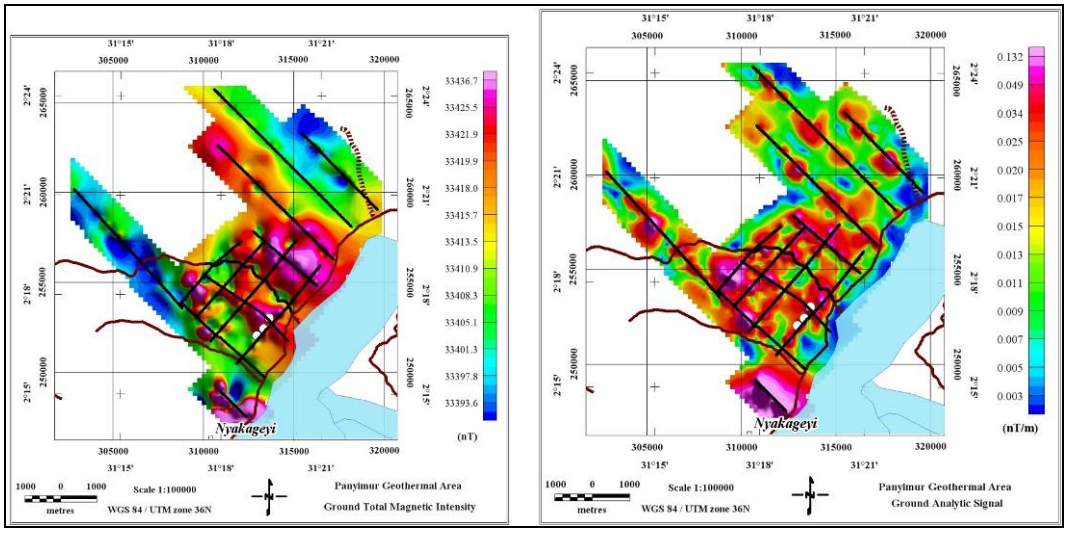


FIGURE 21: Total magnetic intensity map (b) Analytical signal map, brown ticked lines denote roads and white circles are hot springs

Ground gravity and magnetic surveys are still on-going. The occurrence of geothermal evidence at widely scattered localities from one end to the other is highly suggestive of the existence of large geothermal system than previously known. Planned work includes soil gas sampling, MT and TEM surveys. Additional structural mapping is recommended.

Structural control: Diatomites at Panyimur are aligned along faults hence are structurally controlled according to geology map of the area.

Alligned hot springs: Hot springs and hydrothermal deposits are similarly aligned along faults indicating a structural control of these features.
*Hydrothermal activity***:** Diatomites are known to be associated with hydrothermal systems deriving silica saturated waters from hot springs. This association is postulated in this particular case and is plausible.

Source of silica: Diatoms are adapted to a wide range of aquatic environments including marine, brackish and fresh waters. The organism require suitable environmental conditions if they are to flourish including appropriate temperature and photic conditions, a narrow salinity and acidic range, and a stable supply of nutrients including silica, nitrogen, phosphorous, iron, oxygen and carbon dioxide. The only plausible source of silica saturated waters and carbon dioxide in this area could have been geothermal solutions upwelling from a deep geothermal reservoir.

Exploration targets: Since near neutral alkaline solutions with high silica content are targets of most geothermal exploration, areas with diatomite deposits are highly prospective as these might be proximal to the up-flow zone of this system.

Out-flow zones: Hot springs at Panyimur deposits travertine and there is gradual change in chemistry of hot springs from south west to north east. This might indicate that they are at outflow zones which are normally associated with travertine deposits. They might be discharging at the surface after flowing many kilometers down gradient from a hydrothermal reservoir.

Prospectivity: Most promising area in north east from the hot springs characterized by diatomite and cross cutting fault zones.

There is no evidence of volcanism in this area and it is not yet clear what the source of the heat is whether it is from buried high heat producing granites or it is a swallow buried magma body. This can

be confirmed by studying helium isotopes from gases or carbon-13 isotopes of the travertine at Okumu.

- Magnetic measurements do not show indications of intrusive bodies close to the surface. Alteration to the north-east seems to be related to the bed-rock geology.

- Gravity results have differentiated the low density sediments of the blue-Nile from the denser basement rocks mainly consisting of granite-gneiss as evident on the modeled profiles.

Planned work include a combined MT/TEM survey, soil gas survey, integration of data from petroleum companies drill wells, micro-seismic surveys and additional geochemical and isotopic surveys.

2.2.3 Katwe Geothermal Resource Site

Work included studying DEM maps (Figure 22), aerial photo (Figure 23), and satellite images (Figure 24) to map structures. This was followed by ground trothing of the interpreted data.

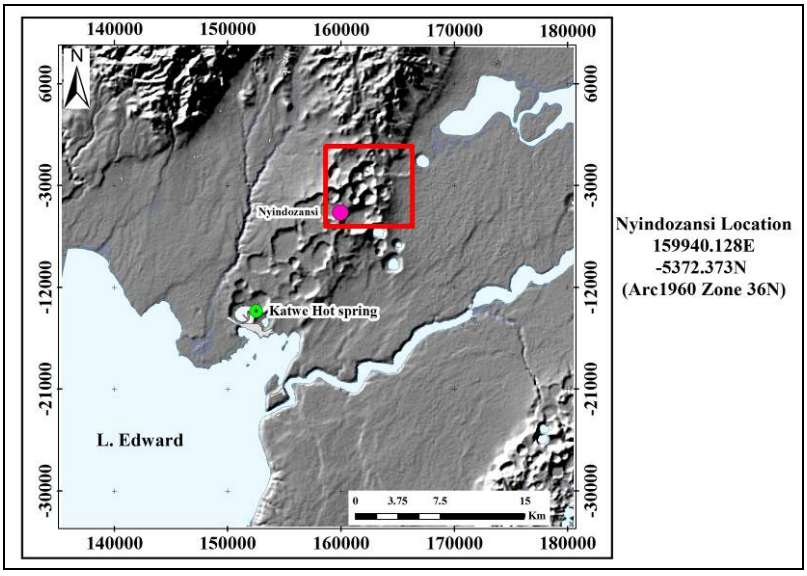


FIGURE 22: DEM map of the area showing structure and explosion crater lakes

During the Sustainable Management of Mineral Resources Project (SMMRP), airborne magnetic data was acquired over 80% of whole country. This data was retrieved and processed around the area of study. Unfortunately the area of study was not covered and hence this data was not useful (Figure 25).

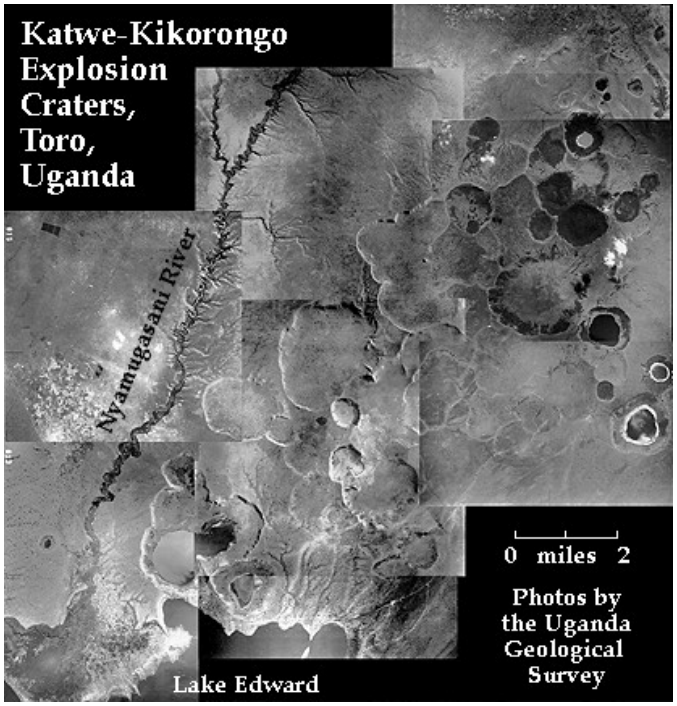


FIGURE 23: photo interpretation of the area

FIGURE 24: Satellite image of the area aided in mapping structures

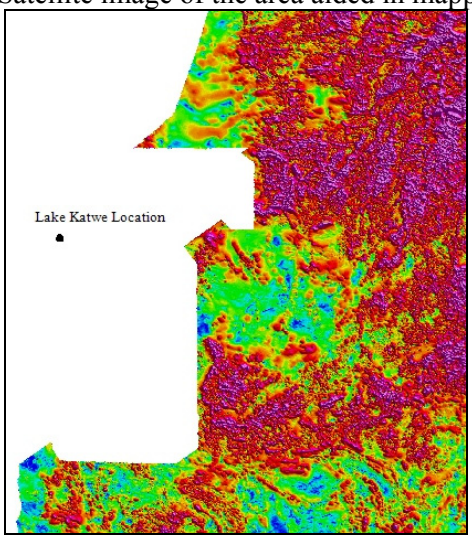


FIGURE 25: Total magnetic map of the study

During Petroleum Exploration campaign (1983-84), airborne magnetic data was acquired over the entire Albertine Graben. Aeromagnetic surveys identified three sub-basins and hence three exploration areas. Katwe-Kikorongo geothermal field lies in exploration area 3. These were very encouraging results. Total magnetic field map reduced to pole was produced for the whole Albertine Graben. This magnetic data was retrieved, processed, analyzed and interpreted. Results are shown in the airborne magnetic maps below.

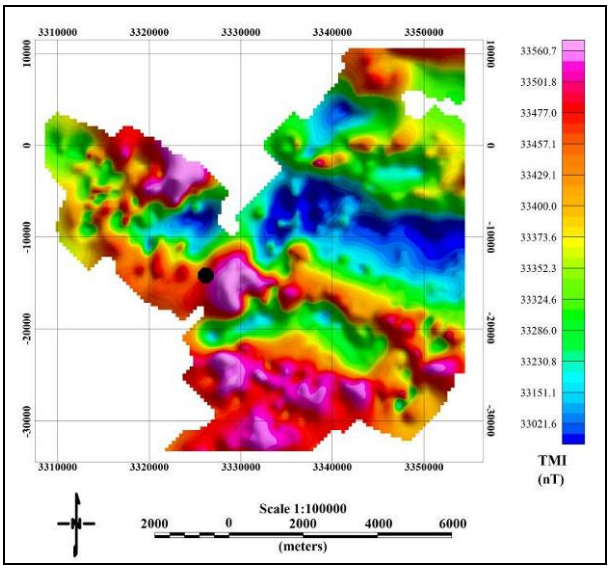


FIGURE 26: Total magnetic intensity map (PEPD data). Note the blue zone standing out with distinct magnetic characters that contrast with surrounding rocks

According to airborne magnetic map above (Figure 26), warm colors (red and purple) indicate areas with high magnetic signature and cool colors (green and blue) indicate areas of low magnetic signature. The linear magnetic lows are interpreted to represent fault zones, some of which appear to correlate with surface geothermal manifestations. These interesting low magnetic signature detected by airborne survey will be followed up with a ground magnetic survey to better define the nature and location of the anomaly. Geothermal activity may have destroyed magnetic fabric in these rocks and produced zones with lower magnetism than the surrounding rocks.

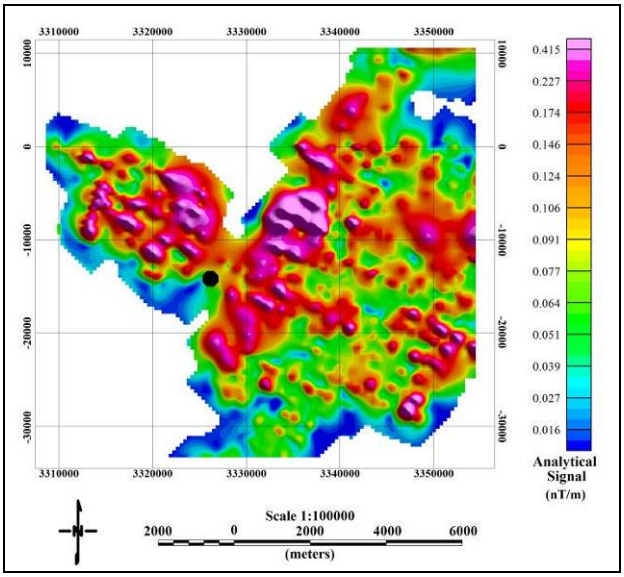


FIGURE 27: Analytical signal map (PEPD data)

The north west south east magnetic grain stand out on this magnetic map (Figure 27). It might correlate with structural trend in this area.

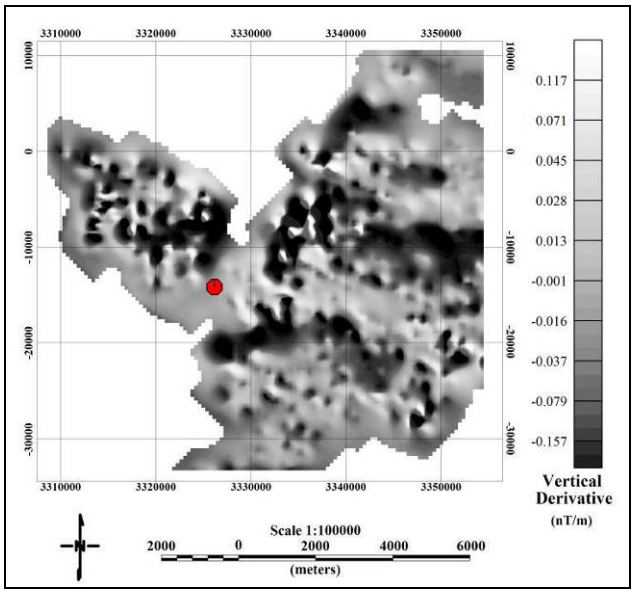


FIGURE 28: Vertical derivative map (PEPD data)

The low magnetic zone east of red dot stand out in contrast with surrounding rocks once again (Figure 28). TMI maps are used to provide a representative sample of the measured data while the AS maps are used to locate the magnetised rocks. The AS is a very good tool that can be used in differentiating the various rock types especially in complex geological situations and delineating structural trends that maybe obscured in the TMI map (Assran S. 2002; Colla 2005).

Old airborne magnetic data from DGSM archives was retrieved, processed, analyzed and interpreted. Magnetic maps are shown below.

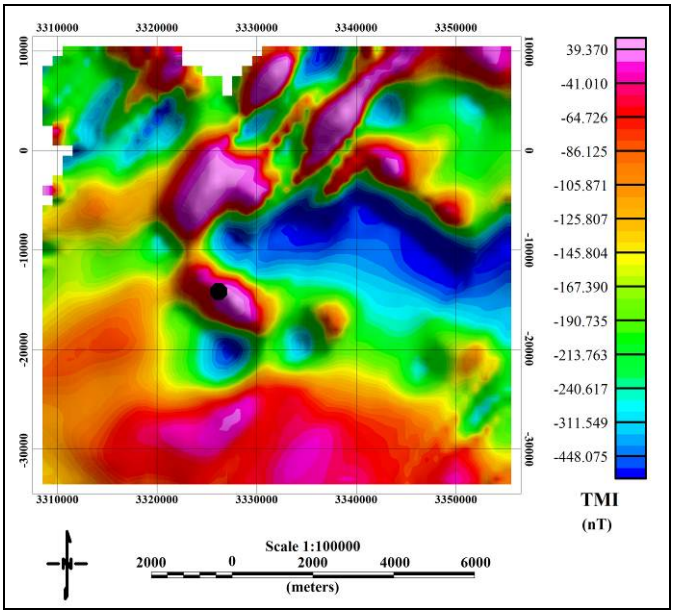


FIGURE 29: Total Magnetic intensity map (DGSM data)

According to airborne magnetic map above (Figure 29), warm colors (red and purple) indicate areas with high magnetic signature and cool colors (green and blue) indicate areas of low magnetic signature. The linear magnetic lows are interpreted to represent fault zones, some of which appear to

correlate with surface geothermal manifestations. Figure 30 and 31 show an analytical signal map and a vertival derivative map, respectively.

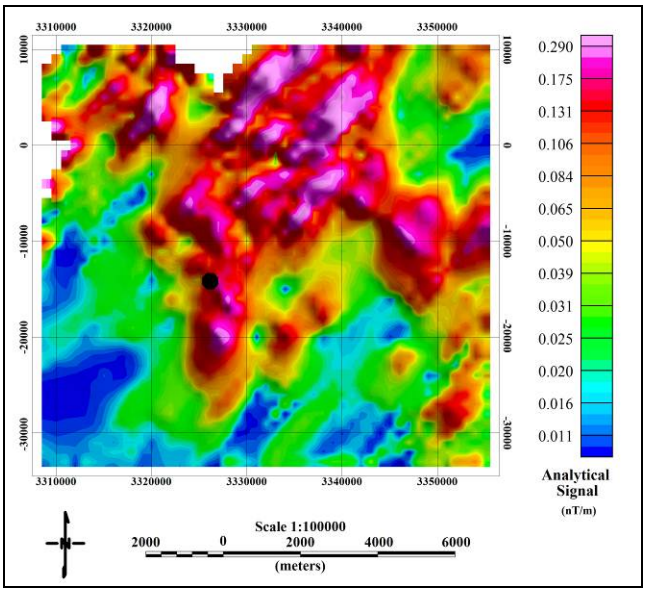


FIGURE 30: Analytical signal map (DGSM data)

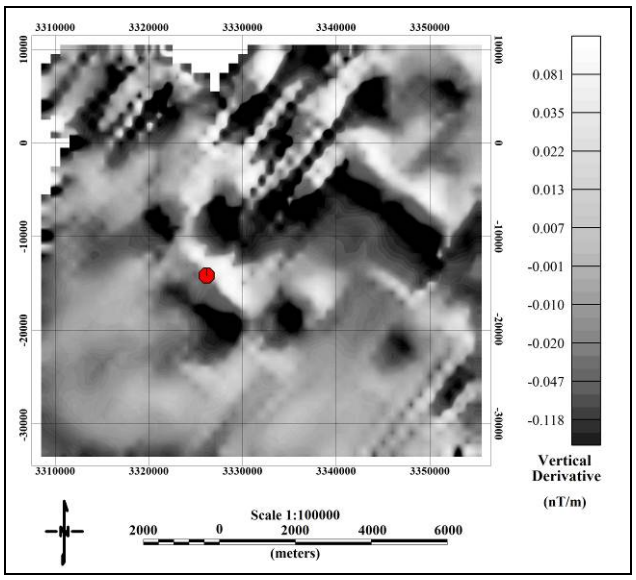


FIGURE 31: Vertical derivative map (DGSM data)

This map shows areas enriched with potassium (Figure 32). These rocks are ultra-potassic but at the same time the potassium rich zone might be due to hydrothermal alteration zone associated with geothermal activity. Katwe-Kikorongo volcano is located on the NE shore of Lake Edward. It is part of a kamafugite-carbonatite province of southwest Uganda in the western rift valley branch. Volcanic rocks at Katwe-Kikorongo volcano contain katungite, which is a potassium-rich glassy olivine melilitite tephra.

Of interest in the coincidence between two data sets indicating a low magnetic signature east and north east of Lake Katwe. It is too early to say it is related to geothermal activity but the area merit further work. Bourger gravity data of the whole Albertine Graben was acquired by PEPD from 1991 to date. This data need to be reviewed and information incorporated.

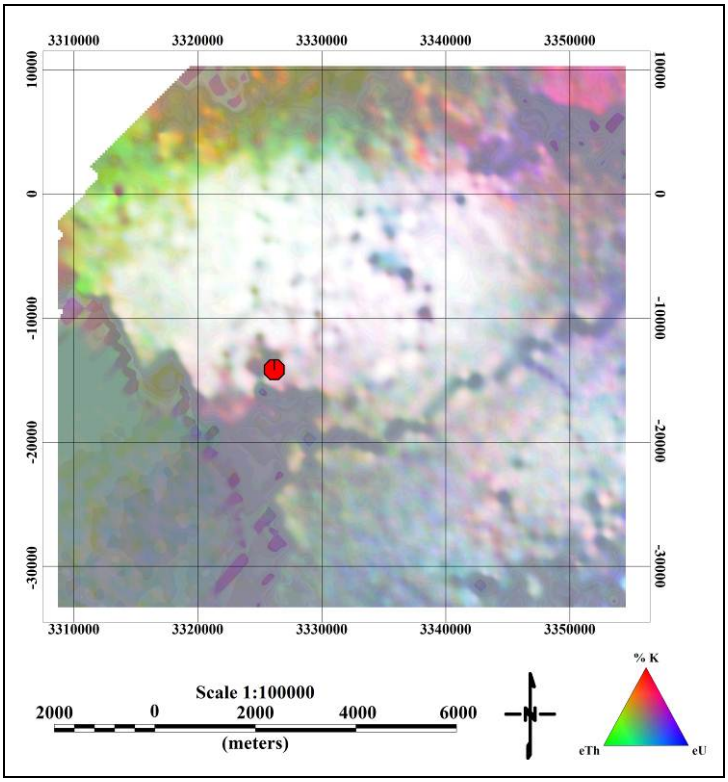


FIGURE 32: Ternary map of the area

Geological mapping has been undertaken in this area as well as environmental baseline surveys. New surface manifestations were discovered and the geothermal area is quite big as evidenced by widely scattered manifestations. Planned work includes combined MT/TEM survey, gravity, seismic, soil gas sampling, more structural mapping, geochemical and isotopic studies.

2.2.4 Buranga Geothermal Resource Site

DEM maps were prepared to aid in structural mapping of the area (Figure 33). Mapping surface manifestations was undertaken and these stretch far than previously known. The occurrence of geothermal evidence at widely scattered localities from one end to the other is highly suggestive of the existence of large geothermal system than previously known.

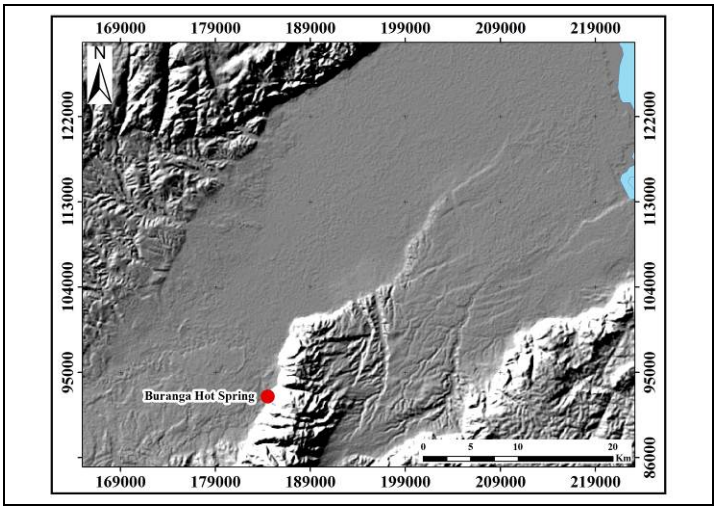


FIGURE 33: DEM map of the area

Of interest here is gas reservoir discovered during oil exploration. It is not clear whether it is of sedimentary origin of related to hydrothermal activity.

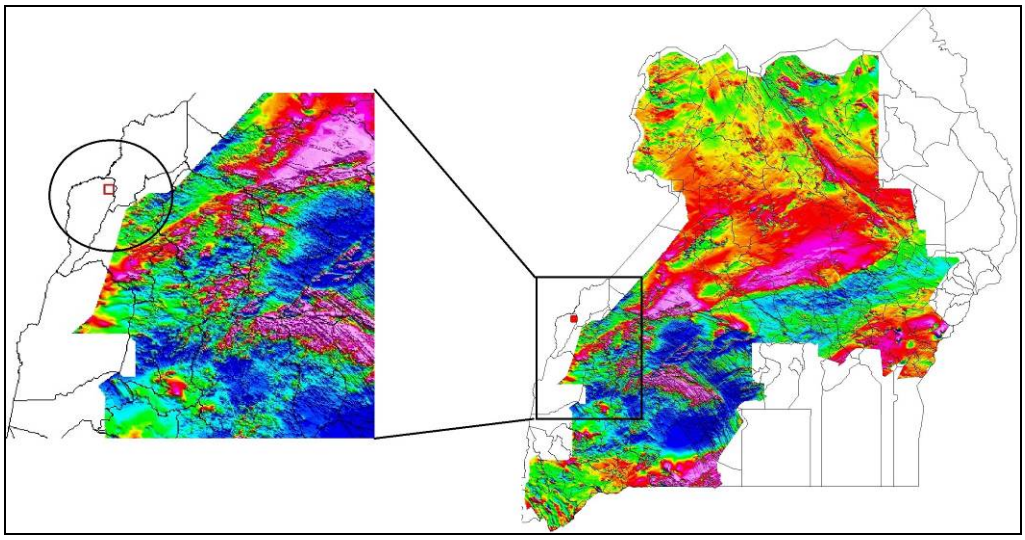


FIGURE 34: SMMRP airborne magnetic data showing Buranga in circle

SMMRP data was not available for Buranga area being near the border as well as being near high altitude Rwenzori (Figure 34). Other sources of geophysical data were considered.

According to airborne magnetic map below (Figure 35) warm colors (red and purple) indicate areas with high magnetic signature and cool colors (green and blue) indicate areas of low magnetic signature.

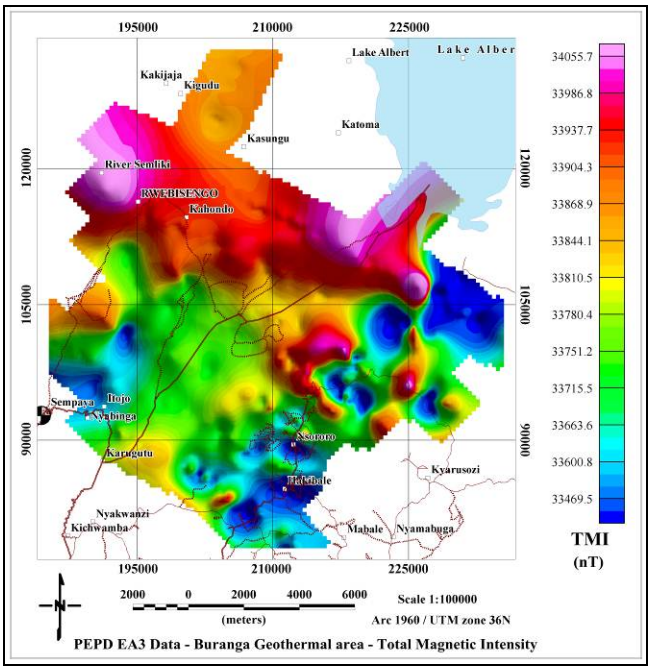


FIGURE 35: Airborne magnetic map

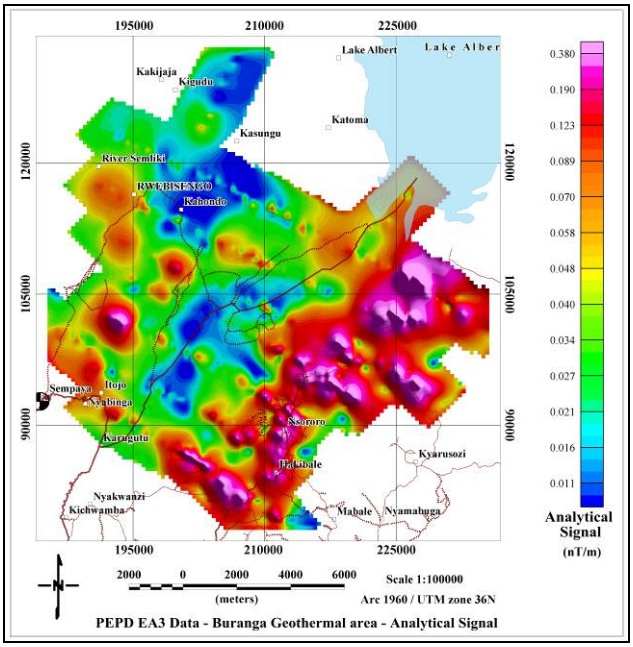


FIGURE 36: Airborne magnetic map

According to airborne magnetic map above (Figure 36), warm colors (red and purple) indicate areas with high magnetic signature and cool colors (green and blue) indicate areas of low magnetic signature.

Ground geophysical methods (magnetics & gravity) so far applied are structural and an electrical method (MT, TEM) should be applied to locate the conductive reservoir. MT surveys can be used to locate high conductivity associated with geothermal reservoirs at depth 2-5 km.

2.3 Jica technical programme

In 2010, JICA undertook a situation analysis study of geothermal development in Africa including Uganda. Following this situation analysis, JICA and Ministry of Energy and Mineral Development are undertaking a joint venture technical study of Uganda's geothermal resources. The preliminary survey is being implemented by West Japan Engineering Consultants Inc. and Mitsubishi Materials Techno Corporation. Seventeen geothermal resource sites were sampled for geochemical surveys. These included Kagamba, Karungu, Bubaale, Kiruruma, Ihimbo, Kanyinabalongo, Rubaare, Kitagata, Minera, Rubabo, Kizizi, Biarara, Rwimi, Kibenge, Muhokya, Rwagimba and Bugoye-Ndugutu. On ground verification of interpreted satellite data was undertaken as well as preliminary geological mapping. Satellite images used included LANDSAT/ETM+ and SRTM/DEM, ASTER, and ASTER/GDEM. The main objective of this study is to locate a prospective site for possible further technical assistance from JICA.

This study was conducted to obtain fundamental information to consider the future contribution by JICA to geothermal development in Uganda. For this purpose, the previous study by JICA (Situation Analysis Study on Geothermal Development in Africa, 2010) will be updated through this study, collecting the latest information about situation and condition of geothermal development in Uganda. In this study, hot spring water and rock samples were collected and are being analyzed for detailed consideration about geothermal potential in Uganda.

2.4 African Rift Geothermal Development Facility (UNEP-Argeo Project)

The Uganda Government submitted a proposal to UNEP in 2011 for technical and financial assistance in order for the Government to undertake surface exploration studies in the Kibiro geothermal resource site. This proposal was prepared in 2011 for which UNEP supported the activity through its consultant. However, the Government of Uganda has undertaken more studies in Kibiro. The data was reviewed by Department of Geological Survey and Mines and UNEP Consultant. Data gaps were identified for future exploration work. The Government of Uganda has re-submitted a proposal to for a prefeasibility study in Kibiro geothermal resource site.

2.5 Mou between the Governments of Uganda, Rwanda and Kenya For exploration and development of geothermal resources

During the last Regional Integration Projects Summit held in Kigali, Rwanda on October 26-28, 2013 the Heads of State directed that a Memorandum of Understanding be finalised and signed before the next summit. In this arrangement the Government of Kenya represented by Geothermal Development Company Limited will be a "Consultant" while Uganda and Rwanda will be "clients".

2.6 Human Capital Development

Several trainings have been undertaken to build a geothermal industry work force with the skills and capacity necessary to enable the rapid development of the industry. These trainings are being conducted at UNU-Iceland, GDC-UNU Naivasha Kenya, West Jec Japan and SEVERAL In-house training seminars. In addition staffs have attended several workshops.

2.7 Geothermal insitution

One of the counter measures to the barriers of geothermal development in Uganda is institution building. This involves intensive capacity building. There is urgent need to have a standalone state-run institution for administration and management, with professional and technical capacities to steer development of geothermal energy in Uganda. This institution must have a budget and logistics. Investigating geothermal sources requires a specialized team, approach, equipment, processing software, and oversight. The Ministry is working with the industry to identify the industry's knowledge gaps in areas of policy, legislation, engineering, science and environment and provide education opportunities to fill those gaps.

The Government of Uganda has restructured the Ministry of Energy and Mineral Development and is in process of establishing a Geothermal Resources Department. Procuring of several survey equipment and software has been initiated.

2.8 Legal and regulatory framework

Cuurently geothermal development is administered under the Mining Act (2003). Lack of legislative and regulatory regimes have constrained effective and efficient permitting and licensing of geothermal exploration companies. Private companies are not willing to come in without legal and business security. It is not easy also to regulate existing exploration programs. There is need to have an action plan for developing and drafting geothermal law. A white paper has been drafted for Geothermal Energy Act.

2.9 Data base management

Data acquired has to be managed if it is to be useful in driving geothermal development in Uganda. DGSM has embarked on developing databases to house all geoscience data relevant to geothermal exploration. DGSM will expedite building the necessary databases and packaging of data for dissemination across the industry. DGSM is also working with UNEP-ARGeo facility in establishing regional data bases.

2.10 Private vs public funding

Since the grant of the first Geothermal Exploration Licence on 12th February 2011, several Geothermal Exploration Licences have been granted and the total number is as of now ten (10). For Geothermal Energy, the associated high risks and costs of proving the resource is one of the key barriers facing the industry. In developing countries like Uganda which lack the required financial and skilled human resources, a combination of both private and public funding may be required along with significant support from both national and international funding agencies (bilateral and multilateral). This support funding may come through grants, loans, or risk mitigation strategies. An application has been submitted to Geothermal Risk Mitigation Facility at African Union.

Due to extremely high risk and costs associated with geothermal exploration, it is difficult to attract sufficient funds from private sector equity investors. Therefore government of Uganda has to play an important role in financing early phase of exploration. Government has demonstrated a strong will towards geothermal development.

3. CONCLUSION

a. **Exploration phase**: Uganda is at exploration phase of geothermal development at Katwe-Kikorongo, Buranga, Kibiro and Panyimur. At other geothermal resource sites studies are at Preliminary phase.

b. **Aeromagnetic data**: Processing and interpretation of aeromagnetic data is cost effective in the contest of survey objectives and budgetary constraints. This should be done prior to initiating expensive and lengthy exploration methods.

c. **Magneto telluric MT Method**: Geothermal exploration currently needs breakthrough geophysical techniques which include indispensable Magneto-telluric surveys (MT) in order to fast track exploration timeline. So far the geophysical methods (gravity and magnetics) used are structural in nature. Other surface geoscience studies like geological mapping will not provide sufficient confidence for a drill target. We urgently need an electrical resistivity / conductivity survey method to breakthrough and generate sufficient exploration data which can image the sub-surface and aid in locating drill targets.

d. **Geothermal Institution**: There is urgent need to have a stand-alone state-run institution for administration and management, with professional and technical capacities to steer development of geothermal energy in Uganda. This institution must have a budget and logistics.

e. **Human Capital Development**: One of the counter measures to the barriers of geothermal development in Uganda is institution building. There is need for intensive capacity building.

f. **Public Funding**: Due to extremely high risk and costs associated with geothermal exploration, it is difficult to attract sufficient funds from private sector equity investors. Therefore Government of Uganda has to play an important role in financing early phase of exploration.

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Presented at *Short Course VIII on Exploration for Geothermal Resources*,
organized by UNU-GTP, GDC and KenGen, at Lake Bogoria and Lake Naivasha, Kenya, Oct. 31 – Nov. 22, 2013.

GEOTHERMAL EXPLORATION IN ERITREA STATUS REPORT AND DISCUSSION

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ABSTRACT

Harnessing the geothermal potential in Eritrea has a significant impact on the economic development of Eritrea as the country relies its electric power generation from imported refined petroleum products, which is wholly based on oil burning plants. The impact can be viewed both the unreliable cost fluctuation mainly increment of fuel cost coupled with the unfriendly environment. Therefore geothermal energy will have an important input in alleviating expenditure on foreign currency while safeguarding the environment. The tectonic setting and geological makeup of the south-eastern coastal zone of Eritrea is a favourable site for having geothermal resources that are potential for the development of geothermal resources mainly for electrical generation and geothermal utilization. Alid and Nabro-Dubbi fields are the notable places with ample geothermal manifestations. There are considerable low temperature-thermal springs potential for recreation spas, health and mineral water bottling, and etc, occur at around the Asmara-Massawa highway, close to Gulf of Zula and within the Danakil Depression, which mostly do not show any immediate association with recent magmatism. The completion of some of the surface studies on Alid prompts here to concentrate on the recent work performed. A more than 2500°C reservoir temperature was estimated using gas geothermometers from Alid geothermal prospect. As recommended from earlier studies, a geophysical assessment was to define the recently an assessment of fracture analysis was conducted since geothermal reservoir is stored in some favourable geological structures. Thorough assessments of Rose diagram and fault and fracture (FFD) analyses have been performed to know areas of up-flow zone. A 70°N trending high fracture zone is well marked on the FFD contour plot. The low resistivity anomaly of the preliminary resistivity survey conducted on the Ghinda-Darere is in line with the contour plot. The hydrogeological assessment performed regionally indicates that the recharge area is mainly from three catchments mainly the input is from highland area. The resistivity survey that was conducted recently has availed an interesting anomaly at the rift floor and opened a wider perspective in exploration.

1. INTRODUCTION

Geothermal energy has become an important energy option both for heating and power generation. This lies mainly on its impact to the environment. Since Eritrea lies within the African rift system, the potential of having a geothermal energy for the use of electric is high. The advantage of geothermal energy resource for Eritrea is not only based on its environmental impact but also mitigates the use of fossil fuel, which the country has spending on hard currency. For this reason, the government has given priority to this sector and investigation is still commencing. The tectonic setting and geological make-up of the southern coastal zone of Eritrea shows that it has good potential for the development of geothermal resources. Surface manifestations are abundant on some of the Danakil zone mainly associated with volcanic activities of which the Alid and Nabbro-Dubbi fields of geothermal manifestations are prominent.

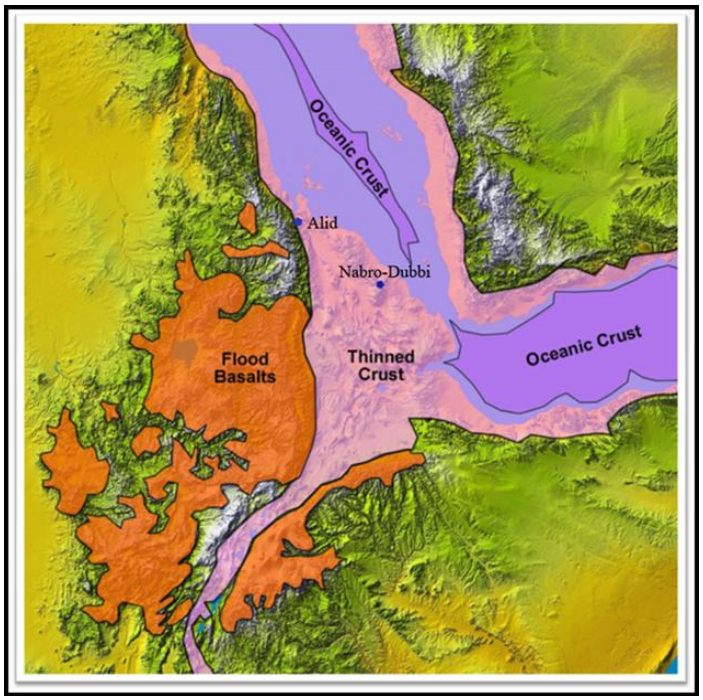

FIGURE 1: Location map of Alid and Nabro-Dubbi in relation to the African Rift Valley

Since the most expeditious progression to power development can be achieved at Alid due to the completion of some of the essential surface studies there, showing the good possibility for resource development, the report here concentrates mainly on recent studies carried out on Alid.

1.1 Previous studies

Previous works are mainly concentrated on the law temperature hot springs and Alid Volcanic center. Angelo Marini from the Italian Institute for Military Geography in 1902 during Italian colony initiated a preliminary study on Alid geothermal manifestations (Marini, 1938). Subsequent decades, however no documented studies on geothermal exploration commenced till 1973, when UNDP sponsored work was done a reconnaissance survey by a Geological Survey of Ethiopia team (UNDP, 1973). At first they located thermal springs along the Asmara-Massawa road and in the Gulf of Zula area south of Massawa. A second one launched from the south during the same year visited some of the fumaroles that occur on Alid volcano. In 1992, the late Prof. Giorgio Marinelli and a staff member from the Department of Energy visited Alid area and prepared proposal for detail study. The Ministry of Energy and Mines refined this proposal later. This laid the basis for the Geological and geochemical studies carried out in the area. In 1994, Mikhail Beyth of the Geological Survey of Israel surveyed the Alid hydrothermal area for the possibility of epithermal gold deposition (Beyth, 1996).

The only detailed geological and geochemical investigation work was that carried out at Alid and its surroundings during January and February 1996, by a team of staff from the United States Geological Survey (USGS) and the Ministry of Energy and Mines of Eritrea (MEM). The work was financed by USAID and the team led by Robert Fournier of the USGS (Clynne et al., 1996). A high temperature reservoir is estimated below the surface of Alid volcanic centre, as the geothermometry analysis of gas samples depicted. A two phase conceptual model, a vapour dominated at the base and steam

dominated at the top was proposed through reinterpreting the water and gas samples of the 1996 USGS-MEM data (Yohannes, 2004).

A fault and fracture analysis was performed on Alid dome in 2005 and found out three structural trends that influence the geothermal fluid path (Yohannes et al, 2005 or Yohannes, 2007). Based on the result of the structure a shallow resistivity profiling conducted on the small locality from Ghinda to Darere (Goitom et al, 2005). But a comprehensive resisitivity survey was conducted recently on the Alid dome and adjacent rift floor mainly MT and TEM methods. Hydrogeological assessment on catchment basis also carried out in 2005 to have a better understanding on the ground water flow in the area (Teklesenbet et al., 2006). In 2008 an MT/TEM resisitivity survey was implemented with the sponsorship of ICEIDA (Icelandic International Agency) in Alid depicting an anomaly at the rift floor (Eysteinsson et al, 2009). However no anomaly zone was depicted on the hill top due to lack of rod penetrating on the hard rock.

2. REGIONAL TECTONIC SETTING

The East African Rift is a zone of crustal extension, in which part of the eastern African continent; Somalia Plate is pulling away from its parent; African plate along one arm, separating the divergent blocks that stem from the Afar triple junction. The Afar Depression or the Danakil Depression is a plate tectonic triple junction, where the spreading ridges that are forming the Red Sea and the Gulf of Aden emerge on land and meet the East African Rift. The western margin of the triangle extends to the Red Sea, while the south-eastern part extends to the Gulf of Aden off the Arabian Peninsula. The growth of the Danakil depression can be viewed in two phases of development. The continental rifting phase marks the change of volcanics from undersaturated trap series basalt to the transitional basalts and associated peralkaline silicic of the rifting phase. The crustal separation phase of the Danakil tectonic development commenced at about 4 to 3.5 Ma, which eventually gave rise to the present day configuration of the Afar Triangle.

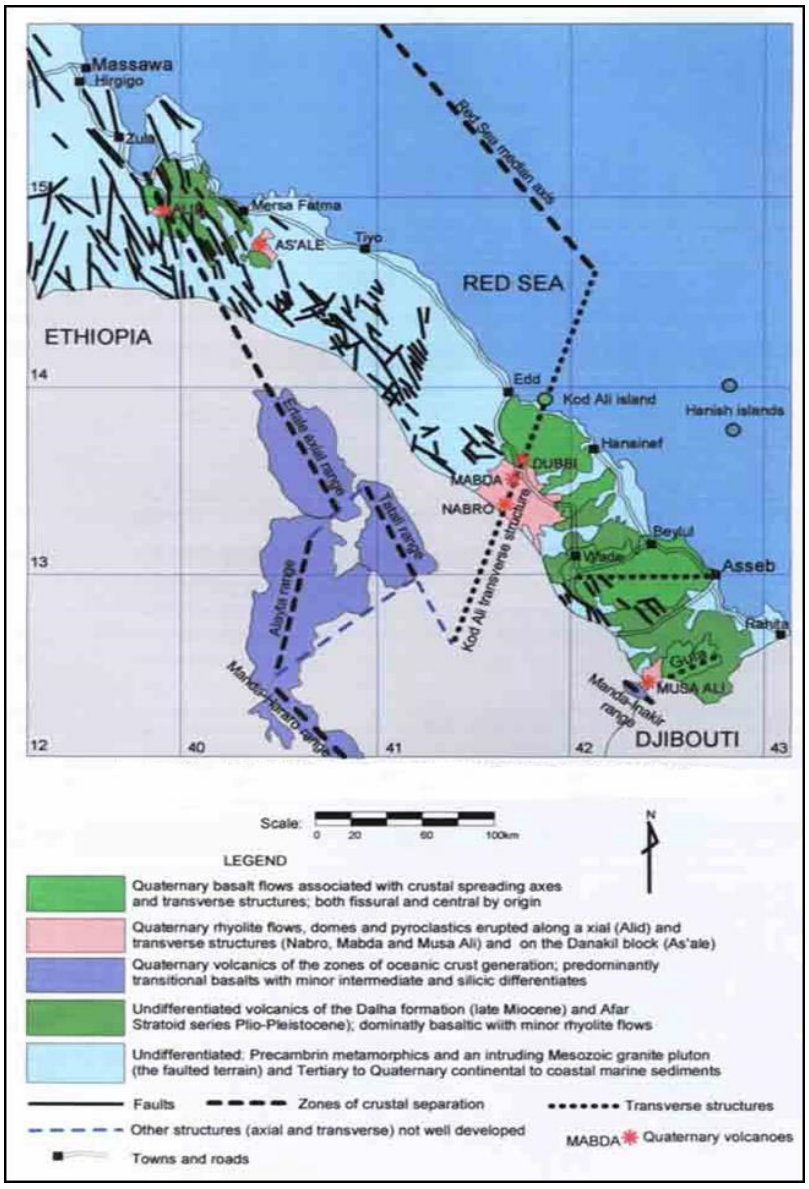

FIGURE 2: Regional geological map of the Danakil Depression

Crustal opening was initiated at the end of the continental rifting phase of the tectonic development of the Afar region during the late Miocene (22-15 Ma), however the main volcanic activities took place at Danakil block at about 4-3.5 Ma. The Alid volcanic centre is located right on the axis of the Danakil Depression in between the Red Sea and the Afar triple junction; whereas the Nabro-Dubbi is situated within the triangle along the line that extends NNE to Kod Ali (Figure 2). Much of the rift consists of down-dropped crustal sections, bounded by deep-rooted normal faults (forming grabens) that cut into the basaltic lavas, extruded in the resulting.

The two volcanic centres are separated by a Danakil Horst, where a Proterozoic metamorphic rocks and Mesozoic sediments are exposed.

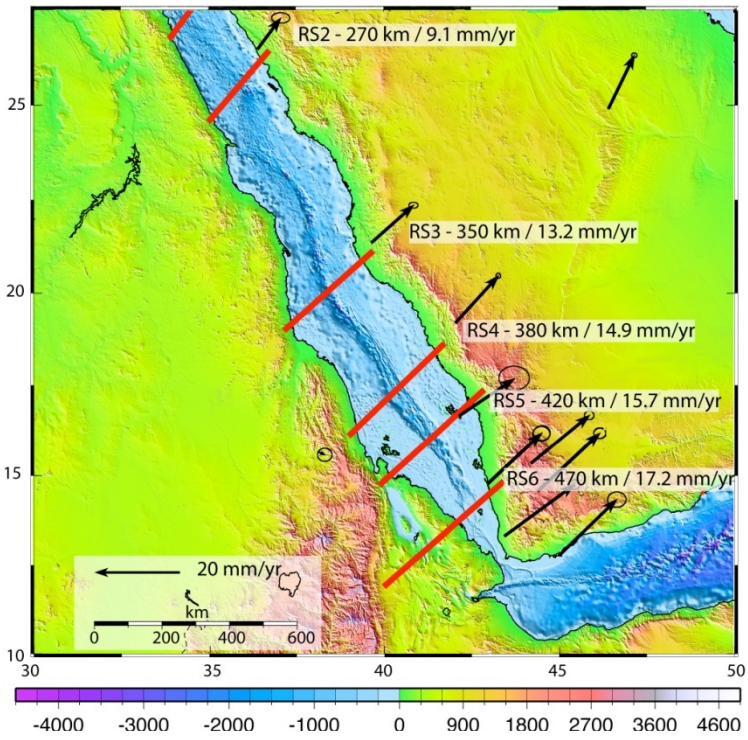

FIGURE 3: Motion of crustal segments from continuous GPS reading showing different displacement rating

Recent studies on present day movement of plates close to the Red-Sea shows that the plates move in segments i.e., there are more spreading centers or axes. This will reinforce the positioning of active zones that will in turn important in delineating the geothermal resource areas. The Danakil depression and possibly the Nabro-KodAli transverse structure could be centers of crustal spreading deciphering from the relative motion of plates (Figure 3).

3. GEOLOGICAL AND GEOTHERMAL SETTING

The suitable tectonic environment of the Danakil Depression subordinated by recent magmatic activities favour a high heat flow on the upper zone of the crust. Consequently several places of surface manifestations of high temperature fields associated with recent magmatism and low temperature hot springs related with no recent magmatic activities occur on Danakil depression and escarpment of the Red Sea.

3.1 Surface manifestation of high temperature zone - Alid volcanic centre

Regionally the Alid volcanic centre is located within the axis of Danakil depression that extends NNW from the Afar triple junction on the graben trace of crustal spreading centre consists of rifted and faulted young deposits of sediments and basaltic flows. Metamorphic complex to the west and basaltic flows forming plateau to the east shoulders the plain.

3.1.1 Geological setting

Alid is a very late-Pleistocene structural dome formed by shallow intrusion of rhyolitic magma, some of which vented as lavas and pyroclastic flows. It is characterized by large-scale rhyolitic volcanism associated with E-W extension. The continuous extension, subsidence and volcanic activities

influence the geological structure of the area. The volcanic succession of rhyolite and basalt are extruded following the NNW fault system of the rift but extended its ellipse towards ENE.

The Alid volcanic centre consists primarily of rhyolite both as massive and as pumice deposits, olivine basalt, and Red Series sediments (Figure 3). Volumetrically the rhyolite and olivine basalt are most abundant. Although volcanism culminated with fissure flows of basaltic lava on adjacent areas, the youngest eruption on the dome is the rhyolite, which dated for about 33 thousand years.

Red series sediments are conspicuous at the side and top part of the dome. It contains gypsum layers within the bed. Shouldering effect of the rhyolite emplacement tilts it at the hillside. Olivine basalt occurs mainly at the top of the dome. The olivine concentration varies from place to place but is generally present abundantly. However weathering is pervasive on olivine. Ignimbritic flows are only confined within the caldera for thin circular pattern surrounding the volcanic centre.

Vitrified flows occur in some places within the rhyolite. Thick pumice deposit is the characteristic feature of this dome. It extends for about 70 m thick. Both white and red collared, and various size fractions occur within the strata. Isolated granite boulders are also found elsewhere within this unit. Pumice covers the plateau portion of the mountain. Roof pendants of kyanite schists expose close to Illegedi. Some of the Illegedi geothermal manifestation occurs in this rock type.

3.2.1 Geothermal setting

Hot mineralized fluids discharge from many location within the Alid volcanic centre, of which most of the manifestations discharge boiling fluids

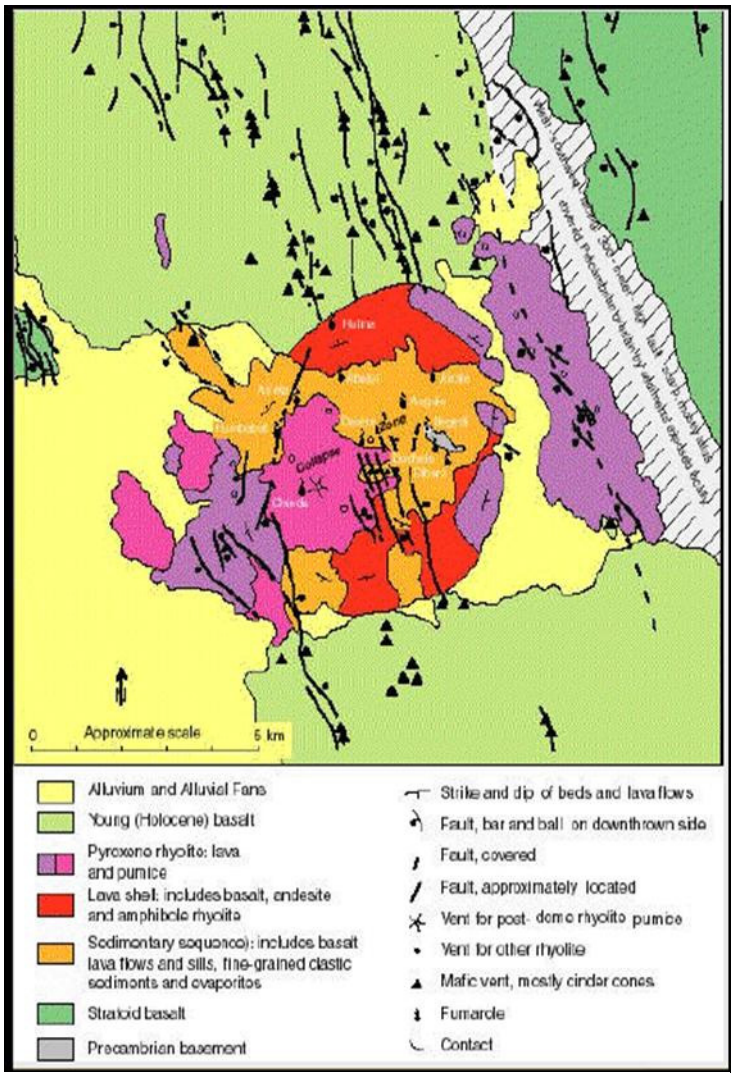

FIGURE 4: Structural features and Tertiary and quaternary volcanic rocks of the coastal region in southeast Eritrea. Note the Danakil Horst in between with ENE structures

FIGURE 5: Surface manifestation with extensive fumaroles at Darere

that release free gases. These manifestations, which are either fumaroles or hot springs, are confined to the northern part of the Alid dome. In most cases the free gas issues sulphur, as a result it precipitates in the form of sulphosalts. Sulphosalts and clays are the main constituents of the alteration zone. The intense of alteration however varies from place to place. Hot springs are more likely to occur where the depth to water table is shallow and subsurface geothermal systems are more likely to be discovered in areas where hot springs are present at the surface. Alteration is wide and intensive at Illegedi and Darere (Figure 5). Sulphosalts and clays of various colours are conspicuous both of present and old precipitates, of which yellowish coloured mainly representing sulphosalts and brown clays, are abundant. Emission of gases through fumaroles is intensive and spatially distributed widely along the stream.

Old silica alterations at places make the rock hardened as clearly observed on Ghinda hill. At Illegedi silica emanations on the present sites form salty like features in thin crusts. Apart from sulphosalts, clays and silica precipitates, considerable malachite stains occur at Humbebet manifestation. The latter alteration could be of potential target for mineral exploration. Geothermal surface manifestations represented by steaming grounds are abundant in Alid. Areas of steaming ground include north of Abakri, parts of Miski Merhada, and Hulma, the northern flank of the dome.

These places of steaming grounds are safe havens of grasses, where the areas are evergreen. Smokes commonly emanate through steam vents, however steaming in other surfaces are also observed.

Geological and geochemical studies indicate that a high-temperature geothermal system underlies the Alid volcanic centre in the northern Danakil depression of Eritrea. Geothermometers indicate that the fumarolic gases are derived from a geothermal system with temperatures in >225°C. The isotopic composition of condensed fumarolic steam is consistent with these temperatures and implies that the source water is derived primarily from either lowland meteoric waters or fossil Red Sea water, or both.

Some gases vented from the system (CO_2, H_2S and He) are largely magmatic in origin. Permeability beneath the volcanic centre may be high, given the amount of intrusion-related deformation and the active normal faulting within the Danakil depression. A conceptual model of two phases a vapour-dominated phase below a steam heated zone is developed for Alid (Yohannes, 2004).

3.2 Surface manifestation of high temperature zone – Nabro-Dubbi volcanic centres

Nabro stratovolcano is the prominent volcano occurs in a line of NE-SW direction SW of Dubbi volcano here collectively named as Biddu or Nabro-Dubbi volcanic complex. The 2218 m high Nabro stratovolcano is the highest volcano in the Danakil depression and elsewhere in the eastern lowland. Nabro volcano (Figure 6) itself forms part of an enigmatic double caldera structure with a neighbouring volcano, Mallahle, which has a sub aerial volume of the order of 550 km^3 (Wiart and Oppenheimer, 2005). Trachytic lava flows and pyroclastic emplace primarily on the Nabro, followed by a post caldera rhyolitic obsidian domes and basaltic lava eruptions inside the caldera and on its flanks. Some very recent lava flows were erupted along NNW trending fissures transverse to the trend of the Nabbro-Dubbi volcanic range (Figure 7). Dubbi is a large volcanic massif rises to 1625m above sea level erupted explosively in May 1861. The volume of lava flows alone, 3.5 km^3, makes this the largest reported historical eruption in Africa (Wiart et al., 2000). Many cinder cones are located at the summit. Extensive basaltic lava fields to the north and NE cover wide area and reach the Red Sea coast. Almost all the cinder cones belong to the most recent eruptive centres at the summit in 1861. The major transverse structure that extends from the Kod Ali island area of southern coastal Eritrea south-westwards across the north-eastern Afar rift margin on the Ethio-Eritrean border forms the terminus, and south-easternmost transfer mechanism into the Afar, of the Red Sea floor spreading axis which ends in the area to the northwest of Hanish islands (DOM, 2004). This structure separates the Danakil block in two separate units of geological makeup: the Pre-rift basement to the northwest and the Plio-Pleistocene volcanism to the southeast. This structure has given rise to the most

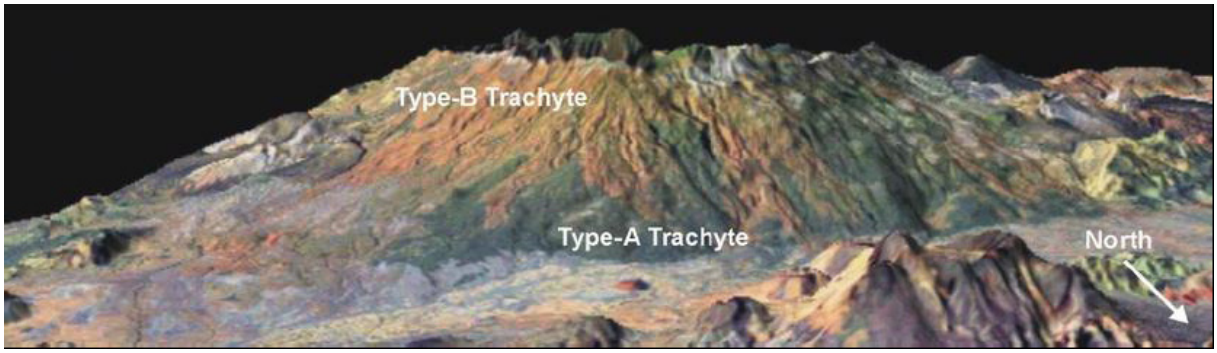

FIGURE 6: View of looking to the south Nabro trachytic volcanic centre

recent and most extensive Nabro, Mabda and Dubbi volcanic activities of the region, where it crosses the numerous northwest-southeast trending faults of the north-eastern Afar rift margin and Danakil block. The Nabro volcanic centre is the intersection of the ENE structure and Kod Ali fault line.

The geothermal resource exploration should thus focus on the areas of young silicic volcanism occurring on the above structure due to evidence for the shallow emplacement of magmatic heat source. The shallow magmatic body would install and maintain active geothermal system with high temperature at economically accessible depth.

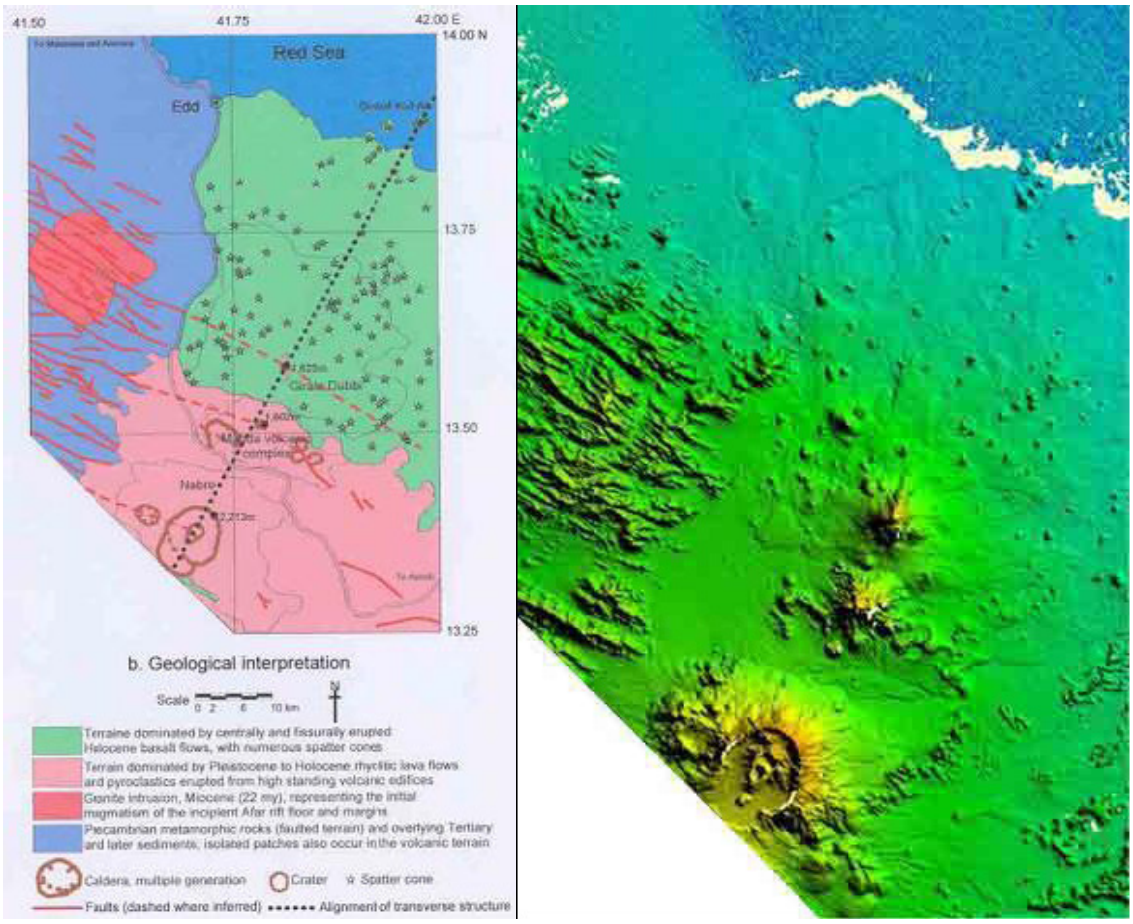

FIGURE 7: Geological interpretation of Nabro-Dubbi area, notice the intersection of structures. The right photo is the DEM of the Nabro-Dubbi (DOM, 2004)

3.3 Low temperature thermal springs

Hot springs in Eritrea occur at the main escarpment along the Asmara-Massawa highway, along the coastal plains and on the Danakil Depressions (Figure 8).

3.3.1 Thermal springs along the Asmara-Massawa highway

The thermal springs along the Asmara-Massawa highway are on a section of the middle to lower levels of the western part of the escarpment of the Red Sea graben. Surface temperature measurements, flow estimation and chemical analyses were carried out for the Ali Hasa, Dongolo, Sabarguma and Ailet spring areas. The hydrothermal features in these areas are classified as warm and hot springs (defined based on their temperatures being lower or higher than 50°C). They issue near-neutral bicarbonate waters with low chemical content. All of the springs are of low energy exhibiting quiet flow with no steam separation or gas evolution.

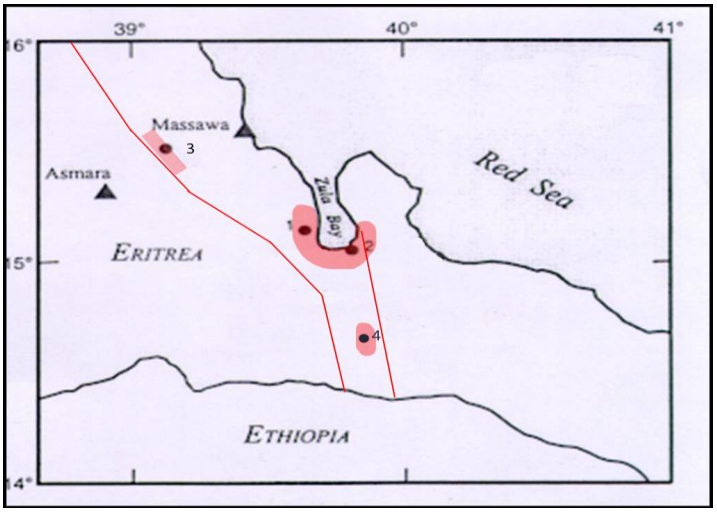

FIGURE 8: Location map of hot springs; locations 1 and 2 are around Gulf of Zula, 3 on the way of Asmara-Massawa and 4 on the Danakil Depression

3.3.2 Gulf of Zula area

Thermal springs occur at Ua-a and Acfat, thermal water wells in Arafali and Zula villages, all to the west of the Gulf of Zula, and in Gelti area on the south side of the gulf. Ua-a thermal spring is located about 20 km northwest of Foro village, situated to the north of Zula town. It occurs in an area covered by fluvial deposits, has a large discharge, a water temperature of 36°C and pH of 7.5. The Acfat group of thermal springs is located about 4 km north of Zula village and about 1.5 km from the sea. The main spring has a temperature of 43°C, a large discharge and a pH of 7.0. The springs occur on the edge of a swamp. A large diameter dug well located in Erafayle village is 10 m deep. Another in Zula town is 20 m deep. Both wells have thermal water with a temperature of 36°C and a pH of 7.0. The Gelti group of thermal springs consists of a large number of thermal springs located on the seashore. The water chemistry indicates a large measure of mixing with seawater. Low-pressure steam vents are located within about 200 m of the shore, being steam thought to be separated at low pressure from underground water bodies flowing toward the seashore.

All the hot springs mentioned above, except for Gelti, the thermal waters along Asmara-Massawa highway in terrain made up of Precambrian rocks and thermal springs close to Gulf of Zula do not show any immediate association with magmatism. They are thought to owe their occurrence to ascent, through the rift marginal faults, of waters heated at depth under typically crustal geothermal conditions, with relatively low geothermal gradients. They are judged to have no association with large volume and high temperature fluid circulation at shallow levels. They are thus believed to have no potential for large-scale commercial development for power generation. They otherwise have potential for small-scale, low-temperature, non-power applications, including for mineral water bottling, health and recreation spas etc, as already demonstrated at the Dongolo, Sabarguma and Ailet springs which have histories of bottling popular brands of mineral water.

The Gelti area thermal springs occur in terrain made up of Quaternary basalt lava. These springs seem to be associated with heating in underground zones of relatively elevated temperature but it is not

certain if they are associated with high temperature and volume of hot water circulation at shallow depth, due to the absence of signs of recent silicic volcanism indicating the existence of a young shallow magma intrusion. Being in the coastal area, and also having association with high permeability rocks that may allow hot water production in adequate volume, the area holds promise for low temperature geothermal resource application in such uses as fish drying etc.

3.3.3 Thermal springs on the Danakil Depression

The springs are located within the Depression issuing high flow of water along fault planes. The Laele and Bolleli thermal springs are the main localities. The latter is located within the weathered stratoid basalt whereas the earlier is related to the axial volcanism.

4. HYDROGEOLOGY OF ALID AND SURROUNDINGS

In general, the study area is divided into two major sources of surface water. These are the eastern and the western surface waters relative to the location of Alid dome that drains from the Danakil horst and the highland plateau, respectively (Teklesenbet et al., 2006). The western surface water flow has relatively gentle topography leading to slow to moderate run off. Recharge occurs in the valleys of the Alluvium cover and other permeable rocks.

Water that reaches the Samoti plain partly infiltrates and partly evaporates. Evaporation exceeds percolation because temperature is very high. The amount of water that infiltrates appears to come out, through a fault, in the form of hot spring in Lake Bada. Rainfall is very little. Some highly jointed and fractured stratoid basalts occur east of Alid, and provide opportunities for direct and indirect infiltration to the plains both north and south of Alid. Regional structure east of Alid, which is reported by Clynne et al. (1996) as "Alid Graben master fault", has a great contribution to the

Wengebo and Samoti ground water recharge and to the Alid geothermal potential indirectly.

In the highlands however, the amount of infiltration is relatively high through the permeable formations at times of intense rainfall and this water moves to the lowlands indirectly as part of ground water.

From the hydrogeological point of view the study area is mainly divided in to three catchments based on the drainage flow patterns (see Figure 9).

1. Wengebo catchment
2. Alid or central catchment area
3. Samoti catchment

Most of the run off from the escarpment percolates into the Pleistocene sediments and boulder beds, where it travels as shallow ground water and replenishes the evaporating Alat oasis which is located at the north-western margin of Samoti plain, south of Alid.
The hydrogeology of Alid and surrounding is mainly governed by:

1. Topographic level
2. Presence of cemented sand and clay deposits, which act as barriers
3. The ground water level is higher than the surface water. Therefore it feeds the surface water

From Geological and hydrogeological observations the Wengebo catchment drains directly to Alid and it can be assumed that the catchment is feeder of surface and subsurface water to the Alid geothermal reservoir. In addition to that ground water from Drawler River can possibly feed the Alid Geothermal

field because the river follows an East-West Fault. However the Samoti catchment is a discharge area with very little contribution, if any, in recharging the ground water to the Alid geothermal potential. The axial tectonic zone extending from the Gulf of Zula in the northwest to the Erta Ale volcanic range located in the southeast in Ethiopia marks one of the zones of oceanization of the Afar crust.

Alid is the Pleistocene to recent volcanism occurs along this zone is a product volcanism fed from a shallow magma body (DOM, 2004).

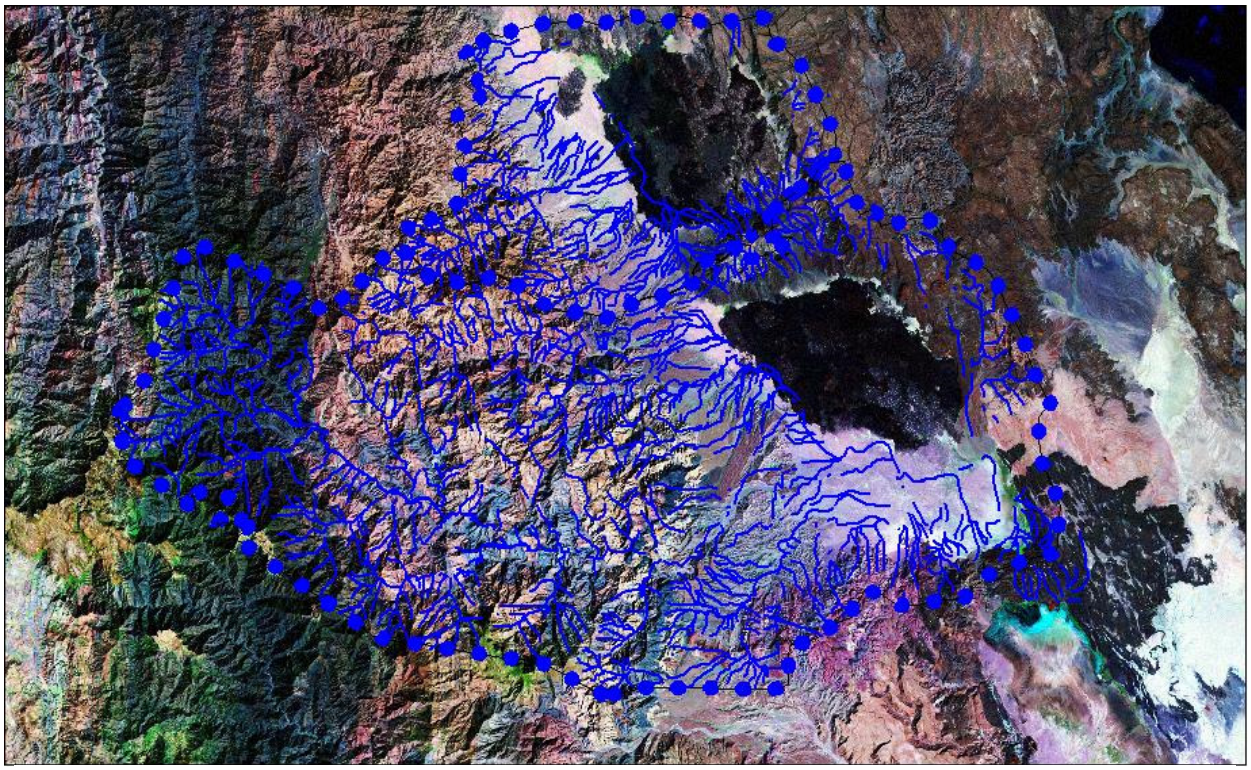

FIGURE 9: Catchments of Alid and surrounding: a, Wengebo (northern part) b, Alid (central small catchment) c, Samoti (southern catchment)

The studies so far carried out show that a high temperature reservoir is estimated beneath Alid volcanic centre (Clynne et al. 1996, Yohannes 2004). Based on the previous studies, lineament mapping and geophysical exploration is conducted to define target-drilling sites in Alid area. And since geothermal energy is the anomalously high heat energy stored in some favourable geological structures within the top kilometres of the earths' crust (Shalivan et al., 2004), it is viable to conduct faults and fracture assessment.

The aim of this of preparing a lineament map of the area of both field and remote-sensing data is to acquire an understanding of the relationship of the lineament with the mapped geothermal manifestation. Therefore structural data pertinent to fractures and faults was measured and geothermal manifestation was recorded. A better understanding of the fractures and faults allows us to identify and locate potential geothermal sites.

Alid volcanic centre a dome shaped outline elongated NNE direction is located 110 km south-south-west of Massawa on the Danakil depression. The dome is an elliptical structural dome peculiarly standing out high on the adjacent plain for 500 m. The major axis of Alid is 7 km, elongate ENE-WSW, perpendicular to the Danakil depression, whereas the minor axis is 5 km long, parallel to the graben (Lowenstern et al., 1997).

The studies so far carried out shows that a high temperature reservoir is estimated beneath Alid volcanic centre (Clynne et al. 1996, Yohannes 2004). Based on the previous studies, lineament mapping and geophysical exploration is recommended to define target-drilling sites in Alid area. And since geothermal energy is the anomalously high heat energy stored in some favourable geological structures within the top kilometres of the earths' crust (Shalivan et al., 2004), it is viable to conduct faults and fracture assessment.

Situated on the Danakil Depression as part of the eastern lowland, generally the area experiences a hot weather environment. However the top part of the Alid dome has relatively colder climatic situation relative to the plain. Rainy season in this area extends from December to February. Temperature during hot season ranges from 30° to above 40°C, where as in winter season is 20° to 30°C. Physiographic settings in the study area range from plain on the periphery of the dome to sharp mountains at Alid with an elevation ranges from 243 to 900 m, respectively. Vegetation is dense at the Wengebo plain while very scanty at the top of Alid Mount.

Geologic lineament mapping is considered an important tool in geothermal exploration. Geothermal systems are associated with areas of active faulting (Koenig and Mcnitt, 1983), because faults and fracture systems are the principal means by which meteoric fluids penetrate deeply into the crust (Coolbaugh and Bedell, 2004). Recent study (Soengkono, 1999) shows that geothermal reservoir is significantly influenced by faults and fractures that can easily be mapped from surface expressions, as they are often marked by topographic lineaments. In young volcanic terrain geological structures mainly faults and fractures have often-recognizable topographic expressions.

Besides statistical studies based on "weights of evidence model" shows that young volcanics and faults have a positive weight in predicting favourable sites of geothermal systems (Coolbaugh and Bedell, 2004).

Since Alid volcanic centre is made up of young volcanics, fractures and faults have great impact in controlling pathways of geothermal fluids whereby eventual sites of thermal flows located. For this reason, an assessment of faults and fractures were carried out in Alid to identify prospective geothermal target areas.

Faults recorded in Alid area are mainly of normal faults type with some strike-slip faults. The opening of the fractures ranges from mm scale to tenth centimetres; particularly the E-W has a wide opening. Fractures and faults were measured along surface manifestation. The relationship between the local surface manifestation and fracture were assessed clearly and described below briefly. Various structural directions were identified in association with the geothermal manifestation. Steaming grounds are mainly associated with the 70°N, although generally the surface manifestations are aligned at NNW, at Illeghedi, the prominent surface manifestation of the area. The NNW fractures are common on most of the surface manifestation. The E-W fractures have wide spacings occur in almost all the manifestation. The lineaments in Alid form a complex pattern but distinct sets of directions.

The systematic examination of faults falls into three major directions related to different tectonic origin by looking at the geological exposures:

1. Lineaments striking ENE (60°-70°): common lineament, related to major axis of the dome.
2. Lineaments striking NNW (330°-340°): Frequently observed especially at north and south of the dome, related to the trend of the depression.
3. Lineaments striking E-W (270°-280°): These are common as dykes and fractures related to rift tectonics.

An analysis of detailed aerial photographs of approximately 1:20,000 scale and land sat maps both the image and shaded relief plots was made to identify lineaments mainly caused by faults and fractures in the Alid area.

A dense lineament pattern is mapped out as shown on Figure 10. ENE lineaments are dominant at central part of the area while northerly striking faults and fractures are concentrated on the southern and northern part of the dome. A contour map of fault and fracture density (FFD), defined as the total length of lineaments per unit area, was constructed for the area (Figure 11).

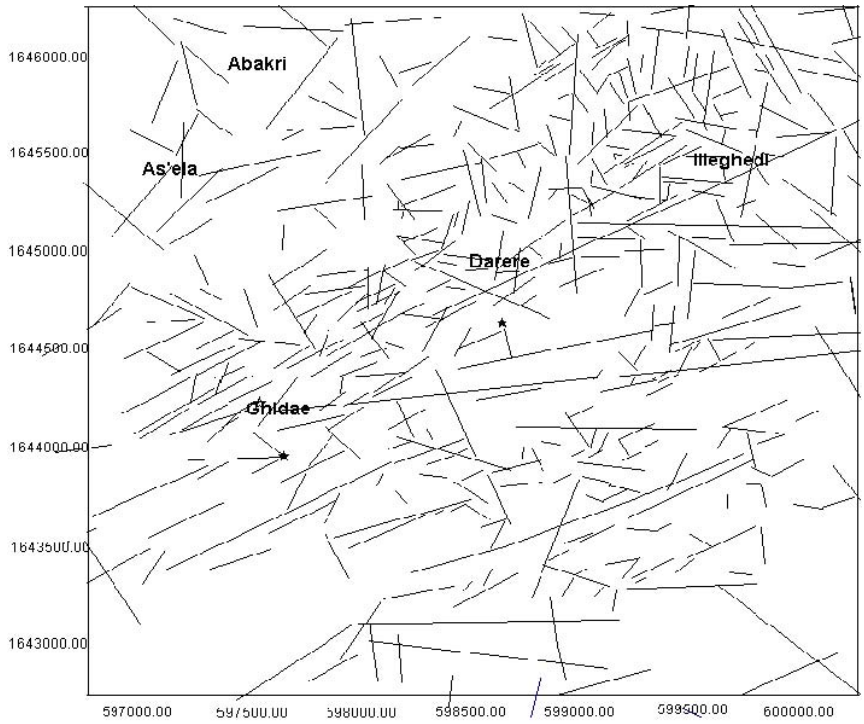

FIGURE 10: Lineaments interpreted mainly from 1:20000 aerial-photograph and digital images

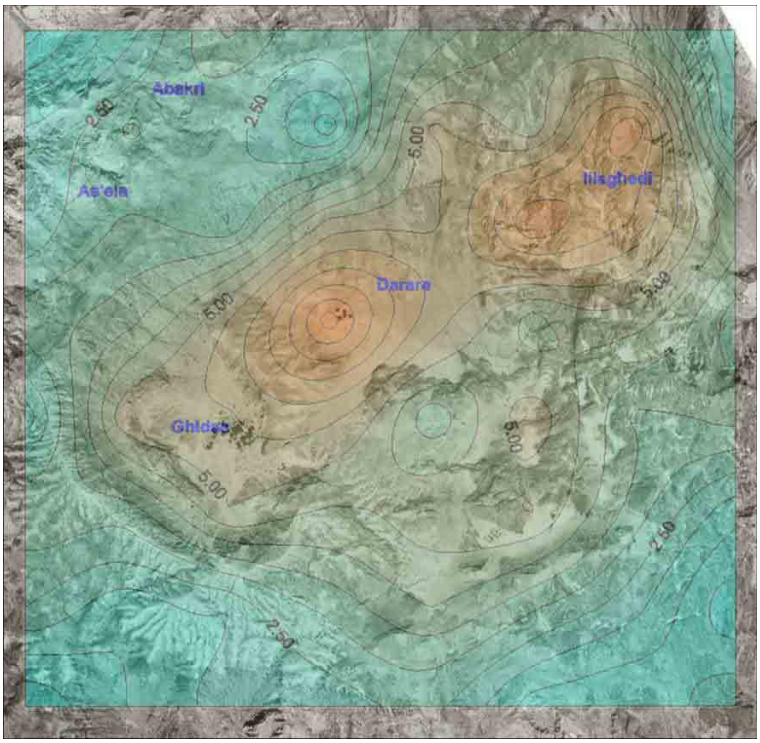

FIGURE 11: Contour plot of Alid area using FFD analysis. Note the high values lie on the Darere-Illeghedi line. It is superimposed on aerial photo

The zone of high FFD complies well with the central manifestation zone where areas of high surface manifestation occur. It extends for about 5 km along a linear pattern. Two peaks of anomalous high areas occur in the close to Darere and illegedi area. It has a direction of 70°N beyond the limit of surface manifestation.

The trend is well conformable with the major NNE fracture system. It shows that the major surface manifestations of the area are well in agreement with the FFD contour map. This suggests the significance influence of geological structures on the hydrology of the geothermal system at Alid.

According to the recommendation from the preliminary assessment, a resistivity survey was carried out to identify drilling sites, which are related to the tectonic map. Darere-Ghinda line was chosen inline with the instrument, as it is not effective in rugged terrain.

6. ALID GEOTHERMAL SYSTEM - ASSESSMENT FROM RESISTIVITY SURVEY

The geological and geochemistry performed on the Alid dome pointed out that a geothermal reservoir to occur beneath the Alid dome. To justify this and know the extent and depth of the reservoir, a geophysical survey was anticipated. Since MT resisitivity survey has the ability to penetrate deep resistivity structures (some tens or hundreds of kilometers), and is practically the only method for studying deep resisitivity structure it was proposed in Alid. Accordingly with the fund from ICEIDA, ISOR (Icelandic Geosurvey) and the Eritrean Geological Survey carried out MT survey on December, 2009 on Alid dome and adjacent area (Figure 12).

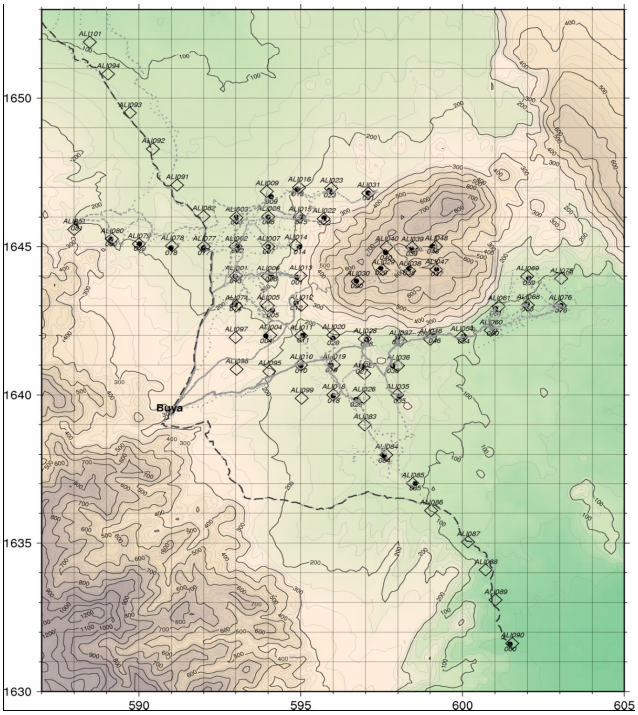

Figure 12: Location of TEM (open diamond) and MT soundings (filled circles). Coordinates are in UTM, km units

The TEM soundings do not suffer telluric shift arising from local inhomogeneity which distorted electric field thus TEM survey was conducted along with TEM. By interpreting together TEM and MT soundings made at the same (or nearly the same) location, the TEM data can be used to determine the unknown multiplier of the MT apparent resistivity.
Resistivity maps at various depths were drawn ranging from 400 meters above sea level to 10,000 below sea level (m.b.s.l). At 3500 m.b.sl. (Figure 13) and below a clear low resistivity NNW-SSE body is depicted west of the mountain and connected to the broader WSW-ENE low resistivity to the south.

The following conclusion on the resistivity structures has been drawn from the MT resistivity study on Alid:

- A SW-NE Lineament. A conductive zone is seen down to about 6–7 km depth (and even more in some places) in the south and southwest of Mt. Alid. This zone has a sharp vertical boundary or a lineament in the depth interval from ½–2 km depth shown by a yellow line on Figure 13. This boundary is best seen on the isoresistivity map at 1 km b.sl. in Figure 13.

- A low resistivity body defined by the NNW-SSE brown line below the western part of Mt Alid and to the west of the mountain there is a low resistivity body, approximately 3 km wide (Figure 14). It reaches the highest elevation at 2–3 km b.sl., and extending down to a depth of about 7 km.
- Beneath most of Mt Alid there is a rather high resistivity**,** compared to the surroundings, and no deep conductor, except in the westernmost sounding on the mountain.

Attempt has been done to relate the anomaly with the geotectonic set up of the area. The ENE direction low resistive anomaly result marked at 3500 meters b.s.l. is an important structure that extends even westward to the metamorphic basement (Yohannes, 2010). It is a deep seated as it juxtaposed the low grade and high-grade metamorphic complexes at the same topographic level. In addition the direction is also in line with the emplacement trend of the dome, which makes more interesting in dealing with the fluid movement.

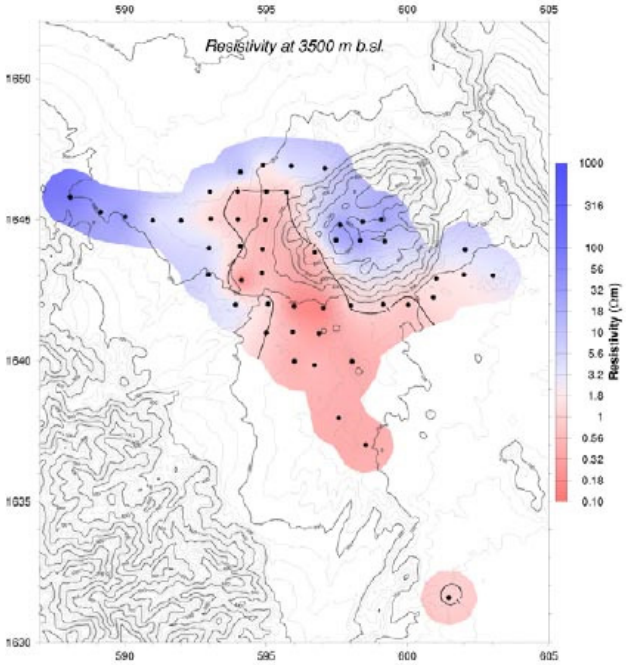

Figure 13: Resistivity map at 3500 metres below sea level. Coordinates are in UTM, km units

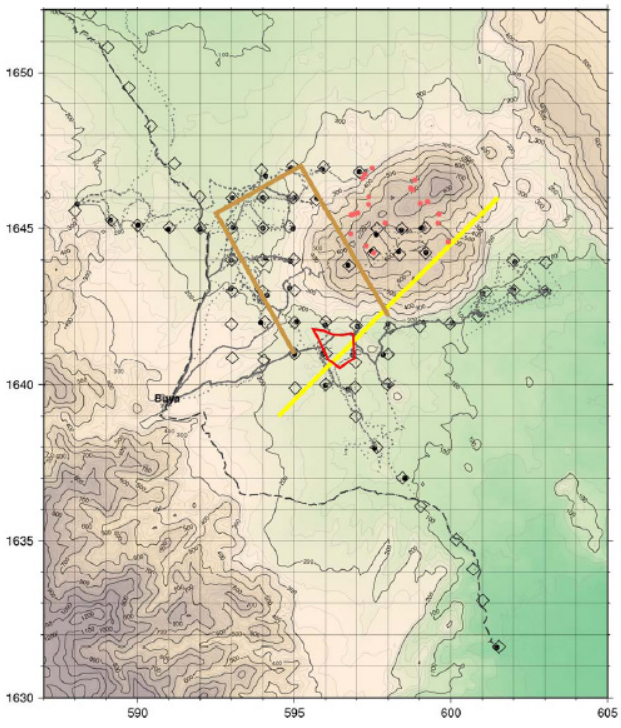

FIGURE 14: The Yellow line shows the location of the vertical resistivity boundary between ½ and 2 km depth. The brown contour lines outline the low resistivity body west of Mt. Alid at about 2 km depth. Red dots are geothermal vents on Mt. Alid

7. SUMMARY AND CONCLUSION

The tectonic setting and geological make up of the Danakil depression provides a suitable environment for the occurrence of geothermal energy.

Alid and Nabro-Dubbi are the two potential targets for high temperature identified from surface studies so far carried out. The estimated high reservoir temperature (greater that 2200C) from previous studies at Alid gave reason to conduct hydrogeology and fracture analysis aiming at selection up-flow zones.

From the hydrogeological point of view, it is found out that highland water is the source of water for Alid.

Lineaments including measurements of faults and fractures at mesoscopic scale and interpreted from aerial photographs and digital images were analyzed to better define areas of thermal flows at Alid. In

order to clearly sort out the relationship between the faults and fractures and thermal flow all the geothermal manifestations were assessed.

Most of the geothermal manifestations are associated with fractures and faults. Rosette and field investigation indicate that lineaments in Alid are of three types: lineaments striking ENE (60°-70°), NNW (330°-340°), and striking E-W (270°-280°).

Maximum lineament zone defined by ENE strike is well marked on the FFD analysis in line with the major fracture set of the area. Two high values depicted on the contour map are well accompanies with the thermal manifestation thus worth to commence geophysical investigation and/or drill slim hole to map temperature gradient of the area.

The MT resisitviity conducted at Alid depicted a very interesting and new site at the rift floor tather than beneath the Alid mount. Therefore it is imperative to study the area in a wider perspective.

The current study recommends the following detail work to be commenced on the future on Alid:

- Conduct CO_2 and other gases (radon and mercury) mapping on the Alid dome to know the gas outflow zone and select site of possible target of drill site.

- Gravity and microseismicity is also important to at mount Alid and surrounding in order to clearly define the target.

Perform the following prospect investigation on Nabro-Dubbi:

- Conduct geological mapping.

- Collect and analyze water and gas samples and perform geochemical interpretation.

Isotope hydrogeology has been conducted in Alid and low temperature fields, the result will be interpreted, and for Nabro-Dubbi prospects the study will be conducted in the near future.

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GEOTHERMAL EXPLORATION AND DEVELOPMENT IN RWANDA

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ABSTRACT

Rwanda needs a safe and clean source of energy for its people. At present the Government of Rwanda is looking at future strategy for solving the country's needs for electricity. When looking at available options, the concept of geothermal appears one of the best options, given that the resource is there and the development cost is acceptable. Rwanda is believed to have a geothermal potential which is estimated to be in excess of 300 MW. The development of geothermal resources is in its early stages and it has reached a point where exploration drilling is carried out to prove the existence of a geothermal potential. Exploration drilling is under way in the Karisimbi area in the Northern part of the country, and the first well has just been completed. This paper outlines the background and current status in geothermal development in Rwanda, the initiatives undertaken and strategy for exploration and development of geothermal resources for the four prospects identified.

1. INTRODUCTION

Rwanda is currently confronted with energy supply problem due to rapid growth of population and limited energy resources. Most of the population use wood as their basic energy need leading to an increasingly scares of fuel wood and thus creating deforestation. Biomass dominates as the principal source of primary energy for 85% of the population followed by imported petroleum fuels for 11% dominating the local industries energy supply. In the third level is electricity which account for 4% and is used by 16% of the population. The electrical energy in Rwanda is currently predominantly on diesel generation followed by hydropower as consequence of low rainfall and an increasing demand for electricity. The high prices of oil are putting a strain on the national budget and constitute presently a serious hurdle to the economic growth for a landlocked developing country such as Rwanda.

Overall, the country vision is to ensure universal access to electricity from both grid and off-grid solutions, over the EDPRS II period (Economic Development and Poverty Reduction Strategy). Detailed plans have been developed to spread the electricity network across the country. In tandem with the relocation driven by urbanisation and resettlement policy, this should bring the grid within reach of around 48-50% of the population (Energy Sector Strategic Plan, 2013).

The present total generation capacity available in Rwanda is 109.4 MWe, with hydro-generation accounting for 52% (56.7 MWe) and 44% (48.3 MWe) from fuel fired plants. The current average cost of electricity is of about 0.26 US$ per kilowatt hour. Therefore, to minimize the dependency on

energy imports, save foreign currency and create conditions for the provision of safe, reliable, efficient, cost-effective and environmentally appropriate source of energy, geothermal development seems to be the long term solution that could end the current energy crisis.

The development of geothermal energy resources in Rwanda is at early stages compared to some East African countries such as Kenya and Ethiopia. The exploration of this resource really boomed in 2006 with a view of diversifying energy sources in the generation of electricity and meets the electricity demand in the country. The volcanoes area, the geological context and the hydrothermal manifestations of Rwanda are an indication of the existence of potential geothermal systems. Early geothermal investigations pointed out the north-west area as a potential for large, high temperature geothermal systems, while the rift in the south-west part of the country along the Lake Kivu is believed to present an environment for low to moderate temperature resources (Demange et al., 1983; Newell et al., 2006).

The current strategy of the Government of Rwanda (GoR) is to know how much geothermal potential is available for the country to meet its energy demand. This step is being implementing by the drilling of the first exploration well in the Karisimbi area to prove the resource.

2. BACKGROUND ON GEOTHERMAL EXPLORATION

Geothermal investigations in Rwanda started in the 1980's but the existence of geothermal resources in identified geothermal prospects still needs to be confirmed through drilling. Several reports exist, indicating two areas as prospective zones for geothermal energy; the first zone (Gisenyi, Karisimbi, and Kinigi) in the north-western region, which is associated with volcanoes and the second zone (Bugarama) in the southern region associated with faults in the East African Rift (Figure 1). Among the four prospects, the development activities for Karisimbi are the most advanced followed by Kinigi and Gisenyi. Bugarama on the other side is at the reconnaissance stage to be followed by geo-scientific survey to estimate the potential of this area.

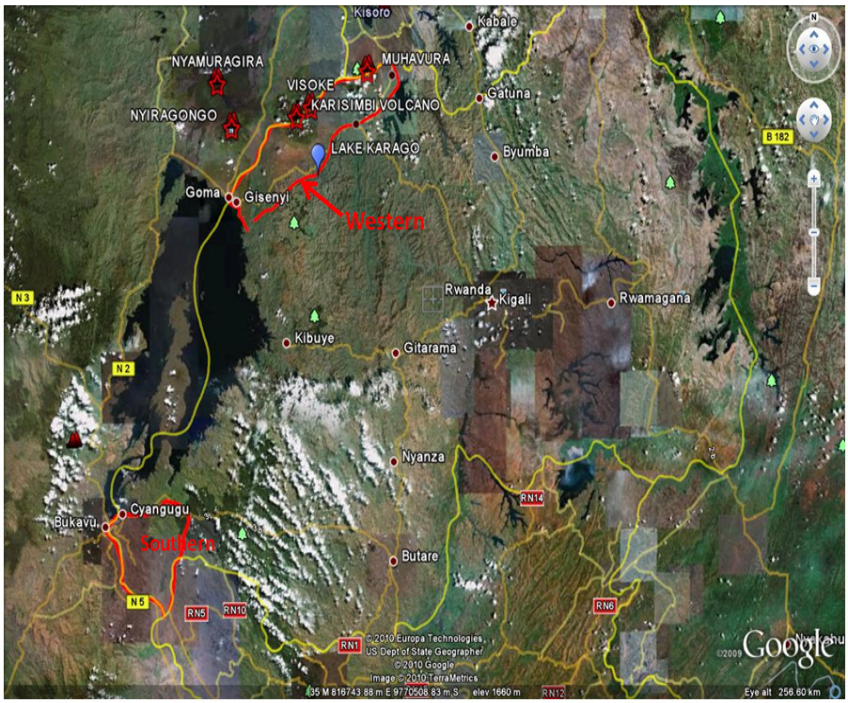

FIGURE 1: Location of the two geothermal prospective zones (Onacha et al, 2010)

Serious investigations on Rwanda geothermal resources started in 2006 with a view of diversifying energy sources for electricity generation and meet the electricity demand in the country. Surface exploration studies to prove the resource have been carried out in several phases:

In 1983, the French Bureau of Geology and Mines (BRGM) identified Gisenyi and Bugarama as potential sites for geothermal energy with estimated reservoir temperatures of over 100°C.

In 2006, Chevron carried out geochemistry studies in the Bugarama and Gisenyi geothermal prospects and estimated the geothermal reservoir temperatures to be more than 150°C.

In 2008, the Germany Institute for Geosciences and Natural Resources (BGR), in collaboration with the Kenya Electricity Generating Company (KenGen), the Icelandic Geo Survey (ISOR) and the Spanish Institute for Technology and Renewable Energies (ITER) carried out surface studies in the Gisenyi, Karisimbi and Kinigi areas. The results from this study concluded that a high temperature geothermal system (>200°C) may exist on the southern slopes of Karisimbi volcano and that a medium temperature geothermal system may exist around Lake Karago (150-200°C).

In 2009, KenGen acquired additional surface studies (geochemistry and geophysics) and carried out baseline environmental impact assessment (EIA) on the southern slopes of the Karisimbi Volcano. Findings recommended drilling three exploration wells in the Karisimbi prospects.

In 2011, an additional geothermal survey was done by the Institute of Earth Science and Engineering (IESE) through Auckland UniServices, New Zealand aiming at developing a conceptual model for the entire western region and locating sites for exploration drilling in the three prospects, Karisimbi, Kinigi and Gisenyi.

Workshops were organised in 2012 and 2013 with panel of experts aiming at merging all findings, to come up with one unified model for the Karisimbi area allowing for the definition of the location of sites for exploration drilling in Karisimbi.

Currently, the four geothermal prospects can be ranked as shown in Table 1.

TABLE 1: Exploration status for Rwanda prospect

Geothermal prospects	Reconnaissance study	Detailed survey	Wells sited	Infrastructure works	Wells drilled
Karisimbi	yes	yes	yes	yes	on-going
Kinigi	yes	yes	yes	no	no
Gisenyi	yes	yes	no	no	no
Bugarama	on-going	no	no	no	no

3. CURRENT EXPLORATION AND DEVELOPMENT

3.1 Karisimbi prospect

The Karisimbi area is located near the Karisimbi volcano within the National volcano park in Nyabihu district. Detailed surface geo-scientific studies and Environmental and Social Impact Assessment (ESIA) have been completed. Drilling of three deep exploratory wells (Figure 2) has been planned and currently drilling of the first well is completed.

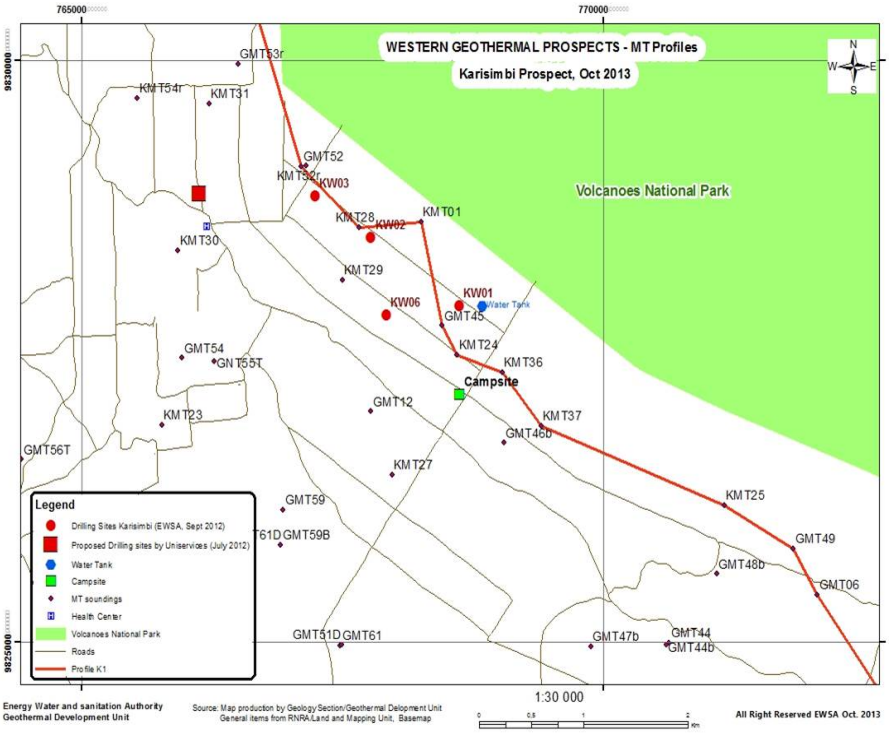

FIGURE 2: Location of wells in Karisimbi prospect (GDU, 2013)

Several contracts have been awarded for the preparation of drilling. Contracts for the supply of drilling materials and drilling services have been awarded early 2012 to the China Petroleum Development and Technology Corporation (CPTDC) and Great Wall Drilling Company (GWDC), respectively. The contract for the rehabilitation of the road to the drilling site was awarded to a local company ERGECO and works are completed. The water supply to the site and civil works contract was awarded to a Kenyan Company, YASHINOYA limited.

Well testing services is provided by the Geothermal Development Company (GDC) from Kenya. Technical assistance prior to drilling was provided to the Geothermal Development Unit by the Japanese Agency (JICA). On job training is provided by the Icelandic Geological Survey (ISOR) through funding from the Icelandic Development Agency (ICEIDA). The drilling supervision for the first well was carried out by Reykjavik Geothermal Company (RG) and funded by the Nordic Fund through NEFCO (Nordic Environment Finance Corporation).

The exploration drilling in Karisimbi of the first well KW01 started in July 18 and was completed on November 7. Well testing of KW01 indicates low temperature and poor permeability at depth. The immediate plan for the Karisimbi prospect is to continue the assessment by carrying out in fill measurement in the area, drilling two additional wells KW02 and KW03 and well testing.

3.2 Kinigi prospect

The Kinigi geothermal area is located in Musanze district, east of Karisimbi. Detailed surface studies Environmental and Social Impact Assessment have been completed. Additional studies for updating of the conceptual model of Kinigi geothermal prospect is proposed and submitted to UNEP for funding. The drilling of three exploratory wells in Kinigi is to be financed by the Government of Belgium through Belgium Technical Corporation (BTC) for an amount contribution up to 27 million Euros. This contribution should cover the infrastructure works and the drilling of three exploration wells. In addition to GoR and BTC commitment to finance the drilling project, Expression of Interest for GRMF funding has been submitted.

3.3 Gisenyi prospect

The Gisenyi geothermal prospect is located in Rubavu district, south of Karisimbi and is defined by a NW trending resistivity anomaly aligned with Nyiragongo and Nyamuragira active volcanoes in the Democratic Republic of Congo. Detailed surface studies have been completed. Additional studies to complement existing geophysical, geological and structural data in the Gisenyi area and to quantify geothermal potential and locate sites for drilling 3 exploration wells have been proposed and submitted to EU for funding.

3.4 Bugarama prospect

The Bugarama geothermal prospect is located in the southern province of Rwanda. The geothermal manifestations in this area are hot and warm springs and travertine deposits, which is being mined as feedstock for a nearby cement factory. This prospect probably extends into Burundi and the Democratic Republic of Congo. No detailed geo-scientific work has been carried out in this area. A regional geothermal exploration study funded by EU has started in November 2013 for the three countries, Democratic Republic of Congo, Burundi and Rwanda. The exploration study will conclude with location of targets for deep exploratory wells drilling. The project is financed by the European Union and the consultancy firm hired for this project is Reykjavik Geothermal (RG). Great Lakes Energy Agency (EGL) is mandated for the implementation of this regional project.

4. OTHER INITIATIVES

A detailed Geothermal Strategy and Geothermal Act have been developed which will both be formally approved. The short term strategy is to take geothermal exploration to a next level by drilling multiple exploration wells to map the geothermal resources in different prospects in the country. In the mid-term, proving the presence and feasibility of geothermal resources is a necessary step in attracting private investors who could scale up the geothermal energy production. In the long term, the plan is to develop over 300MWe of least cost, base load and environmentally friendly geothermal energy through public and private sector partnerships. To achieve this, funds are required immediately for detailed surface exploration, exploration drilling, production drilling, feasibility studies and power plant construction. This will be achieved by strengthening the institutional, technical, legal and regulatory and policy framework.

A clear policy of giving out concessions and payment of royalties will be established through the Geothermal Resources Exploration, Development and Management Law and regulations which are currently being discussed by all stakeholders. The Law will also ensure sustainable utilization of geothermal resources with a negotiate cost reflective tariff structure.

Technical assistance and capacity building are provided and financed by several institutions; the Japanese International Cooperation Agency (JICA), The Icelandic International Development Agency (ICEIDA), the United Nations University Geothermal Training Programme, the African Rift Geothermal Development Facility, the European Union Energy Initiative (EUEI) and others. The Geothermal master plan is to be developed by JICA.

A new institutional framework for the Geothermal Development Unit in EWSA is being discussed with development partners to fast track the geothermal programme in the country.

5. ISSUES AFFECTING THE DEVELOPMENT OF GEOTHERMAL ENERGY IN RWANDA

Theoretically, the estimates of geothermal energy potential can supply all the national power needs for Rwanda for the next 10 years. However, the pace and level of development of geothermal resources has not been effective. This is mainly due to lack of funds and the perceived risk in developing the geothermal resources. Financing from multilateral institutions or international lenders is difficult without adequate data. The Geothermal Risk Mitigation Facility for East Africa (GRMF) is one of the alternatives to be utilized. Based on the request from the African Union Commission AUC to submit expression of interest for GRMF, Rwanda has submitted Kinigi and Gisenyi prospect sites for exploration drilling.

Geothermal energy development generally has very high project development costs. Unlike diesel plants, where you can purchase the fuel when required, in geothermal you have to prove the availability of fuel (steam) in advance before power construction.

Other issues affecting the development of geothermal energy are marketing, institutional, and policy impediments. The role of geothermal development in the energy mix needs to be clearly defined with set and funded targets to prove the viability of a geothermal resource. There is need to share and disseminate information among all stakeholders and potential investors. The fear of developing geothermal energy has to be overcome among policy makers and opinion leaders. There is need to build adequate human resource capacity while at the same time encouraging local education institutions to provide training relevant to geothermal development. Clear guidelines on the level of participation of local community and other stake holders in geothermal development and utilization are required.

6. CONCLUSIONS AND RECOMMENDATIONS

Rwanda has very positive indicators of geothermal prospects, which can be exploited commercially for electricity generation and industrial uses. Four potential geothermal areas, Karisimbi, Gisenyi, Kinigi and Bugarama have been identified and exploration drilling is underway in Karisimbi area. There is however need to carry out a thorough assessment of the data to minimise the risks of sinking unproductive wells. A criterion for sitting wells needs to be established. A cautious approach will be utilised in the exploration program to increase the success rates. Enabling environment should be created for the private sector to undertake development of geothermal resources in the country. The establishment of a legal and regulatory framework is urgently required. Furthermore, to implement effectively the geothermal development plan of the country, additional staff should be hired and trained, and institutional provisions must be developed for the Geothermal Development Unit (GDU).

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Presented at *Short Course VIII on Exploration for Geothermal Resources*,
organized by UNU-GTP, GDC and KenGen, at Lake Bogoria and Lake Naivasha, Kenya, Oct. 31 – Nov. 22, 2013.

3D VISUALIZATION OF GEOTHERMAL WELLS DIRECTIONAL SURVEYS AND INTEGRATION WITH DIGITAL ELEVATION MODEL (DEM)

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ABSTRACT

High spatial resolution topographic data is essential to assist volcanic field work, for volcano morphology analyses, and for hazard modelling of volcanic flow processes. The stereoscopic capability of ASTER data provides the opportunity to derive DEMs at a spatial resolution of 15 m for the many regions lacking accurate topographic maps. For visualization, a three dimensional model DEM of the geothermal field with the directional wells and other geographical phenomena were incorporated into the GIS program. The three dimensional model viewers were used with directional geothermal well featuring in the Greater Olkaria geothermal field.

The three dimensional modelling of geothermal wells was done using the deviation surveys data by linear referencing. The tool was developed in an excel based program developed using a Visual Basic for Application (VBA) procedures (macros) which is the excel visual Basic Editor (VBE).
Geographic Information System (GIS) technology was used to model geothermal well directional survey data. This aids in visualizations suggesting interrelationships between well bore productivity. Running these data through a model in ArcGIS, 3D maps can be created showing where well bores corkscrew their way down through the earth's crust. This phenomenon is difficult to see on a two-dimensional map or cross-section view. The 3D map is more intuitive to KenGen's team in exploration and production who are accustomed to thinking in three dimensions. This model is of interest to potential drillers because it shows that a well bore went down this way. With respect to this model, geological rock units can be incorporated in the model thus showing the rock unit penetrated by a particular geothermal well bore.

1. INTRODUCTION

A directional survey is a series of measured depths points down the well path with corresponding hole inclination and direction. From these points, the spatial position of the well path needs to be calculated.

A map showing directional well surveys and how the engineering/survey data behaves is required. A two- or three-dimensional view of the directional survey is necessary. The three dimensional view aids in the geophysical visualization and interpretation leading to the discovery of new geothermal

reservoirs. A map helps determine the volumetrics to calculate reserves, and a map view of proposed drilling helps avoid intersecting an existing geothermal well.

Digital Elevation Model (DEM) can be extracted and integrated in visualization GIS environments for landscape representation and further analysis. This paper focuses on the extraction of DEM from ASTER DEM generation for visualization of calculated directional well survey data as well as modeling of surface processes of Olkaria geothermal field. Directional survey data were extracted using the ArcInfo GIS software such as elevation, aspect, slope angle, vertical curvature, and tangential curvature.

2. VIEW OF GEOTHERMAL WELL DIRECTIONAL SURVEYS

The directional data survey (actual depth, the inclination and azimuth) was input in an excel based program developed using a Visual Basic for Application (VBA) procedures (macros) in Figure 1 which is the excel visual Basic Editor (VBE).

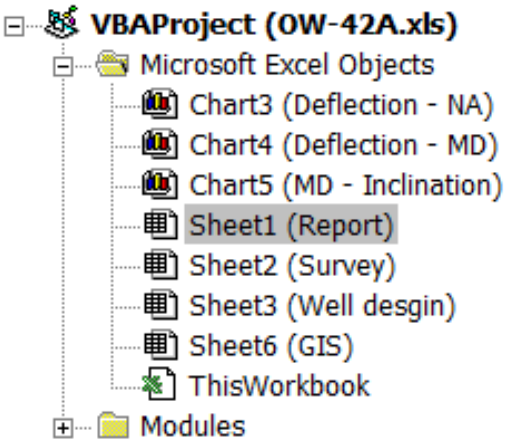

FIGURE 1: A Visual Basic Application Project for directional well data (OW-42A)

When drilling a well, the possibility exists that the well may not be perfectly vertical. Depending on the drilling technique used and the geological formations that were encountered during the drilling process, a well may deviate from the intended vertical direction. The amount of deviation from vertical measured in degrees will affect the True Vertical Depth (TVD) of the well. If the inclination of the well is determined, then the true vertical depth (TVD) can be calculated (IHS, 2007).

The information about a particular well e.g. OW-42 from the directional well survey data was generated as shown in Figure 2 below:

KenGen NE Field OW-42A Generate report 7/16/2012

MD [m]	TVD [m]	Inclination [°]	Azimuth [°]	Northing [m]	Easting [m]	Deflection [m]	X	Y	Z
0	0.0	0.00	0.0	0.0	0.0	0.00	200284.0	9902917.9	2000.4
0	0.0	0.00	0.0	0.0	0.0	0.00	200284.0	9902917.9	2000.4
385	385.0	0.59	244.0	-1.7	-3.6	3.96	200280.5	9902916.2	2385.3
399	399.0	0.87	314.8	-1.6	-3.7	4.04	200283.9	9902916.3	2399.3
414	414.0	1.20	320.4	-1.3	-3.9	4.14	200283.8	9902916.6	2414.3
434	433.9	2.91	322.7	-0.5	-4.5	4.56	200283.4	9902917.4	2434.3
453	452.9	4.76	330.5	0.8	-5.3	5.37	200283.3	9902918.8	2453.2
473	472.7	6.88	333.7	3.0	-6.4	7.03	200283.0	9902920.9	2473.1
492	491.5	9.10	343.6	5.9	-7.2	9.30	200283.2	9902923.8	2491.9
511	510.2	11.01	354.9	9.5	-7.5	12.11	200283.7	9902927.4	2510.5
531	529.6	13.45	2.2	14.1	-7.4	15.93	200284.2	9902932.1	2530.0
550	547.8	16.79	6.2	19.6	-6.8	20.72	200284.6	9902937.5	2548.1
570	566.4	21.48	6.3	26.9	-6.0	27.52	200284.8	9902944.8	2566.8
745	711.9	33.74	7.6	123.2	6.9	123.40	200296.9	9903041.1	2712.3
826	781.0	31.55	10.3	164.9	14.5	165.54	200291.6	9903082.8	2781.3

FIGURE 1: A form showing the report about OW-42 in the NE geothermal field

where:

- TVD- True vertical Depth
- MD- Measured Depth

The result of the this VBA project is X,Y,Z and well name data which are then exported to GIS to create shapefiles. Table containing X coordinates (Longitude) and Y coordinates (Latitude) is brought into ArcMap and converted to a shapefile or geodatabase feature class taking into consideration the correct spatial reference

X	Y	Z	Well
200284.04	9902917.93	2000.35	OW-42A
200284.04	9902917.93	2000.35	OW-42A
200280.48	9902916.19	2385.33	OW-42A
200283.89	9902916.34	2399.33	OW-42A
200283.84	9902916.58	2414.32	OW-42A
200283.43	9902917.39	2434.30	OW-42A
200283.26	9902918.76	2453.23	OW-42A
200282.98	9902920.91	2473.09	OW-42A

FIGURE 3: X,Y,Z and well name to be exported to GIS for the generation of shapefiles

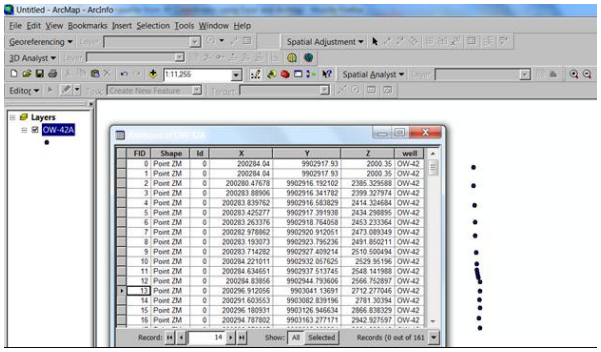

FIGURE 4: A map directional well surveys and the converted engineering/survey data to GIS format for display on a map.

The data consist the creation of 3D model which was done in ArcInfo with 3D Analyst tool extension. However, 3-D modelling of directional geothermal wells requires more steps. It deals with linear features and elements located along them. These features assume any direction and orientation in a 3-dimensional space. The available application tools that could allow precise generation of 3D lines from XYZ coordinates were utilized.

The 3D directional geothermal wells were generated from XYZ coordinates of the vertices which were extracted from the deviation survey data. The shapefile generated were then transformed into 3D points in ArcInfo. This process was performed for each well. The heights from an ASTER DEM were utilized in ArcScene and a vertical exaggeration set to enhance 3D visualization.

A map provides a two- or three-dimensional view of the directional survey, which aids in the geophysical visualization and interpretation that leads to the discovery of new geothermal reservoirs (Kenez, 2008). A map helps determine the volumetrics to calculate reserves, and a map view of proposed drilling helps avoid intersecting an existing well. The map in Figure 4 above shows directional well surveys and the converted engineering/survey data to GIS format for display on a map.

3. 3D MODELING OF OLKARIA GEOTHERMAL FIELD TERRAIN

Viewing data in three dimensions gives new perspectives about the derived data, adding insights that would not be readily apparent from a planimetric view. Having multiple viewpoints of the data guarantees to have a first raw exploration of their quality. The ASTER-DEM was imported into the ArScene for 3D visualization. GIS, and in particular ArcScene, allows the management and visualization of geographic data, for interactive fly-through of user-defined flight paths. The geographical phenomena can also be draped multiple GIS layers and raster data, even if some aliasing effects are present in the produced video animations (Poli, Remondino and Dolci, 2004).

Digital Elevation Models (DEMs) from ASTER are a type of raster GIS layer. Raster GIS represents the world to be a regular arrangement of positions. In a DEM, each pixel has a value corresponding to its elevation (Cote, 2010). The fact that spatial locations are arranged regularly allows the raster GIS to infer many interesting associations among locations: Which cells are upstream from other cells? Which locations are visible from a given point? Where are the steep slopes? One of the most powerful applications of DEMs is adding synthetic hillshading to maps so that the map reader may see the relationship between terrain and other features that may be mapped as in Figure 5.

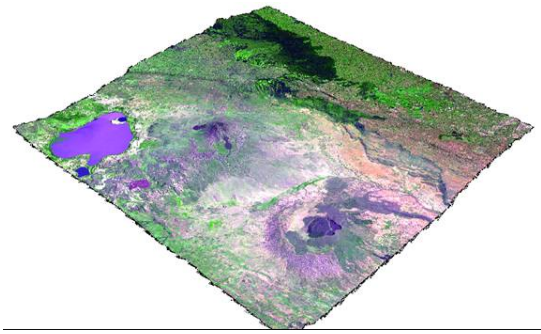

FIGURE 4a: 3D view of Olkaria volcano Digital Elevation Model (Baseheights are obtained from ASTER DEM)

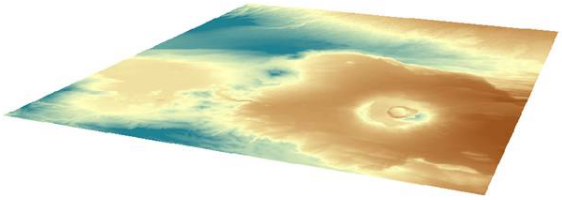

FIGURE 4b: An ASTER DEM that is registered in GIS

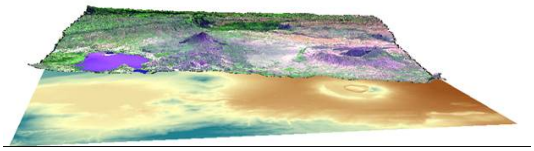

FIGURE 4c: LANDSAT Image draped on an ASTER DEM for Olkaria Volcano

ASTER consists of 3 down looking sub-systems. The Visible and Near-infrared (VNIR) has three bands covering the wavelength range 0.52-0.86µm (green, red, near-infrared), with a spatial resolution of 15m; the ShortWave Infrared (SWIR) has 6 bands in the range 1.6-2.4µm, with a spatial resolution of 30m; the Termal InfraRed (TIR) has 5 bands in the range 8.1-11.3µm, with a ground resolution of 90m.This was developed jointly by the Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). The ASTERGDEM shown in Figure 6 was georeferenced in ArcMap using the metadata provided in (The Ministry of Economy, Trade and Industry of Japan (METI), & Spacesystems, 2008).

The 3D model of Olkaria geothermal field was generated from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) for 2008. The Advanced Spaceborne

Thermal Emission and Reflection Radiometer (ASTER) is one of the instruments carried on the EOS-AM1 platform, launched on December 18, 1999.The ASTER instrument covers a wide spectral region

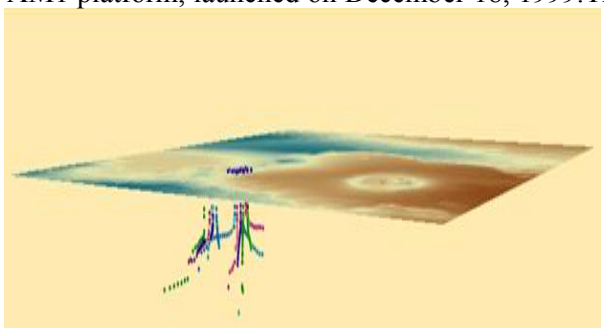

FIGURE 2a: ASTER DEM model of Olkaria geothermal field showing 3D view of geothermal directional wells.

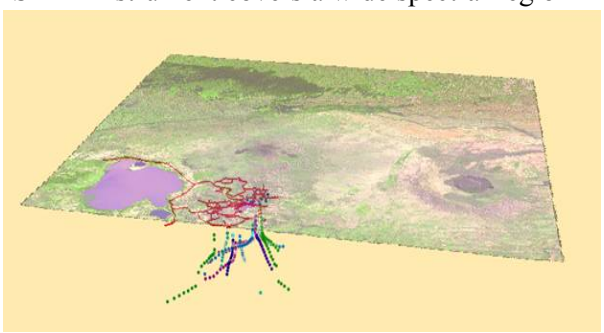

FIGURE 5b: 3D view of the geothermal directional wells, road network in a LANDSAT image. The base heights were from ASTER DEM shown in Figure 6.

with 14 bands from the visible to the thermal infrared with high spatial, spectral and radiometric resolution. An additional backward looking near-infrared band provides stereo coverage.The ASTERGDEM was georeferenced in ArcMap using the metadata.

4. DISCUSSION AND CONCLUSION

This paper demonstrates the power of developing a VB model for geothermal well directional survey computation. This study focused as well on the usefulness of building a 3-D digital elevation model to visualize directional geothermal wells in a GIS environment. This aids in the geophysical visualization and interpretation that leads to the discovery of new geothermal reservoirs. This model could now be used as basis for many exploration investigations.

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organized by UNU-GTP, GDC and KenGen, at Lake Bogoria and Lake Naivasha, Kenya, Oct. 31 – Nov. 22, 2013.

OVERVIEW OF GEOTHERMAL RESOURCE EXPLORATION AND DEVELOPMENT IN THE EAST AFRICAN RIFT SYSTEM

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ABSTRACT

The East African Rift System (EARS) is one of the major tectonic structures of the earth where the heat energy of the interior of the earth escapes to the surface. This energy flow takes place in the form of volcanic eruptions, earthquakes and the upward transport of heat by hot springs and natural vapor emissions. The EARS extends for about 6500 km from the Middle East (Dead Sea-Jordan Valley) in the North to Mozambique in the South. The EARS passes through Eritrea, Djibouti, Ethiopia, Kenya, Tanzania, Uganda, Rwanda, the Democratic Republic of Congo (DRC), Zambia, Malawi, Mozambique and Madagascar. Estimated Geothermal energy resource potential in the EARS is more than 15,000 MWe.

Despite the high geothermal potential of the EARS, only Kenya and Ethiopia have installed a capacity of about 217 MWe. Countries such as Djibouti, Eritrea, Tanzania, Uganda, Rwanda and Comoros are at various exploration stages. So far, other countries such as Burundi, DRC, Malawi, Zambia, and Mozambique have not gone beyond the inventory work of the resource potential.

Geothermal energy presents a clean and more environmentally friendly alternative to traditional fuels. Geothermal energy has the potential to provide long-term, secure base-load energy and greenhouse gas (GHG) emissions reductions. Accessible geothermal energy from the Earth's interior can supply heat to generate electric energy and for direct use. Climate change is not expected to have any major impact on the effectiveness of geothermal energy utilization, but the widespread deployment of geothermal energy could play a meaningful role in mitigating climate change.

Geothermal development, in the East Africa region, has been constrained by the risks that are associated with resource exploration and development and financial risks associated with investment in power development projects. Lack of appropriate investment and institutional settings in many countries have also contributed to the slow pace of development. Therefore, overall strategy to reduce the above risks and to accelerate geothermal development in the countries of EARS is to adopt a regional geothermal resource development approach. One of the main regional geothermal programmes in the region is the African Rift Geothermal Development Facility Programme (ARGeo).

The ARGeo Project originated in 2003 with a view of the fact that the region has a large and untapped geothermal resource potential that is indigenous, environmentally clean, economically viable and renewable energy resource. The project's objective is to promote geothermal resource utilization by reducing the risks associated with resource's exploration and development. ARGeo aims to accelerate geothermal energy investments in both public and private sector. The utilization of the resource in agriculture and industry will also be promoted.

1. INTRODUCTION

Energy use in Africa is the lowest in the world and also has the least developed structure. The continent has about 15 % of the world's population but its share of electricity use is less than 5 % of the world. Only about 25 % of the African population has access to electricity. More than half of the current energy use is traditional biomass that causes health problems and deforestation. Although Africa endows with abundant energy resources such as hydropower, geothermal, wind and solar it is only less than 10% and 1% of the continent's hydroelectric and geothermal power generation potentials have been developed to date, respectively.

African countries that are located along the East African Rift System (EARS) have the largest hydroelectric and geothermal potentials of the continent. EARS is one of the major tectonic structures of the earth where the heat energy of the interior of the earth escapes to the surface. This heat energy flow takes place in the form of volcanic eruptions, earthquakes and the upward transport of heat by hot springs and natural vapor emissions. The EARS extends for about 6500 km from the Middle East (Dead Sea-Jordan Valley) in the North to Mozambique in the South (Figure 1). The EARS passes through Eritrea, Djibouti, Ethiopia, Kenya, Tanzania, Uganda, Rwanda, the Democratic Republic of Congo (DRC), Zambia, Malawi, Mozambique and Madagascar. Estimated Geothermal energy resource potential in the EARS is more than 15,000 MWe.

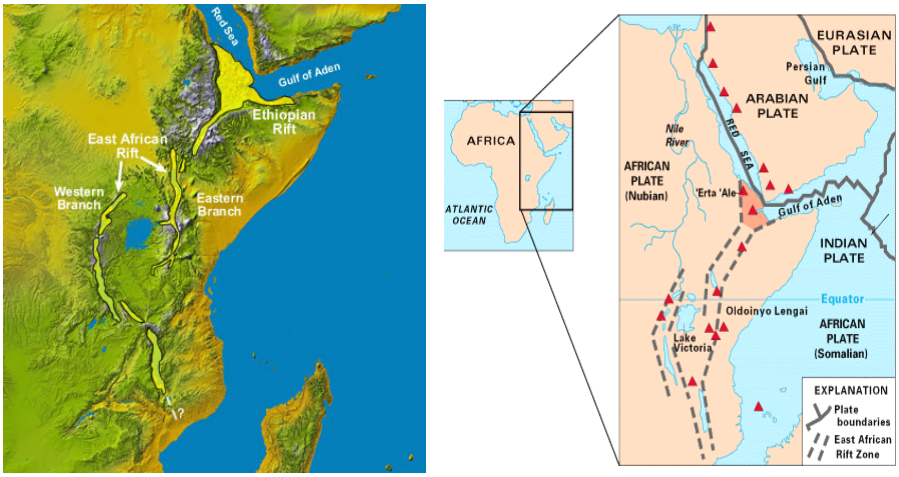


FIGURE 1: The Great East African Rift System

Despite the high geothermal potential of the EARS, only Kenya and Ethiopia have installed a capacity of about 217 MWe. Countries such as Djibouti, Eritrea, Tanzania, Uganda, Rwanda and Comoros are at various exploration stages. So far, other countries such as Burundi, DRC, Malawi, Zambia, and Mozambique have not gone beyond the inventory work of resource potential.

The governments of East African Countries are keen to investigate and further develop geothermal energy in order to supplement and diversify energy sources. This commitment arises due to:

- Strong growth in electricity demand & urgent need to increase access to electricity
- Hydro proven unreliable as a base load source due to climatic fluctuations
- Volatile price of petroleum fuels etc.

All East African countries import petroleum products mainly for transport and electricity production. Renewable energy sources (hydro, geothermal, solar, etc.) represent a small portion of total energy production, averaging less than 10% for hydropower, solar, wind and geothermal production combined.

Hydropower is currently the predominant mode of electricity production in the region (~70%), yet climatic fluctuation and silting of reservoirs pose questions concerning the reliability of these resources. Thermal production (mainly diesel generation) is used in most countries and is the only source of power production in Eritrea and Djibouti. Volatile prices and high import costs make diesel based power production costly.

Therefore, to decrease imports and save foreign currency and in the face of the increasingly recurring severe drought it is important for the region avoid relying solely on hydroelectricity and to make geothermal energy generation a complementary part of future development, as generation mix. Most of the East African countries with geothermal potential are turning to their own indigenous resources to help them meet their growing energy needs.

Geothermal energy presents a clean and more environmentally friendly alternative to more traditional fuels. Geothermal energy has the potential to provide long-term, secure base-load energy and greenhouse gas (GHG) emissions reductions. Accessible geothermal energy from the Earth's interior supplies heat to generate electric energy and for direct use. Climate change is not expected to have any major impacts on the effectiveness of geothermal energy utilization, but the widespread deployment of geothermal energy could play a meaningful role in mitigating climate change.

This paper is an update and a summary of literature review from various papers presented and/or published in various geothermal workshops and conferences and their proceedings. The paper also covers the main observations, strategies for development and regional geothermal development approach.

2. PRESENT STATUS IN DEVELOPMENT AND UTILIZATION OF GEOTHERMAL ENERGY

2.1 The world

The history of geothermal usage began with bathing, washing, and cooking by native peoples throughout the world. One of the earliest historical uses of power from geothermal energy was produced in Larderello, Italy, in 1904.

At present, a total of about 24 countries in the world have over 10,000 MW generating facilities that use geothermal energy. Many more use the energy resource in agriculture, industry, especially in agro-industry, and in the health, recreation and tourism industries.

A developing country, the Philippines, is now the second world leader (next to USA) in geothermal resource development, having nearly 2,000MW installed electricity generation capacity using geothermal resources. This capacity is about ten times the total electricity generation capacity from geothermal sources in the East Africa Region.

2.2 The East African rift region

Using today's technologies, Eastern Africa has an estimated potential of more than 15,000 MWe. Despite this potential, only Kenya and Ethiopia have geothermal operations as part of the country's electricity generation infrastructure. The progress of geothermal development in the region is affected by (among others):

(i) High upfront cost of exploration including drilling;
(ii) Inadequate access to funding and guarantee;
(iii) Inadequate policy and legislation as well as institutional and regulatory framework to attract private developers and
(iv) Inadequate infrastructure and database in resources.

East African countries that have identified the presence of geothermal energy resource and/or carried out research on, geothermal resources include: Burundi, Comoros Islands, Djibouti, Democratic Republic of Congo (DRC), Eritrea, Ethiopia, Kenya, Rwanda, Malawi, Tanzania, Uganda and Zambia. Brief description of exploration and utilization of geothermal resources in some Eastern Africa countries is given below.

2.2.1 Kenya

In the East African Rift region, Kenya is the leader in advancing geothermal resource exploration and development. This has partly been due to the problems that it has in developing its limited hydro resources and the successes that it had in small scale development since 1981. Kenya's first electricity generating plant has been operating now for more than 25 years and has proven reliable and economic, running at 98% availability. This compares very favourably with the 50-60% that is typical for hydro-power plants, effectively reducing the investment cost per unit of energy produced. This has confirmed experience elsewhere that geothermal power plants operate at much higher load factors compared to hydro and are particularly suited for base-load power supply. This has encouraged Kenya to speed up its geothermal power development program and is now generating about 210 MWe.

Kenya has fast tracked the development of geothermal resources in the country as a source of affordable and clean power. The Government established the Geothermal Development Company (GDC) with the sole purpose of making available enough steam for electricity generation by Independent Power producers (IPPs) and KenGen. At present, GDC is carrying out deep exploratory drilling in Menengai. Menengai is the second geothermal field outside of the Olkaria geothermal field. Other geothermal areas such as, Eburu, Silali, Longonot, Suswa, etc. are at a various stages of exploration (Figure 2).

In the process of these activities, Kenya has acquired considerable expertise in geothermal related earth sciences and engineering. It has also lead to a development of the institutional infrastructure that is necessary for geothermal resource exploration, development and utilization.

At present, the Government of Kenya submitted a project proposal to the United Nations Environment Programme for acquiring technical and financial assistance to carry out surface investigations in Silali geothermal prospect area with a view to confirm the resource potential and minimize the drilling failure risk.

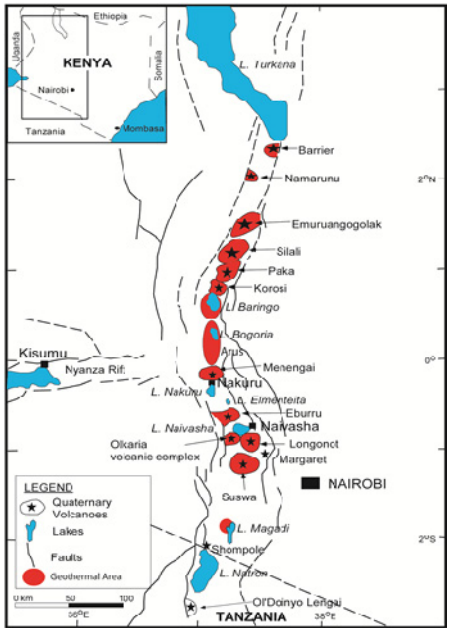


FIGURE 2: Location of geothermal prospects areas in the Kenyan rift (Omenda, P. 2010)

2.2.2 Djibouti

Djibouti lies at the junction of three active, major coastal spreading centers: (a) the Eastern Africa Rift zone; (b) The Gulf of Aden Rift; and (c) and the Red Sea Rift (Figure 3). This structural junction is unique being the focal point of very high heat flux.

According to various studies (GEA, 1999; Mohammed, 2010) the geothermal potential in Djibouti is between 230-860 MWe from a number of prospects including: (i) Lake Assal; (ii) Lake Abbe; (ii) Hanle; (iii) Gaggade: (iv) Arta; (v) Tadjourah; (vi) Obock; (vii) and Dorra (Figure 3) .

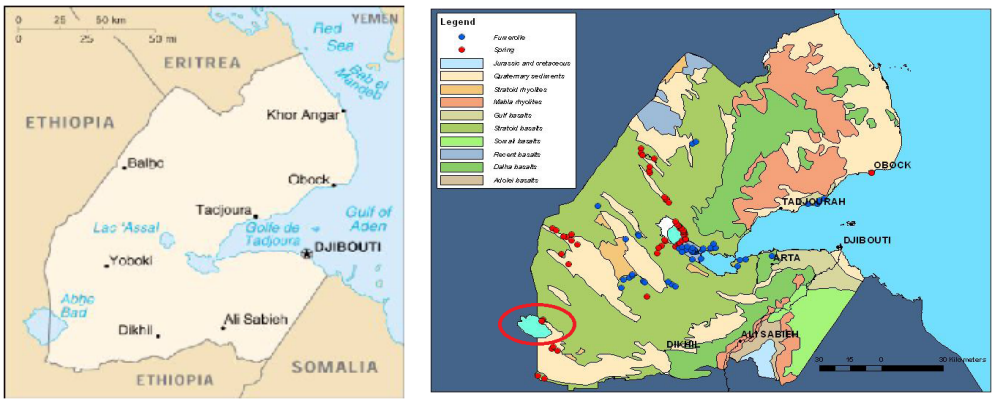


FIGURE 3: Location of geothermal prospects areas in Djibouti (Mohammed, 2010)

Much effort has been expended in Djibouti since the 1970s, in view of the country being deficient of indigenous energy resources. Djibouti's' current energy production is by fossil fuels. The first concerted effort to assess and explore Djibouti's geothermal resources took place in the Assal area from 1970-83. About six exploratory wells were drilled in the Assal geothermal fields. While a very high temperature system has been successfully located, problems related to high salinity of the discovered fluids, which is due to the close proximity of the field to the Gulf of Aden, has delayed resource development and exploitation.

Recent geothermal investigations have also been carried out in Djibouti in new target area of the Lake Assal Rift Zone, in Nord Gubhet and Lake Abhe geothermal prospect areas (Mohammed, 2010).

2.2.3 Eritrea

In 1973, the United Nations Development Programme (UNDP) identified potentially significant exploitable geothermal resources in Eritrea. In 1995 with help of United States Geological Survey (USGS), Eritrea identified the Alid geothermal prospect area for follow up detailed investigations. This area is located about 120km south of Massawa (Figure 4).

The eastern lowlands of the country are of potential geothermal interest. First priority was given to the Alid Volcanic center for exploration as it has numerous manifestations in the form of hot springs and fumaroles. Detailed geoscientific investigations revealed a reservoir temperature of about 250°C (Yohannes, 2011). There are also other sites (e.g. Nabbro Dubbi) suitable for discovery of a high temperature resource. A recent volcanic eruption took place in Nabbro Dubbi area (Yohannes, 2011).

At present, the Government of Eritrea submitted a project proposal to the United Nations Environment Programme for acquiring technical and financial assistance to carry out surface inviestigations in Alid geothermal prospect area with a view to confirm the resource potential and minimize the drilling failure risk.

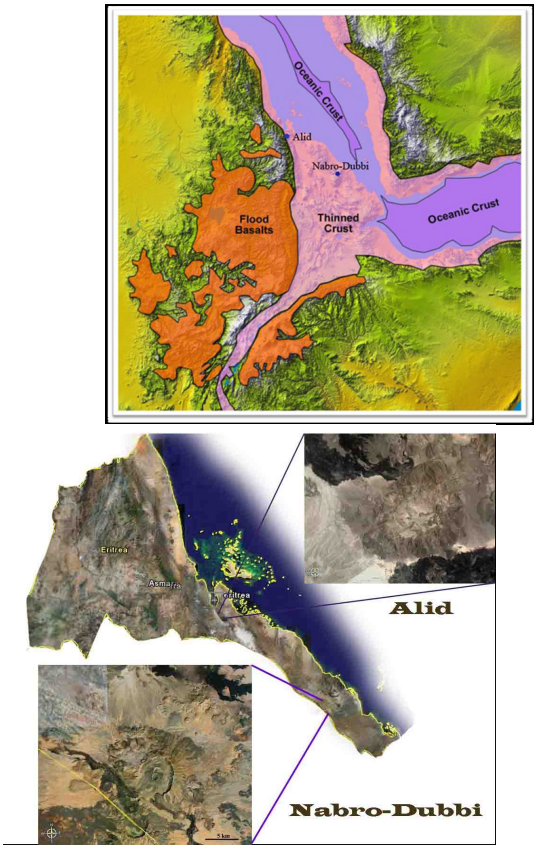


FIGURE 4: Location of geothermal prospect area in Eritrea (Yohannes, 2011)

2.2.4 Ethiopia

Ethiopia started a long-term geothermal exploration undertaking in 1969. Over the years, a good inventory of the possible resource areas has been built up and a number of the more important sites have been explored in the Ethiopian Rift Valley. Of these areas, about sixteen are judged to have potential for high temperature steam suitable for electricity generation (Figure 5). A much larger number are capable of being developed for direct utilization of geothermal heat in agriculture, agro-industry etc.

In Ethiopia, estimated geothermal resource potential for power generation is about 5,000 MWe. So far, exploratory drilling has taken place in Aluto-Langano (1982 to 1985) and Tendaho (1993 to 1998) geothermal fields. Detailed surface exploration has been completed in four other geothermal prospect areas (Corbetti, Abaya, Dofan Fantale and Tulu Moye).

A 7.3 MWe geothermal pilot power plant has been installed at Aluto. This pilot plant is currently generating about 4 MWe. Feasibility study for the expansion of the Aluto Langano Geothermal power has been recently completed with the Japanese Overseas Development Assistance. The study indicated expansion of the Aluto Geothermal power to additional 35 MWe is feasible (Kebede, 2010). On the basis of this study, drilling of four deep appraisal wells is planned for 2011 with the technical assistance of government of Japan and loan from the World Bank. Other geothermal prospect areas in the Ethiopian Rift Valley that are at reconnaissance stage of exploration are: Teo, Danab, Kone and others (Figure 5).

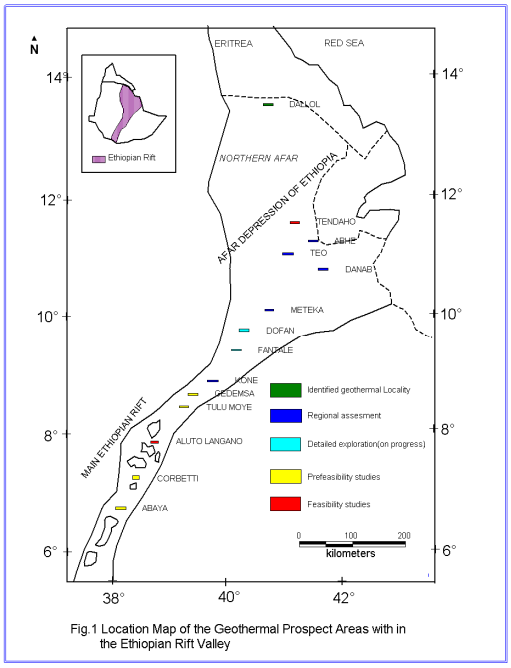


Fig.1 Location Map of the Geothermal Prospect Areas with in the Ethiopian Rift Valley

During the four decades that the geothermal resources exploration work was carried out in Ethiopia, a good information base and degree of exploration capacity has been developed. This is especially true in the human capacity and basic infrastructure development that will be critical in ensuring that future selected resources sites are advanced to the development phase much more rapidly than before.

FIGURE 5: Location of geothermal prospect areas in Ethiopia (Teklemariam and Kebede, 2010)

At present, the Government of Ethiopia submitted a project proposal to the United Nations Environment Programme for acquiring technical and financial assistance to carry out further surface investigations in Tendaho geothermal prospect (new target area) with a view to confirm the resource potential and minimize the drilling failure risk.

2.2.5 Tanzania

Geothermal exploration in Tanzania was carried out between 1976-79. Reconnaissance studies for surface exploration were carried out in the north (near Arusha, Lake Natron, Lake Manyara and Maji Moto) and in the south (Mbeya region) (Mayalla, 2010). Geothermal work in all locations in Tanzania is at the surface exploration stage.

Two potential target areas for geothermal exploration singled out so far are: (a) Arusha region near the Kenyan border in the North; and (b) Mbeya region between Lake Rukwa and Lake Nyasa in the southwest (Figure 6). Another potential area (Luhoi) was prospected during 1998-2002 by First Energy Company (a local firm). It conducted important project definition and reconnaissance evaluation work. This area is located 160 km south of Dar es Salaam. The work conducted so far indicates the existence of a geothermal reservoir with a temperature greater than 200 °C .

FIGURE 6: Geothermal prospect areas in Tanzania (Mayalla, 2010)

2.2.6 Uganda

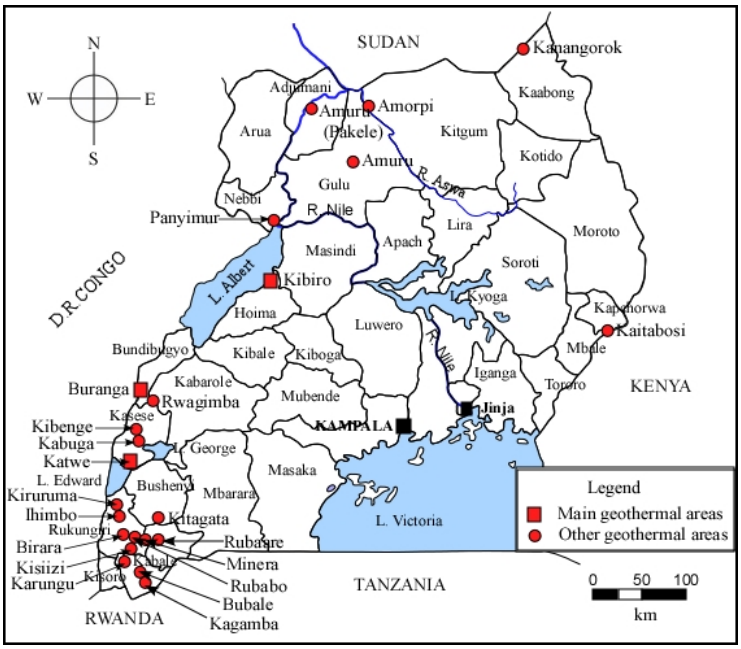
Exploration for geothermal energy in Uganda has been in progress since 1993. The studies have focused on three major geothermal areas namely Katwe, Buranga and Kibiro (Figure 7). The three areas are in semi-detailed to detailed stages of surface exploration (Bahati and Natukunda, 2010). The overall objective of the study is to develop geothermal energy to complement hydro and other sources of power to meet the energy demand of rural areas in sound environment.

FIGURE 7: Location of geothermal prospect areas in Uganda (Bahati and Natukunda, 2010)

At present, the Governmnt of Uganda submitted a project proposal to the United Nations Environment Programme for acquiring technical and financial assistance to carry out surface investigations in the kibiro geothermal prospect area with a view to confirm the resource potential and minimize the drilling failure risk.

2.2.7 Others

Countries such as Rwanda and Comoros are also at a stage of semi-detailed and detailed stages of geothermal resource exploration. Rwanda is now carrying out a detailed geothermal investigation in Karisimbi geothermal field (Gisenyi) with a view to start exploratory drilling and develops power from geothermal energy resource (Irabaruta, 2010). Other countries such as Burundi, DRC, Malawi, Mozambique and Zambia are not gone beyond the reconnaissance geothermal resource exploration and resource potential inventory.



3. LESSONS LEARNED

3.1 Main observations

Exploration, Development and utilization of geothermal energy resources in the East African region for the last four decades have indicated that:

- The region has a large untapped geothermal resource potential (> 15,000 MWe);
- The geothermal resource is an indigenous, reliable, environmentally clean and economically viable, renewable energy resource;
- Development of geothermal resources are constrained by (among others): (i) the risks that are associated with resource exploration and development; (ii) High upfront cost of exploration including drilling; (iii) the financial risks that are associated with investment in power development projects ; and (iii) Inadequate policy and legislation as well as institutional and regulatory framework to attract private developers.
- Diversified use of geothermal energy augments energy supply from hydro power plants and improves the generation mix. It avoids vulnerability to climatic and oil price fluctuations.
- Holistic Utilization of Geothermal energy resource (both Power generation and Direct Uses) can create wealth, tackle food insecurity and boost socio economic development.

4. STRATEGIES FOR DEVELOPMENT

In order to promote the geothermal resource exploration and utilization optimal strategies for development are to:

- look for loans and grants from International Organizations to finance the projects for further exploration and development;
- Look for Private Sector participation and financing from developers, investors, equipment suppliers and development banks;
- Establish long-term conducive policies and incentives that attract private investment;
- Promote Public Private Partnership
- Establish Regional Training Center to build skilled manpower
- Establish a Risk Guarantee fund by donor and development agencies for exploratory and appraisal drilling of projects;
- Set up Regional Network of Geothermal agencies to ensure the promotion and use of geothermal expertise in the East Africa Region.

5. AFRICAN RIFT GEOTHERMAL DEVELOPMENT FACILITY PROGRAMME

The African Rift Geothermal Development Facility (ARGeo) was originated in 2003 with a view of the fact that the East Africa Region has a large untapped geothermal resource potential that is an indigenous, environmentally clean, economically viable and renewable energy resource. The ARGeo Project's objective is to promote geothermal resource utilization by reducing the risks associated with such resource's exploration and development. ARGeo aims to accelerate geothermal energy investments in both public and private sector.

The project is funded by the Global Environment Facility (GEF) and was initiated by six countries: Djibouti, Eritrea, Ethiopia, Kenya, Tanzania, and Uganda. The project has two main components: (i) a Regional Network and Technical Assistance component implemented by United Nations Environment Programme (UNEP) and (ii) Risk Mitigation Fund component implemented by the World Bank (WB). The WB and UNEP are the Implementing Agencies for their respective components of the project.

The project partners are: the Icelandic International Development Agency (ICEIDA), the German Federal Institute of Geosciences and Natural Resources (BGR), the United Nations University-Geothermal Training Programme (UNU-GTP), and the International Atomic Energy Agency (IAEA).

The UNEP ARGeo Component has already started its operation whereas the World Bank's ARGeo Component is not yet operational.

5.1 UNEP ARGeo component moving full steam ahead

The ARGeo project was officially launched on November, 22nd, 2010. On that occasion, it was agreed that priority focus (for the UNEP component) be on the upstream geo-scientific surface investigation work of geothermal prospect areas in ARGeo countries. The results of this work would generate viable proposals for exploration drilling to the RMF with minimized drilling failure risks.
Some progress milestones to note:

- Four project proposals from Eritrea, Ethiopia, Kenya and Uganda received for surface exploration studies with a view to minimize the "Drilling Risk"; these proposals were reviewed and prioritized to be technically and scientifically evaluated by the Technical Advisory Team and start surface exploration studies.
- East Africa Countries status report published, report on inventory of equipment and manpower prepared, and East African geothermal data-base developed with the support of ICEIDA.
- UNEP held discussions and reached to an "in principle" agreement with African Union Commission (AUC) – German Development Bank (KfW) with a view to exploit synergy and take advantage of complementarities with its Geothermal Risk Mitigation Facility Programme.
- The Second ARGeo Steering Committee Meeting held in Kenya (September 1, 2011) leading to accelerated plans for implementation. A linked meeting (September 2, 2011) at "ARGeo Ministerial Level" was held leading to greater commitment at political level to move the project forward quickly.

5.2 Expected output of ARGeo

- Potential number of geothermal fields explored in the region;
- Number of geothermal resources sites with confirmed energy potential;
- Number of skilled human resources in geo-scientific investigations and management of geothermal projects;
- Adequate networking and information exchange;
- Partnership developed and synergy and complementarities created.

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STATE OF KNOWLEDGE OF THE GEOTHERMAL PROVINCES OF THE REPUBLIC OF DJIBOUTI

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ABSTRACT

Owing to an exceptional geodynamic situation, the Afar Depression, an emerged triple junction of the Red Sea, Gulf of Aden and East African rifts, where volcanic and tectonic activity occurs since 30 My, the Republic of Djibouti (23000 km2) is characterized by numerous current and past hydrothermal activities. Schematically, the country can be divided in two sectors, westward regions composed of plateaus and plains formed since 3.4 My and Eastward regions elevated and mountaineous lands separated by the Gulf of Tadjourah ridge. Most of the current hydrothermal activities are located in specific zones of the recent western regions formed by the opening of the Afar Depression and the Danakil plate anticlockwise movement. Few other current and past hydrothermal activities are found in the Eastern part around the Gulf of Tadjourah ridge. Already in the early geological explorations these hydrothermal manifestations were described as a result of potential geothermal resources.

About twelve geothermal provinces are identified in the country according the location of surface manifestations. All of the surface manifestations are fracture controled and occur within the recent volcanic and sedimentary rocks or at the contact of recent and old formations. Asal rift and Hanle/Gaggade areas were considered as priority sites for geothermal explorations. Gradient wells and geophysical prospections were undertaken at different stages to assess geothermal reservoirs on these prospects. Deep drillings revealed a high enthalpy reservoir in Asal rift zone and a low enthalpy reservoir at medium depth. Results in Hanle plain demonstrated low temperatures caused by a high underground fresh water flux.

Although potential geothermal reservoirs have been recognized in the Republic of Djibouti, the power generation from geothermal energy is still to be achieved. However, given that energy is a key sector for the economic and social development of the country to alleviate poverty, the Government of the Republic of Djibouti is strongly committed in developping as much as possible the geothermal resources. Over the years 2000, Djibouti conducted a significant policy of capacity building of CERD, the national research center, in order to give the capability to realize prefaisability studies for the geothermal prospects. As a result CERD has completed the Nord-Goubhet surface studies and will finalize the lake Abhé prospect studies by the end of 2011, including well siting.

1. INTRODUCTION

The Republic of Djibouti is one of the several African countries located on the East African rift system where geology is also resulting from the two other ridges of Red Sea and Gulf of Aden. Such a particular geodynamical situation gives to the area a remarkable position for the development of the geothermal energy. Effectively, the underground heat sources are expressed on the surface by numerous hot springs and fumaroles mainly distributed on the Western part of the country and along the Gulf of Tadjourah ridge. In spite of the significant geothermal studies and the deep drilling explorations conducted since 1970 on several geothermal prospect zones, the geothermal energy in Djibouti is still to be developped. However, since few years, Djibouti enters a new era for the geothermal resources with the involvement of the private sectors in the Asal rift and in the region of lake Abhe.

This paper summarizes exhaustively all the geothermal explorations undertaken in the Republic of Djibouti. The most advanced exploration prospects, recognized by deep drilling, are first described and analysed: Asal rift and Hanlé. Secondly, the Nord-Goubhet and Arta prospects are presented for their relatively complete surface studies. Finally, the other potential geothermal zones are summarized with a more detailed presentation for Obock and Lake Abhé prospects, and the advancement of the geothermal exploration sector in the Republic of Djibouti.

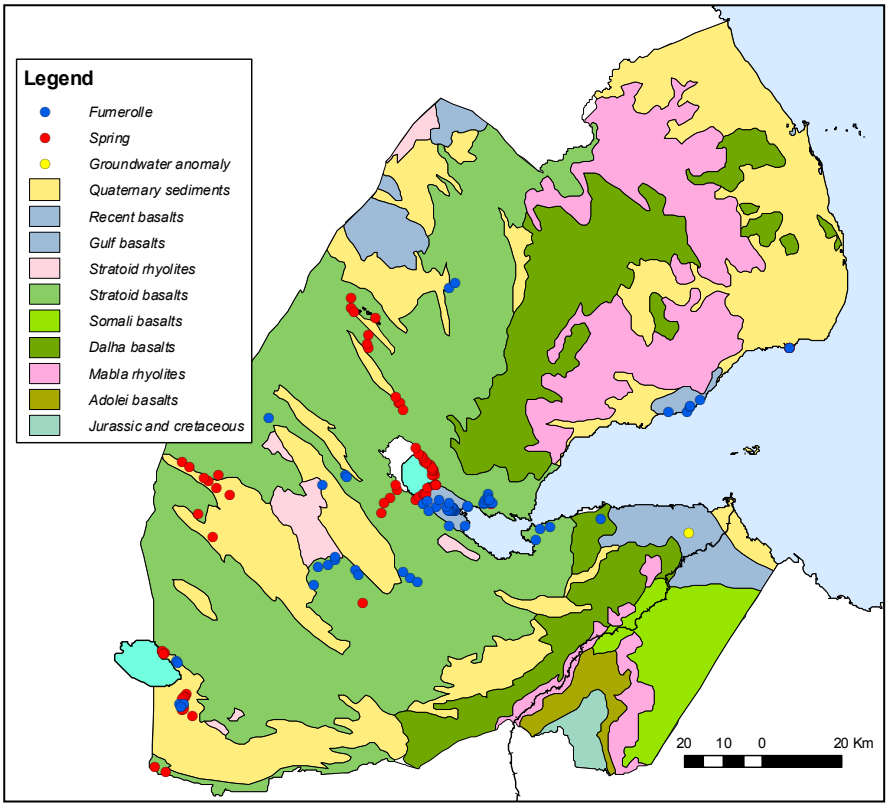


FIGURE 1: Geology and hydrothermal activity of the Republic of Djibouti

2. GEOLOGY

The volcanic series overlie the basement rocks (Jurassic limestones and Cretaceous sedimentary rocks) as a result of the Red Sea, Aden gulf and East African rifts triple junction system, related to plate tectonic movements in the last 25-30 Ma. Adolei basalts characterize the first rupture movement within the Arabo-Nubian block which occurred during the later Miocene period (Figure 1).

During these first movements the area is under an Ethiopian rift tectonic pattern with N-S extension faults system (Gaulier and Huchon 1991). There then followed a period of slow expansion during which the Mabla rhyolites outcrop formed (15 Ma) in a large senestral shear zone. Oldest Ethiopian structure oriented N-S to N20°E are reactivated as senestral strike-slip faults. Mabla rhyolite located in

the Northern part of the country were then submitted to a diffuse extension phase with associated N160°E normal fault system. After an interval during which these rhyolites were eroded, the Dalha basalts were laid down with an angular unconformity (3.4 - 9 Ma). The Somali basalts outcrop was formed practically contemporaneously in the eastern part of the region. N160°E extension links to early movements during the emplacement of Dalha basalts. Progressively this extension turned to N20°E. Between 3.4 and 1.5 Ma, the Stratoid basalts and Gulf basalts poured out as the Gulf of Tadjourah opened (Black et al., 1974; CNRS-CNR 1973). At the early stage of the opening of the Gulf of Tadjourah the western border of Ali Sabieh horst acts as a wide dextral strike-slip zone with related N-S to N20°E extension which turned to N40°E. Recent volcanic formation are mainly located in the Asal rift and the Manda Inakir rift.

Sedimentay rocks are encountered in coastal areas, in tectonic basins in the southwestern part of the country and along the main stream beds. During the miocene-pliocene, sedimentary rocks (clays and alluviums) are interbedded in Dalha basalts. Alternative humid and arid climates went through the pliocene period with the outcrop of stratoid basalts. Limestones, clays and diatomites are interbedded in these basalts and fill tectonic basins. In the plains, the thickness of the sedimentary rocks can exceed several hundred of meters and in stream bed it remains between some meters to some tens of meters. During the quaternary period, marine sediments (coral limestones and limestones) were deposited in coastal areas. Since 100 000 years BP five phases of major extension of lakes in the tectonic basins were developped during the humid climates and has formed limestones, diatomites and clays outcrops (Gasse et al., 1980).

3. ASAL RIFT EXPLORATION

3.1 Geochemical origine of the springs and the geothermal reservoirs of Asal

Few geochemical studies were undertaken in Asal rift zone to understand the origine of the numerous springs and the geothermal reservoirs fluids (San Juan 1990; Fouillac et al. 1983; Fontes et al. 1980, 1989). Several groups of springs are identified in the Asal area: Manda springs are located on the Eastern side of lake Asal where Korili spring is considered separately, wadi Kalou springs in the Southern part of lake Asal, Alifita and Eadkorar springs on the Northern side of the lake.

The analysis of the correlations between major elements associated to the study of trace elements as lithium, strontium, bromine and borum, and to the strontium isotopes allowed to show that the fluid compositions can be explained by the sea water-basalt interaction and by evaporation (San Juan 1990). The absence of any anomaly in the bromine/chloride ratio confirms that evaporites dissolution does not intervene significantly in the fluids composition. A vapor dominated geothermal reservoir can be supported by the low value of the bromine/chloride ratio.

All the springs chemical composition analysis show a sea water relationship except one, located in the Kalou waddi in the Southern part of the lake Asal. The latter would have a continental water that has reacted with basalts. The geothermometer gives a maximum of 100°C very close to the emergence temperature. Other springs from Kalou and Korili show also a mixing with lake Asal and sea water. The degre of interaction with basalt is more or less intensive for each groups. This is accordingly to the advancement of the reaction or to the mixing of variable proportion between a water that has reacted intensively and a sea water that has poorly reacted with basalts. It has been shown that the hypersaline water of lake Asal contribute also to the reservoir fluids.

Given the sea water mixing, the geothermometer Na/K could not reveal suitable results. The calculated temperature are lower than 100°C except Eadkorar springs. Equilibrium between water and rocks components has been reached only in the reservoir fluids. Therefore, the superficial water circulations would not be in direct contact with the reservoir fluids, either there is no contact or this contact is limited and followed by equilibrium. Evaporation, is the other factor that must be taken into

consideration to explain the fluid composition. It has been globaly evaluated on the basis of the concentration by evaporation and dilution by the meteoritic waters. Deuterium and 18O relationship shows the effect of evaporation on the fluids. It describes also the mixing of the fluids with sea water and lake Asal (Fontes et al. 1980).

3.2 Geophysical surveys of the Asal rift

Gravimetric survey points out several heavy body anomalies having different dimensions (CFG 1993). Those located in the central part of the rift are correlated with the injection of magmatic chamber and the collapse of the ground. Localy small anomalies could be the result of an intensively fractured zone. The comparison with the aeromagnetic data and the gravimetric modeling, with the help of geothermal data, demonstrate the existence of a basement represented by the old Dalha basalt series, splitted in several compartments delimited by intensive fractured zones.

Accordingly to the AMT method, the investigation depth was limited and did not exceed 400-500 meters thus unavailing characterisation of the deep geothermal reservoir and the shallow reservoir BRGM (1979, 1983). However, the different interpretations of AMT data bring out a fairly good correlation with the previous methods in determining the interface, representative of the Dalha and stratoid basalts contact.

The EM survey has also a limited investigation depth in the order of magnitude of few hundred of meters (ORKUSTOFNUN 1988). The survey was mainly focusing on the Eastern-central part of the Asal rift in the continuation of the well Asal 5. Results presented here are from the interpretations of ORKUSTOFNUN and BRGM. An "upflow" has been demonstrated in the "lava lake" area based on a supposed hydrostatic level higher than sea level and the absence of high resistivities in depth. The top of the conductor body delineates the groundwater flow gradient toward the lake Asal from the Goubhet, sea water. The latter follows the form of the heavy body identified by gravimetry except in the positive wells area in the Southern part where the geological context is different. The analysis of the difference between the resistant layer and the heavy body altitudes establishes the location of heavy and conductor bodies in the zone of Fiale, which configuration could be of interest for the geothermal exploration.

Previously, another EM method called MELOS was applied by BRGM (1973) to contribute in the first exploration wells location. Although the method has a low investigation depth it has pointed out a superficial elongated conductor anomaly on which the first Asal1 well was located successfully. This anomaly is correlated with a main fracture zone in the Southern part of the Asal rift on which several hyaloclastite complexes are recognized. Two conductor anomalies are identified close to lake Asal and Goubhet probably in correlation with the sloping of the gravimetric interface. The third conductor anomaly is located in the productive wells area and therefore it could express a possible extension of the geothermal reservoir.

The contribution of the electrical rectangle method (BRGM 1983) support mainly the previous interpretations for the superficial structure. It corroborates fairly well the gravimetric interface for the Northern resistant anomalies behaviour. Such correlation is not apparent in the productive well area where the conductor characteristics is more to be related to the geothermal reservoir existance as pointed out by the MELOS method.

Two magneto-telluric methods, MT5EX and low frequency, were applied with a limited number of stations. Only the first one could bring out interesting results in comparison with the electrical method (CFG 1993).

The seismicity completed by seismic reflexion and PSV methods were also analysed (CERD-IPGP; Hirn et al. 1988). It appears that the geothermal reservoir(s) identified in Asal1 area has a fractured origin and located on the intersection of main faults. Secondly, 2000 to 2300 m below well ASAL4,

which has reached a maximum depth of 2013 m, numerous and significant anomalies would correspond to the top of a geothermal reservoir. Finaly, the observed seismicity is exclusively concentrated in the "lava lake" area between 2500 and 3000 m dephts. This activity would be explained by the interaction between the top of a magmatic chamber area and water circulations.

As a conclusion, although significant results were obtained for some structural and geometrical settings in the Asal rift based on various geophysical methods, questions on the geothermal reservoirs extensions remain unsolved, either for the deep or the shallow one, respectively at 1000 m and around 700 m depths. This is explained by the limitations of some geophysical method which investigation depth is low. However, their results allow to more adequately programme new geophysical surveys, mainly based upon electro-magnetic methods.

Finaly, within the framework of the new Asal rift project with the Islandic private sector company, Reykjavick Energy Invest, a new geophysical survey applying TDEM and AMT methods to complete the previous data from 1988, was achieved by ISOR. The analysis taking into consideration other available studies led to a new conceptual model for the Asal rift integrating specialy the results from the deep drillings. These studies results together with complementary field works are leading the well siting operations for the next faisability phase.

3.3 Deep drilling findings in the Asal rift

Six wells in Asal have various depths between 1137 m and 2105 m (AQUATER 1989; BRGM 1975a,b). Asal 1, Asal 3 and Asal 6 are in the same area, within an explosion crater of hyaloclastites. Asal 4 and Asal 5 are located toward the central part of the rift. They encountered the superficial underground flow toward Asal between 250 m and 280 m. The stratigraphic analysis and the geological cross section are in good accordance with the general geological settings (Figure 2). The geological series are found up to the Dalha basalts and it is assumed that Mabla series appear down the hole of Asal 4 (CFG 1988). The authigenic mineral assemblage is in good agreement with the measured temperatures in five of the six wells (Zan et al. 1990). Asal 4 is almost well correlated for the two first levels of Asal series and stratoid series, meanwhile Asal 5 in the central part of the rift do not allow any easy correlation. Two clayey layers, pleistocene and pliocene, mark the separation of the three principal stratigraphic units, Asal series, stratoid series and Dalha basalts, in the area of Asal 3, Asal 6, Asal 2 and Asal 4.

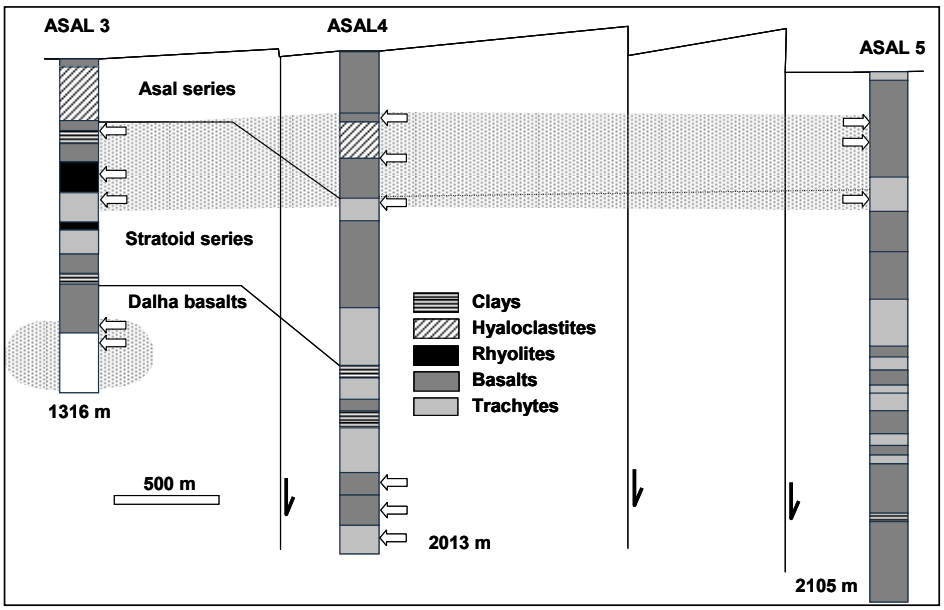


FIGURE 2: Interpreted cross-section in the Asal rift zone

The temperature profiles of Asal 3 and Asal 6 are almost similar and show one intermediate and one deep reservoirs, while the latter do not appear on Asal 4 and Asal 5. The significant inversion on the temperature profile of Asal 5 might be explained by the superficial underground flow toward lake Asal which goes deeper on this well. The flow at higher temperature and at intermediate depths is fed most likely by geothermal fluid circulations in major tectonic faults bordering the central part of the rift. The deep reservoir has been tapped by Asal 3 and Asal 6, the first being located 40 m East of Asal 1 and the second 300 m North-West from Asal 3. Its permeable levels on Asal 3 are at 1075 m and between 1225 m and 1250 m, and on Asal 6 they are between 1100 m and 1300 m. The bottom hole temperatures are respectively 263.5°C and 280°C. At high depths, Asal 4 and Asal 5 exhibited low permeability levels, between 1725 m and 1775 m, and between 1950 and 2000 m for the first, and between 2000 m and 2050 m for the second. Their bottom hole temperatures are 345°C and 359°C.
As the objective of the different geothermal drilling explorations was the deep high enthalpy reservoir, the intermediate geothermal reservoir in the Asal rift zone was neglected and only few datas are available. Asal rift is between Goubhet and Asal lake (150 m below sea level) thus an important underground flux of sea water occurs in the upper part of the recent volcanic series toward lake Asal mainly through the opened fractures. Below the superficial reservoir and before the deep high enthalpy reservoir all the six drillings in Asal encountered the intermediate reservoir (ENEL 1990; Jalludin 1992). According to the stratigraphic analysis of the six well logs, stratoide basalts and rhyolites, and the lower part of the recent volcanic series constitute the intermediate reservoir between 240 m and 600 m depth. In the central part of the rift, zone of Asal 4 and Asal 5, the reservoir is mostly composed of recent basalts of Asal characterized by a high degre of permeability related to the fractures, scoriaceous layers and also holes. In the Southern part of the rift, zone of Asal 3 and Asal 2, the reservoir is represented by the top of the stratoid basalts and rhyolites known for their high permeability too. According to the drilling observations, the rhyolites seem to be the most permeable layers.

The association of the geophysical results to the well log data, suggest the presence of the intermediate reservoir with a certain continuity in the Asal rift area, which is not the case for the deep reservoir (CFG 1993; ENEL 1990; ORKUSTOFNUN 1988; Hirn 1988; Jalludin 1992)

On the wells Asal 1, 3 and 6 temperature profiles describe two anomalies: one related to the deep reservoir and the second between 300 m and 600 m. The temperatures are about 140°C for the upper anomaly which is correlated with circulation losses during drillings. The highest temperature for the intermediate reservoir is yielded on well Asal 5, 190°C, in the central part of the rift. A thermal study on the superficial underground flow from Ghoubet to lake Asal and the thermal leaching, and the comparison to the springs temperatures at the lake of Asal result in a substantial balance between the removed heat and the geothermal flow (ENEL 1990). From this it follows that the lower intermediate reservoir with temperature range of 140°C to 190°C must be thermally protected. Chemical analysis of the reservoir fluid evaluated the total dissolved solids at about 50 g/l which is at least half of the deep reservoir total dissolved solids. This characteristics are particularly interesting from the scaling standpoint.

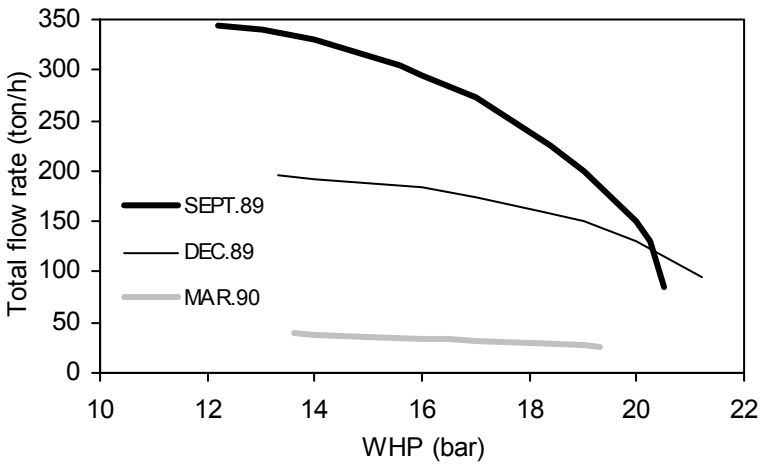


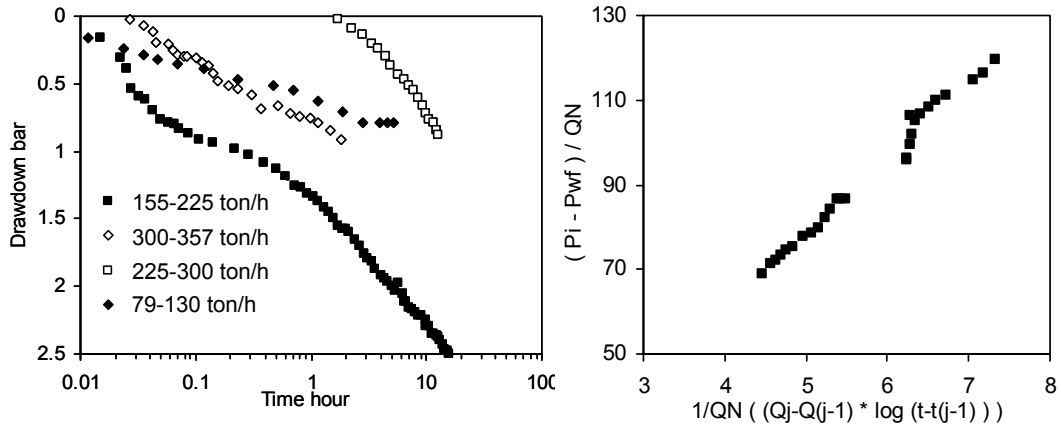
FIGURE 3: Successive output curves of the well Asal 3

3.4 Production tests and well testing in Asal

The deep liquid-dominated reservoir was produced three times for more than nine months in total. At the initial stage the well Asal 3 evidenced high range of mass flow rates, as have been measured, 360 t/h for 12.5 bars at the well head with a production temperature of 265°C and a vapor fraction of about 35 % AQUATER (1989). But most of the time the output rate has remained between 160 t/h and 200 t/h. According to the temperature profiles, the productive zones are between 1000 m and 1300 m. The total dissolved solids content in the reservoir is about 116000 ppm and the non condensable gases yield for 1700 ppm mainly represented by CO2. The analysis of the production data pointed out several changes in the reservoir and the wellbore conditions during and at the end of the production: important decrease of the output (Figure 3), the bottom hole pressure dropped by 3.5 bars and scaling was observed in the wellbore and the surface equipements. Scale samples analysis showed sulphides (PbS, ZnS) deposits at high pressure and amorphous silica with Mn and Fe at low pressure (BRGM 1975; VIRKIR-ORKINT 1990). Calcite deposits in low proportion has also been detected within the wellbore. A caliper was run down and measured a maximum of 10 mm of scaling in the flash zone and around 6 mm to 8 mm up to the wellhead. Resevoir engineering studies (Battistelli et al. 1991) concluded that the Asal 3 output decline was related to a combined effect of the wellbore scaling and the decrease in average reservoir pressure. The reservoir might be limited in extension by reservoir boundaries as a decline of the bottom hole pressure is observed. It is also demonstrated that the wellbore scaling represents the main factor that constrains the deliverability of the well.

Well test data analysis has been conducted mainly with semilog, Agarwal, multirate drawdown and build-up methods (Figure 4). Transient pressure measurement were undertaken at 1075 m depth. Permeability-thickness product calculated from well test data gives 6.3 dm and 15 dm for Asal 3 (AQUATER 1989; Battistelli 1991; Jalludin 1996). Asal 1 and Asal 6 in the area of Asal 3 are characterized respectively by 2 dm and 5 dm. A low value of Kh has been obtained for Asal 4, 0.6 dm. It is assumed that the reservoir has a relatively high permeability in a limited area close to the well Asal 3 and the boundary effect is confirmed by the low permeabilities of Asal 1 and Asal 6. With a specific well test method Battistelli (1991) interpretated the behaviour of the reservoir as a double porosity medium but noted that the permeability is in majority controled by fractures as already pointed out by BRGM (1981). According to VIRKIR-ORKINT (1990) interference test in Asal 3 zone the storativity is low indicating an average porosity of 5% or less. From the available results it seems that the deep reservoir is limited to the Asal 1 area and does not extend in the transverse direction of the Asal rift. Localy the permeability could be high enough to sustain geothermal wells production but the average permeability would be relatively low in the Dalha basalts.

FIGURE 4: Drawdown and multirate drawdown curves of the well Asal 3



3.5 Recent advancements for the Asal rift prospect

Since the last exploration by drillings in 1988 and other few studies by the 1990 on the corrosion and scaling in the Asal rift geothermal prospect new exploration activities have taken place only by 2008. Such activities were initiated by the cooperation of Djibouti and Iceland Governments and the involvement of a private sector, Reykjavick Energy Invest, REI. Within the frame of this new exploration phase, agreements including general agreement, the head of terms of the document project and the head of terms of the power purchase agreement were signed.

The programme realized a new and complete geophysical coverage of the Asal rift using TEM and MT methods. From this 106 TEM and 102 MT soundings were executed. In addition a tectonic/structural survey was conducted based on aerial and satellite images and field works (Figure 5).

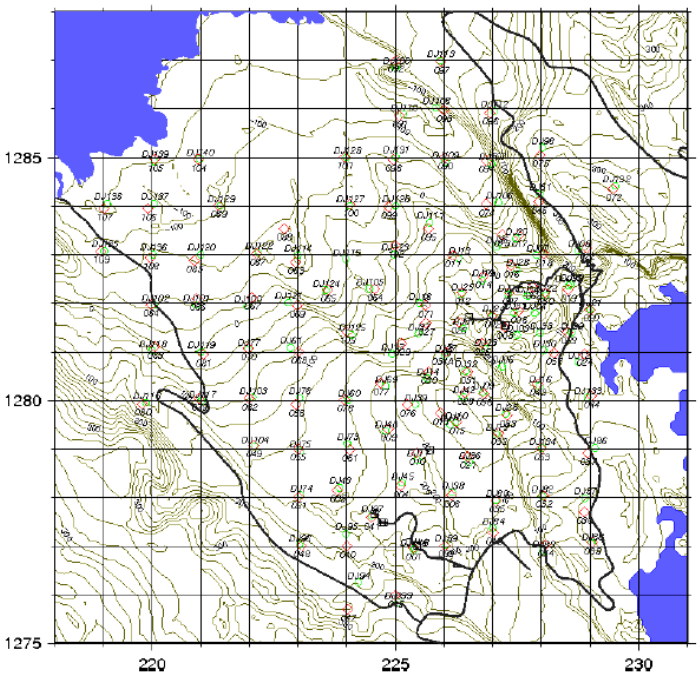


FIGURE 5: TEM and MT surveys of Asal rift (REI-ISOR 2008)

The analysis of the results brought REI to propose a more targeted area of exploration within the Asal rift, known as Fiale and represented by a collapsed large caldera. The previous explored area of the well Asal 1 is located close to the Southern margin of the Asal rift. Based on those results, a faisability study programme was prepared including deviated exploratory wells.

An Environmental Impact Assessment study has been also undertaken by the programme of REI for the Asal rift region.

Given the complex Asal geothermal reservoir with the presence of brine a modeling project has been undertaken. The PhD-project (Daher 2010) involves the study of the Asal geothermal resources based on the analysis of existing and new field data collected by REI. The principal tool used is a detailed numerical reservoir modelling, while other methods of reservoir analysis are used as well as interpretation of underground resistivity data. Chemical data also provide input for the project. The aim of the study is to:

- Significantly improve understanding of the nature of the complex Asal brine geothermal system. Asal geothermal reservoir capacity assessment between 115 and 329 MWe with 95% interval confidence is done by using the Volumetric method.
- Develop a conceptual model of the system on the basis of all available old and new data (geological logs, hydrothermal alteration, chemical analyses, well production). The resistivity data collected from October to December 2007 are of major importance here.
- Develop a numerical model of the Asal system based on forward modelling with TOUGH2. TOUGH2 is a numerical simulator for non-isothermal flows of multicomponent, multiphase fluids in one, two, and three-dimensional porous and fractured media (Figure 6). It is widely used and considered the most advanced and powerful geothermal reservoir simulator available.

- Inverse modelling with iTOUGH2 is applied, which helps in the development of the conceptual model. This inverse modelling software was developed for the non-isothermal, multiphase, multicomponent numerical simulator TOUGH2 to facilitate automatic history matching and parameter estimation based on data obtained during testing and exploitation of geothermal fields. The iTOUGH2 code allows one to estimate TOUGH2 input parameters based on any type of observation for which a corresponding simulation output can be calculated.
- Underground resistivity is incorporated in the modelling study, during forward modelling, and is attempted during the inverse modelling phase.

The numerical model will furthermore be used to select the most appropriate region for future reinjection.

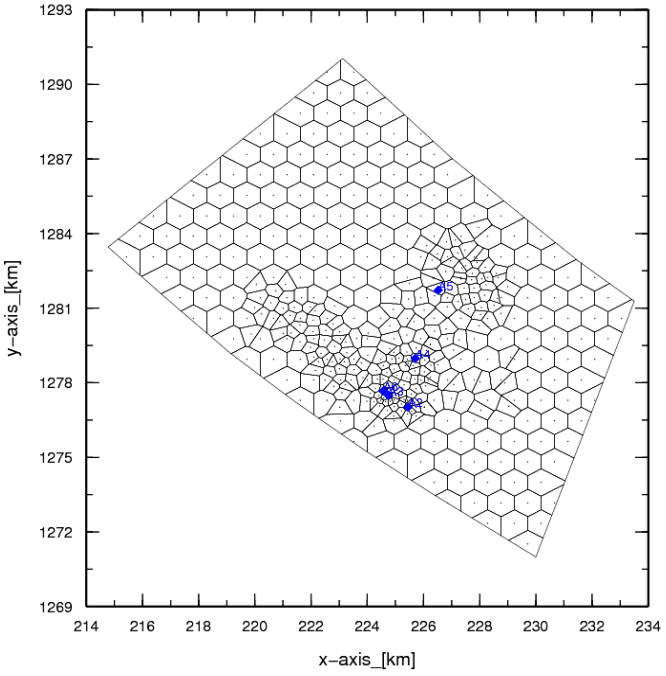


FIGURE 6: Mesh for the Asal rift geothermal system modelling

The next immediate step for the Asal rift prospect is the faisability study with at least three deviated wells in the Fiale area (REI 2008). Such exploration drillings might lead to the development of the geothermal energy with a minimum of 50 MW power plant.

4. HANLE-GAGGADE EXPLORATION

4.1 Surface studies

The prospect site is located in the South-Western region of the country where stratoid basalts circumscribe a succession of high plateaus and sedimentary plains between lake Abhé and lake Asal. Within this wide zone several fumerolles and hot springs are identified in lake Abhé area, Galafi plain, Eastern site of the rhyolitic Baba Alou mountain and along the Northern border of the Gaggadé plain. Temperature of the hot springs can exceed 60°C. The prospection included the plains of Hanlé and Gaggadé.

Geochemical studies undertaken by AQUATER (1981) recognized 5 hydrochemical groups that can be related to the different aquifers or can show mixing between them. The group 1 type is bicarbonated-earth-alkaline and exhibit low mineralisation. It corresponds to the low depth waddi bed alluvium aquifers and is characterized by direct recharge from intermittent stream waters. The group 2 type is chlorinated-alkaline and represents all the boreholes catching the regional volcanic aquifer. Several springs located in Hanle plain at the contact of sedimentary rocks and basalts fault scarps fall also among the same group 2. The springs in lake Abhe area (Gobaad Plain) are characterized by chlorinated-alkaline-earth-alkaline type of waters and form the group 3. The latter may pertain to the group 2. The groupe 4 is represented by the sedimentary aquifers which waters type is chlorinated-bicarbonated-sulfated-alkaline. Finaly, the group 5 correspond to the mixing of waters between goup 1 and group 4, streambed alluvium and sedimentary aquifers. The geochemical anomalies in CO2, NH3 and H3BO3 allowed to define the ascending fluids mechanisms. On the basis of these hydrochemical analysis an underground water circulation model is provided by AQUATER (1981). The schematic

model suggest that there exist an important undergroud flow through the stratoid series which is recharged from the downstream valley of Awash river.

Geophysical prospection has been mainly based upon geoelectrical method (AQUATER 1981) to assess the top of the stratoïd basalts and the sedimentary filling thickness. Previous aeromagnetic data has been also considered and a seismic network was implemanted to determine the seismic activity. The sedimentary filling, identified by low to very low electrical resistivities du to clays, has important variable thickness probably mainly controlled by the underlying Afar stratoïd basalts faults system. This is illustrated by electrical discontinuities in the transverse electrical profiles and the resistivity map. Below this unit the study recognised the group "T" respectively resistant and conductor at its upper and lower part. Its thickness can exceed 200 meters. More deeper, a resistant substratum is represented which upper part can correspond to the top of group "T". Based on geological approach, the group "T" and the resistant substratum are considered as part of the Afar stratoïd basalts. Lower resistivity layers within the group "T" could be explained by intercalation of hydrothermal alteration or layers of a different nature as fluviatile sediments and paleosoils.

4.2 Gradient wells and deep drillings in Hanlé

The first part of the exploration began with three gradient wells of about 450 meters depth in Hanlé plain (Teweo1, Garabayyis 1 and Garabayyis 2) in order to confirm the hydrogeological settings and to assess the temperature gradients before carrying on with the deep drillings (GEOTHERMICA 1985; GENZL 1985). They showed heterogeneous sedimentary sequences comprising sandy aquifers overlying stratoid basalts aquifer. Temperature measurements gave a maximum of 87°C on Garabayyis 2 and the estimated temperature gradients are between 1.3°C/100m and 2°C/100m.
Two deep wells (Hanlé 1 and Hanlé 2) realized in Hanlé plain reached respectively 1623 m and 2038 m (AQUATER 1989). Hanlé 1 recorded a maximum of 72°C at 1420m. After the lacustrine deposits the well crosses a rhyolitic complex between 94 m and 307 m overlying a monotonous sequence of basaltic flows. Permeable zones are encountered in the rhyolitic complex, at the contact with the basalts and in the scoriaceous layers. The well is impervious below 800 m. The maximum temperature in Hanlé 2 is 124°C at 2020 m. The lithological sequence is represented mainly by basalts. Highly permeable levels are found down to 450 m (fluid TDS 2 g/l) and the rest of the well remains impervious (AQUATER 1989; Jalludin 2003).

On the basis of these results on permeability and temperature the ongoing programme in Hanlé was revealed not satisfactory for geothermal purposes.

The discussions upon those data pointed out some arguments to explain the geothermal situation in this area. The bottom hole cores give respectively an age of 1.4 My and 18.8 My for the first and the second well. The late age of the volcanic formation in this part of the Afar Depression denies the hypothesis that the crust under the Hanlé plain is build up with young volcanic series derived from a recent spreading axis. The two gradients measured in the impervious part of the wells give 36°C/km and 24°C/km support that the crust is significantly thick without any shallow thermal anomalies related to intrusions or magma chamber. The fumarole of Garabayyis would therefore represent an exceptionnel situation were the major fault system connect to some very deep thermal anomalies.

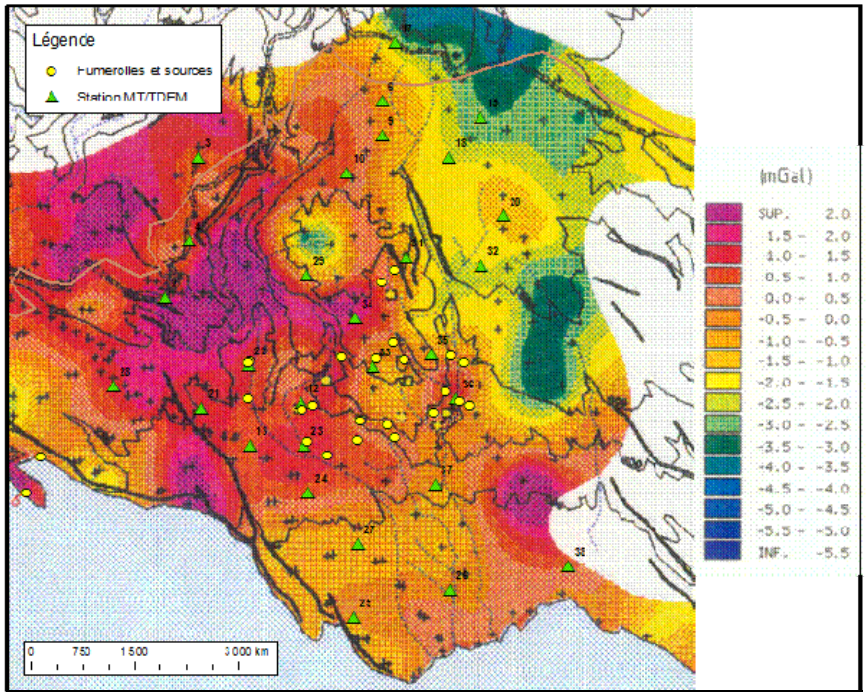


FIGURE 7. Nord-Goubhet prospect with gravimetric survey (BRGM 1983) and TDEM/MT stations by CERD

5. NORD-GOUBHET SURFACE STUDIES

5.1 Previous studies of Nord-Goubhet

The Nord-Goubhet area is located North-Eastward but close to the Asal rift. Goda mountain and Makarassou region are found in the Northern part and the study zone is limited by the sea in the South. Compared to the Asal rift, the area is elevated up to 500 to 600 meters of altitude. The geology is marked by the Dalha basalts outcrops covered by the more recent Gulf basalts and Pleistocene sediments. The fracture network is well developped. The area is situated between different zones of different tectonic pattern and therefore is affected by several tectonic trends: Asal rift NW-SE faults, Makarassou N-S trends (Tapponnier et Varet 1974) and old trends identified in the Goda mountain. As a consequence, the area is tectonically active, confirmed by some faults in the recent sediments and large panels of steep cliffs formed of Dalha basalts (Figure 7).

Along the scarped valleys of the wadis several fumaroles and one boiling spring are found at the bottom of the volcanic cliffs. Different methods applied to the chemical data from the condensate of the fumaroles give estimations for the possible reservoir temperature: 220°C and 170°C (Geothermica 1987). Stable isotopes analysis of the fumaroles describe an assumption of the origin of the waters. Compared to the fumaroles of the Asal rift zone, Nord-Goubhet fumaroles have significantly lower δD and $\delta^{18}O$. It is suggested that no primary steam from undiluted or diluted deep water exist in this zone. Fumaroles would be more likely the result of a secondary steam from previously condensated steam or boiling groundwater (Geothermica 1987).

Three geophysical surveys were conducted in the area of Nord-Goubhet: gravimetry, AMT and electric (rectangle method) (BRGM 1983). The gravimetric results point out several heavy and light anomalies not distributed regularly. Although these anomalies are of low amplitudes they are more or less clearly delimited by the different linear trends, correlated to the tectonic of the area. From their analysis, BRGM retain three main guidelines. First, the Southern Asal rift system delimits light anomalies. Parallel to it and Northward, a large axis comprises a succession of heavy and light

anomalies. In the central part, a similar axis is identified along a NNW-SSE trend. It can be noticed that the major part of the hydrothermal activity is located between these two axis. Finally, light anomalies cover the Eastern part of the prospect. The geoelectrical survey shows globally low resistivities and three main zones can be observed. The first one is located on the Eastern part of the prospect. The second low resistivity area is located on the South-Western zone but higher resistivities are found along a NNW-SSE axis. The last and very conductive area is located in the North-Western part. It has been estimated that the bottom of the conductive zone would reach around 1000 meters. The AMT survey identifies in the central zone of the prospect an uplifted conductive body. The results from the three geophysical surveys cannot be completely intercorrelated. However, findings from the gravimetric and the geoelectrical methods bring out interesting approach of the underground structures in relation with the surface hydrothermal activities that can guide a drilling exploration.

5.2 New surveys at the Nord-Goubhet prospect

A new phase of exploration has been completed by CERD by the end of 2010. This prospection comprises firstly a geophysical survey that applies TDEM and MT methods. Surface manifestations as fumaroles and hot springs are also sampled for geochemical and isotopic analysis. A peculiar analysis is undertaken of the surface manifestations and the weathered zones according to the geology and the structural features.

According to data collected a conceptual model is proposed for the geothermal site of North Goubhet. From the different analyses, it is hypothesized that a heat source is located at depth beneath the horst Moudoud in North Goubhet. This approach is supported by the negative anomalies of the horst and the volcanic crater north of the horst. Throughout the study area, MT reveals very low to moderate resistivity of several hundred meters. Given the geology of the site which is represented by Dalha basalts essentially represent the resistivities alteration caused by hydrothermal activity beneath. Below such impervious zone, it is suggested that low to moderate resistivity are possible targets for the geothermal reservoir. Recharge of the system is provided by runoff in the wadis through tectonic faults. Moreover, given the hydrogeological context of the site, the system would also be recharged by groundwater flow from the Goda Massif. In the coastal zone it is necessary to consider the intrusion of marine waters too.

6. ARTA SURFACE STUDIES

This geothermal prospect zone is located on the Southern shore of the Gulf of Tadjourah and 45 km West from the town of Djibouti. It has been identified by its particular geological situation, the existence of an active fumarole and an altered area significant of a near past hydrothermal activity. The geological formations are mainly represented by the Miocene Dalha basalts and the other units comprise Mabla rhyolites, stratoid basalts and Gulf basalts. The plain is filled with coarse quaternary sediments. The zone shows a particularly intensive fracture network controlled by strike slip faulting and recently by normal faults (Arthaud et al. 1980). This geological situation implies the existence of a volcanic and tectonic activity in the area with the presence of a close magmatic chamber, however this activity would have stopped over the last 2 My ago (Geothermica 1982). This past activity has probably been at the origin of the past hydrothermal activity recognized on the field by the altered areas. The interest for the geothermal development remains as the fractured Arta zone is located close to the Gulf of Tadjourah ridge and there exist surface hydrothermal manifestations.

Geochemical studies of shallow wells and springs determine two main chemical types. One is alkaline-bicarbonated characterizing superficial groundwaters with typical recharge from wadi beds during run off. The geochemical temperature is slightly under 75°C (Geothermica 1982). The second type is alkaline-chlorine in relation with sea water intrusion and probably in relation with underlying high TDS waters as it has been demonstrated in the country (Bouh 2006; Jalludin et al. 2006). The geochemical temperatures range from 75 to 95°C. Likely, these waters do not exhibit any anomaly

corresponding to a possible geothermal reservoir. This fact might be explained by the insulation of the geothermal reservoir by the existence of a cap rock zone. However, the ammonia content in the fumaroles could be the results of the boiling at 100°C of a reservoir of pure alkaline-chloride type (Geothermica 1982).

Two geophysical methods explored the Arta area with gravimetry and electric. The gravimetric survey delineates an upwelling zone with positive anomaly that would be represented by a rhyolitic dôme. The underground structures showed by the mapping of the anomalies seem to corroborate one of the main fracture trends, NE-SW. The main findings from the geoelectrical soundings are constituted by the presence of a several hundreds meters thick conductive layer. Within the scope of the geological situation of the area, this might be related to highly altered volcanic rocks, most likely Dalha basalts, as it is observed also in the field elsewhere. Consequently, from the geothermal reservoir standpoint, this analysis sustain the existence of a cap rock of relatively elevated thickness.

In order to fulfill the geothermal reservoir exploration in the Arta region, Geothermica (1982) suggest that the objective would not be at shallow depth and drilling exploration might cover two thousands of meters to possibly tap a deep geothermal reservoir.

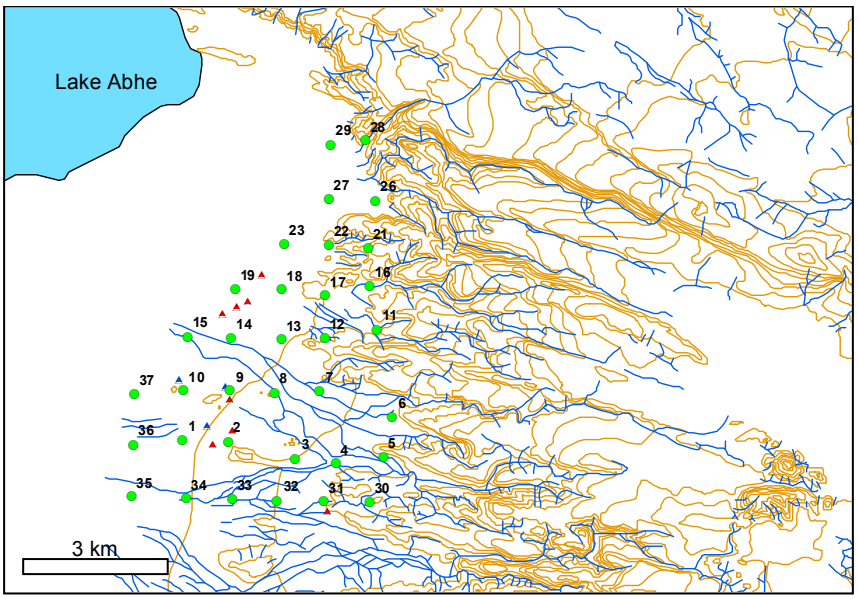


FIGURE 8: Lake Abhe geothermal prospect with MT/TDEM stations

7. LAKE ABHE PROSPECT

Lake Abhé zone is located in the South-Western region of the country, on the border with Ethiopia. This hypersaline lake is the Western end of the Gobaad plain and the Eastern end of the dowstream valley of Awash river coming from the Ethiopian plateau. The geology is characterized by th stratoid basalts plateaus limited by E-W faults configuring the Gobaad plain, filled by quaternary and probably late Pliocene sediments. The lake area is particularly rich of surface hydrothermal manifestations with fumaroles and hot springs but also travertine constructions, some of them being elevated at more than 60 m above ground level. The travertines are aligned on the main fracture trends. Fumaroles are located on those travertines and the hot springs occur at the bottom of these travertine chimneys. The temperature of resurgence of the hot springs is generally higher than 90°C. Only geochemical preliminary studies cover this prospect and give mainly two types of waters. Most of the hot springs are alkaline-chloride-sulphated and few of them present also a bicarbonated type as a result of surface water mixing. The surface hydrothermal manifestations are spread over an area of about one hundred

square kilometres. This observation suggests that in Lake Abhé zone there exist an important thermal anomaly representing potential geothermal reservoir.

CERD has launched the surface studies of the Lake Abhé prospect including geology, hydrogeology, geochemistry and isotopes, and the geophysical survey with MT and TDEM methods. For the geophysical survey 34 stations are covering the prospect beyond the area occupied by the surface manifestations. The analysis of the data is undergoing and the study might be completed by the end of 2011 with the well siting.

8. OTHER POTENTIAL GEOTHERMAL ZONES

Besides the previous geothermal zones explored by advanced surface studies and by drillings for some of them, there are several other potential sites concerned by the geothermal development in the Republic of Djibouti. These geothermal sites are identified by the surface hydrothermal activities, hot springs and fumaroles, and also groundwater abnormally elevated temperatures: Obock, Sakkalol, Tamataco, Wead (Djibouti plain), North of lake Asal, South-Goubhet and Dora. The first two are briefly described in the following.

The Obock prospect zone is close to the town of Obock located on the Northern shore of the Gulf of Tadjourah on its Eastern limit. This geothermal site is based on the resurgence of several hot springs and one fumarole on the beach. Some hot springs can be identified only during low tides. The outcrops close to the hydrothermal manifestations are formed of Quaternary madrepores covered by the alluviums all over the wide Obock plain. In the upstream part, are found the volcanic rocks dominated by the intensively fractured Mabla rhyolites in forms of mountains and scarped reliefs. The fractures on the quaternary plain area are observed exclusively close to the shore as E-W open fissures in the madrepores. Based upon marine geophysical and tectonic studies, the surface hydrothermal activity appear to be related to the near Gulf of Tadjourah ridge which fault system reaches the Obock site (Manighetti 1993). Some geophysical prospections were undertaken for the purpose of groundwater development and also for the geothermal development, but their outcomes are not significant as they are limited in investigation depth or not complete. These are electrical soundings with short AB lenghts (CGG 1965) and magnetic survey with insufficient points (Essrich and Brunel 1990). Geochemical analysis give an alkaline-chloride dominated waters in relation with sea water. Geothermometers found a possible reservoir temperature of 210°C (Houssein 1993).

9. CONCLUSIONS

The detailed glance at the geothermal studies in the Republic of Djibouti, based upon a consistent bibliographical research, results and data analysis, brings out several interesting conclusions as far as methodology-technics and geothermal resources in Djibouti are concerned.

Asal rift zone is the most advanced in exploration with the demonstration of deep and intermediate reservoirs. The applied geophysical methods can be compared in some way to the drillings data but reveal how much the Asal rift is a complex structural system and correlations are not systematically evident. More generally, some geophysical methods applied in the past show their limits in investigating geothermal reservoirs at medium and high depths and their interpretation remains sometimes questionable. New geophysical campaigns applying new technics are therefore necessary to better appreciate the structural features for the explorations and for the reservoirs geometry to give directions for the next drillings.

Numerous surface hydrothermal manifestations clearly located on the Western part of the country where recent stratoid basalts outcrop and along the Gulf of Tadjourah ridge support an important thermal anomaly in these regions. At least twelve sites of surface hydrothermal manifestations are

therefore identified including the Asal rift. The preliminary or advanced geochemical studies describe fairly well the underground thermal water circulations and their relationships with permanent water bodies and meteoritic waters. This is mainly the case of Asal and the South-Western regions. Estimated possible reservoir temperatures from geothermometers range between 170 and 220°C. This knowledge completed with the surface structural features and geology, give a strong support for the existence of geothermal reservoirs in the Republic of Djibouti and for the programmes for their explorations.

The energy sector in Republic of Djibouti needs a clean and cheaper energy in order to boost the social and economical development of the country. However most of the geothermal prospects are not studied and slow down the resources evaluations. Therefore, the Government of Djibouti conducted an intensive programme and actions to build up the capacities of CERD, the national research centre, to be able to undertake the prefeasibility studies of the geothermal prospects.

Those studies are already undertaken since 2010. The research centre of Djibouti, CERD, completed the Nord-Goubhet prefeasibility study with well siting and the lake Abhe prospect is well advanced with data collection for surface studies and its final report might be available by the end of 2011.

The commitment of the Government of Djibouti has brought private sectors on two main prospects, Asal rift and lake Abhe. Asal rift feasibility programme with deviated exploration wells is on the stage to be launched. In the case of lake Abhe prospect prefeasibility studies, surface studies, would start in the next future.

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WHAT DOES GEOTHERMAL COST? – THE KENYA EXPERIENCE

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ABSTRACT

The industrial practice is to use the levelized cost of power to express the cost of power. On the basis of levelized cost, power projects are evaluated for approval, investment and/or financing by prospective investors. The levelized cost is premised on the net present value of cash flows arising from a power project. This cost includes all conceivable costs chargeable to the project. It is designed on the basis of the economic life of the project, the recovery of invested capital, operation and maintenance costs, and the generation of the desired return on investment or profitability to the investors. However, different variants of the levelized cost computation exist with and without taxes and depreciation. The computation that considers tax and depreciation provides better basis for investment decision.

The levelized cost of power is project specific and must therefore be established for each individual project. Published data indicate an upper limit of about 13 US cents per kWh for geothermal projects. Kenya's upper limit is about 10 US cents per kWh. There are many cost factors which may influence the levelized cost. The key among them are project size, well output, wells and plant costs, operation and maintenance costs, interest on debt, loan tenure, payback period and financial leverage. These factors may be categorized as installation or initial investment cost, operation and maintenance costs, capital and financing costs, economic factors costs and legal and regulatory costs.

Sensitivity analyses carried out using a generic financial model indicate that the project size, well output, payback period, loan tenure and financial leverage have an inverse relationship with the levelized costs while all direct costs and interest on debt have a direct relationship. It is further observed that the overall inverse relationship is predominant. The level of sensitivity of the levelized cost is not constant but varies with most cost factors. From this model, the project size, well output, payback and interest on debt may have the most significant impact on the levelized cost. The direct and inverse relationship of the various factors to the levelized cost means that the levelized cost can be optimized by undertaking informed cost factor selection so as to obtain the least cost factor combination.

Often times the installation or initial investment is used to give an indication of what geothermal would cost. This figure must be understood to represent the financial requirement and may not represent true reflection of what the levelized cost of power would be. The installation cost is also affected by the various cost

factors and relates with them both directly and inversely. Published data indicate that installation costs ranges between 2.5 to 6.5 million US$ per MWe. Kenya average installation cost is about 3.6 million US$ per MWe. Kenya is increasingly employing early power generation using modular wellhead generation units.

Use of early generation can greatly reduce the installation cost as well as reduce the levelized cost. They can aptly be incorporated in a project to achieve optimization.

1. INTRODUCTION

1.1 Levelized cost of geothermal electric energy

The cost of generating geothermal electricity is normally expressed on a kWh basis otherwise referred to as the levelized unit cost of electricity. Levelized Cost of Energy (LCOE) is the constant unit cost (per kWh or MWh) of a payment stream that has the same present value as the total cost of building and operating a generating plant over its life (Levelized Cost of Energy Calculation:). Knight has defined the levelized as the times series of the capital and operating expenditure divided by the net power supplied, discounted to their present values (Knight, 2009). While Knight only considers capital and operational cost in his computation, other variants exist that include tax and depreciation (Levelized Cost of Electricity Literature Review). It is an economic assessment of the cost of the energy-generating system including all the costs over its lifetime: initial investment, operations and maintenance, cost of fuel, cost of capital. It is a very useful industrial tool for comparing technologies with different operating characteristics. It is on this cost basis that the geothermal projects are evaluated for investment, approval and financing by prospective investors, governments, consumers or regulators and bankers or credit providers.

On average, the levelized cost for new geothermal projects ranged from 6 to 8 US cents per kilowatt hour. According to Ingvar (Geothermal Energy for the Benefit of the People) quoting UN World Energy Assessment Report indicates electrical energy cost for geothermal to be 2-10 US cents/kWh while Wikipedia (Geothermal electricity) alludes that the levelized energy cost is in the order of 0.04-0.10 € (0.05-0.13 US cents) per kWh. However, it is recognized that the cost for individual geothermal projects can vary significantly based upon the various cost factors, and that costs for all power projects change over time with economic conditions.

Kenya has fixed its feed in tariff for a geothermal plant of 70 MWe or less at 8.54 US cent per kWh. This cost further informs any other development. The country is unwilling to consider proposal whose levelized cost of power exceeds 10 US cents per kWh.

1.2 Investment cost

In addition to the levelized cost, geothermal cost is oftentimes expressed as an investment or installation cost per unit of plant capacity i.e. per MWe. This cost includes all capital expenditure necessary to construct a plant in addition to interest (cost of debt) during construction. It must be understood that the investment cost is a measure of financial requirement. Low or high investment cost may not necessary indicate lower or higher levelized cost electricity. This is because the operation and maintenance cost might outweigh the capital investment for lower investment cost resulting to high levelized cost and vice versa.

Wikipedia indicates that the investment cost for electrical plant construction and well drilling would be about 2-5 million € (2.6-6.5 million US$) per MWe of electrical capacity. In their report (Renewable cost of generation update, 2009), the California Energy commission indicates the projected installation cost for several plants to be between 2.603 and 5.329 million US$ per MWe. Kenya average installation cost as about 3.6 million US$ per MWe.

2. COST FACTORS

2.1 Installation cost

Installation costs are all initial costs excluding transmission and distribution that are incurred in the construction and commissioning of a power plant. The costs can be categorized into resource exploration, appraisal, production drilling and plant construction costs.

2.1.1 Exploration costs

The costs under this category include the cost of desk top data review, detailed surface study, infrastructure development and drilling of exploration wells. Depending on the whether in-house capacity or external consultants are used, the duration, the methodology used, remoteness of the resource, the detailed surface studies including the desk top may cost up to about 2 million US$. The infrastructure is a one off (fixed) cost that entails construction of access roads and water reticulation system. This cost will vary from project to project and is greatly influenced by the project's remoteness and availability of drilling water. It is common practice in Kenya to drill 3 – 4 exploration wells; one as a discovery and two as confirmation wells.

2.1.2 Appraisal costs

Appraisal entails drilling additional wells and undertaking a feasibility study. In Kenya it is typical to drill 6 – 9 appraisal wells. Thereafter, a bankable feasibility will be undertaken on the basis of which the prospect is approved for development. The feasibility study is mainly a desktop study that would include reservoir simulation and undertaking a preliminary design of proposed power plant. The feasibility study would cost about 2 million US$.

2.1.3 Production drilling costs

Production drilling entails drilling to provide adequate steam to operate a specific size of plant at full capacity and reinjection wells. The energy output from individual wells is highly variable, depending on the flow rate and the enthalpy (heat content) of the fluid, but is commonly in the range 5-10 MWe and rarely over 15 MWe per well (2010 Survey of World Energy). The world largest producer well produces about 50 MWe of steam. Several others wells world over produce about 30 MW and others as low as about 1 MW. Wells in Kenya produce between 1.5 MWe (old and shallow wells) and 18.5 MWe. Productivity is a affected by many variables including, well completion size, drilling fluids employed, permeability (primary and secondary), understanding of the field, the development phase, depth and the resource itself. Figure 1 indicates the observation made as drilling progressed at Olkaria IV. The first exploration well produced 1.5 MWe, the first appraisal 4.5 MW and the average production wells output at about 8 MWe.

Wells in high temperature fields are commonly 1.5-2.5 km deep and the production temperature 250-340°C. Kenyan geothermal wells range between a depth of 900 to 3200 m. A typical well in Nevada costs about $10 million to drill. In Kenya, drilling wells using owned rigs cost about 3.5 million US$ and about 6.5 million using hired rigs.

2.1.4 Power plant construction

Rarely does one find cost of geothermal generation equipment stated alone. In addition, the cost of plants would vary even for plants of the same size because they are designed to match the resource characteristics in particular turbine inlet pressure. Recent Kenyan experience has shown that different manufacturers may give greatly varying costs for the same size of plant and field. The price of generation equipment including installation may range between 1.5 million US$ to about 2.8 million US$.

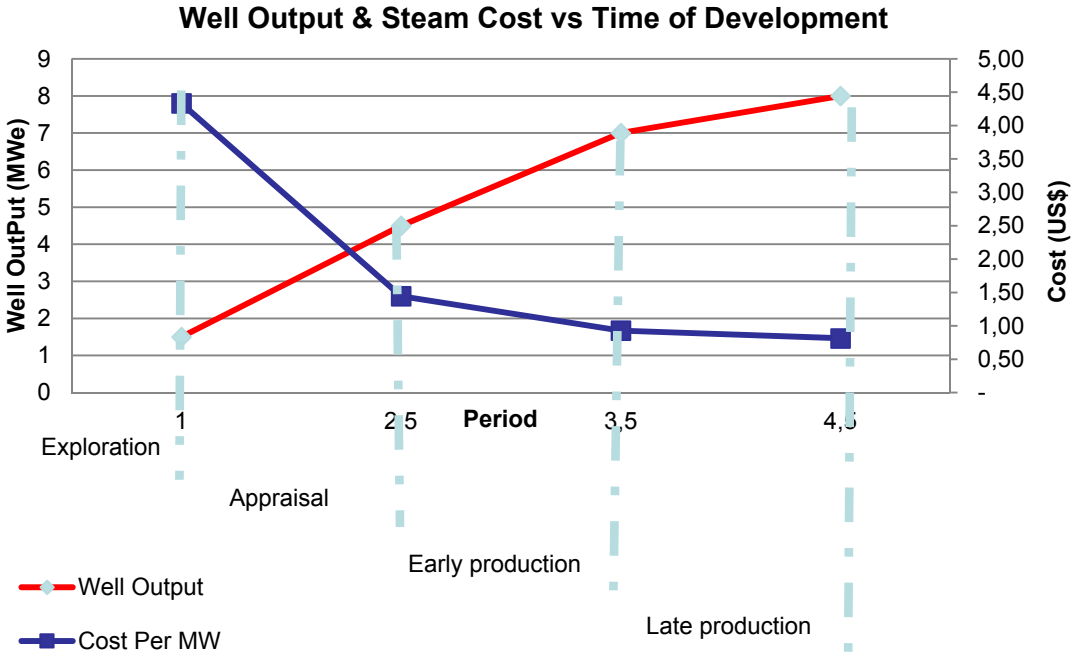

FIGURE 1: Well output over development time, Olkaria

2.2 Operation and maintenance cost

The operation and maintenance cost factors may be categorized as ordinary O & M costs which include staff, administrative and cost of spares, the plant inefficiency, reservoir management costs and cost of capital associated with increased working capital.

2.2.1 Ordinary O&M

The rate of operation and maintenance is fairly low for geothermal. The renewable energy cost of generation update (August 2009) indicates a figure of 0.0117 US$ per kWh. The Kenya experience indicates the cost to be about 0.00763 US$ per kWh (Least Cost Power Development Plan, 2009).

2.2.2 Plant inefficiency cost

Power plants suffer failures and breakdown. They do not operate at design capacity over their entire life but with time the efficiency decreases and the plants require timeout for inspection, repairs, refurbishment, rehabilitation and overhauls. The timeout costs money for maintaining staff and depreciation. This cost is captured through the capacity factor. The renewable energy cost of generation update (August 2009) indicate capacity of 90% for binary plants and 94% for the flash steam plants. In Kenya the range of 90 to 95 % has been used.

2.2.3 Steam field management cost

The steam field requires close monitoring during steam production to forestall serious steam declines, cold flow invasion, scaling and other adverse effects. Management and remedial works may be undertaken including drilling make-up and additional re-injection wells, work-overs, tracer injections and injection of scale inhibitors. These costs will vary greatly from one project to another and from one field to another.

2.2.4 Working capital

Firms require funds in their normal day to day operations. Besides paying out debts that become due, firms need to establish inventories of most critical spares. Experience has shown that lead times for some key power plant parts can be in excess of half year and it is not unusual to receive parts a year after making an order. Capital retained for this purpose will cost the company money to secure. However, the cost of working capital is relatively small.

2.3 Investment and financing cost

As noted in the previous section, implementation and operation of the geothermal projects requires funds. Geothermal projects are financed from equity, revenues accruing from the project and may include debt.

2.3.1 Equity

Investors provide equity in the hope that they will make a return on their investment. The return on equity (investment) constitutes a cost to the project. Investors are residual beneficiaries after payment has been done to lenders/creditor and preferential shareholders. Since payment of dividends is discretionary to the directors, investors offer the project a cushion in cash flow management. They bear greater risk than the other financiers and for this reason they require a higher return. In Kenya, the rate of return on equity (ROE) is 15% and above. The Government requires a ROE of 15%, while private investors would normally ask between 18% and 23% but it is not unusual to get higher requests.

2.3.2 Debt

Geothermal projects are capital intensive; large sums of money are required for their implementation. These sums of money are difficult to raise from a firm's internal sources. In addition, debt is much cheaper than equity. Further, firms prefer to lower their risk profile in a project by adopting project finance where other investors in particular lenders/creditors are invited to share profits and also bear some of the project risk. Thirdly, for most countries interest arising from debt is a deductible expense for income tax purposes. This provides price advantage normally known as a tax shield.

There are many sources of debt which include local and international commercial banks, bilateral and multilateral funding institutions, stock markets (bonds) and pension schemes. Figure 2 shows the various interest rate available to investors. Lending institutions and governments may provide interest free fund (grants) to a project, concessional finance or at commercial rates which also differ from one institution to another. The long term cost of capital from the local Kenyan commercial banks is about 12%. In addition, the long term cost of government infrastructure bonds are slightly cheaper.

2.3.3 Revenues

Revenue is another source of financing for a geothermal project. Revenues arise from the sale of electricity. While in principle equity and debt are designed to finance drilling of wells, buy and install the power plant, revenues are designed to generate resources used for operations, maintenance, debt payback, and to generate profits for the investors. To a firm, revenue costs are zero rated.

2.4.4 Payback period

Payback period is not a cost by itself. However, it represents choices that investors make in order to reduce risk. Power plants have a long life surviving several political regime changes. Investors are always concerned whether the successful regimes will maintain the same policy assuring the investor their return on investment. To minimize this risk, investors may require that a project pays back after

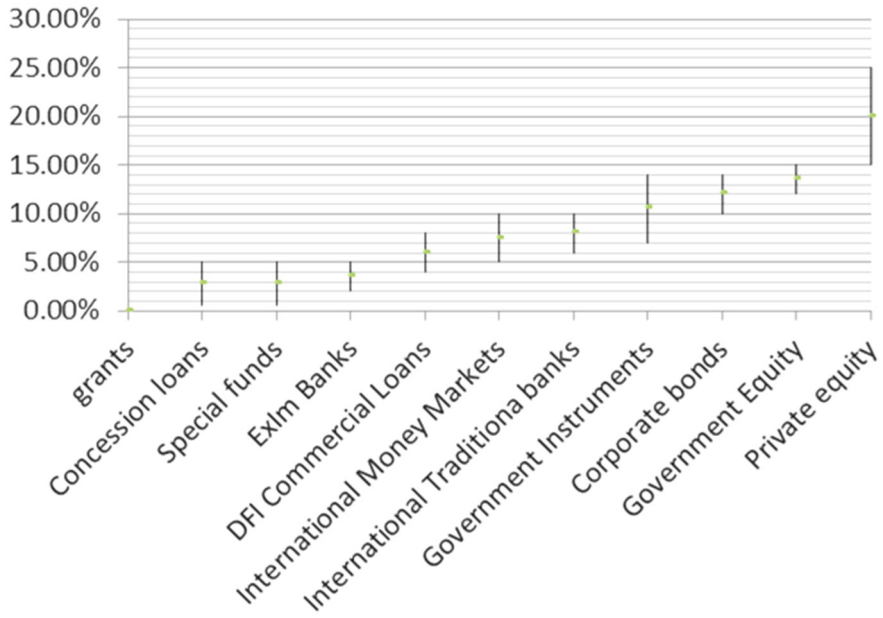

FIGURE 2: Interest rates for various financial sources

a specific period of time. A requirement for a shorter time will have a net effect of increasing the price of generated power.

2.4 Economic factors

2.4.1 Foreign currency exchange rate variation

In Kenya, generation costs are pegged on the US dollar in order to shield both the power off taker and the generator from currency exchange risks. However, the consumers pay for the electricity in the local currency. The cost of the exchange rate variation is assessed on a monthly basis which is then billed to the consumers directly.

2.4.2 Inflation

Over time money loses its value such that a fixed amount of money will buy fewer goods in the future. If left unaddressed, inflation can erode the investors return on investment and may lead to poor management and maintenance of the power plants. In Kenya, the cost of inflation is an aspect of the power purchase agreement and is adjusted on an annual basis.

3.5 Legal/taxation factors

Countries levy income taxes on all profit making entities except in exceptional circumstances. Further they may levy or exempt certain economic sector special taxes or grant tax incentives. In Kenya, the corporate income tax is levied at 30%. However, power plants are exempted from import duty and value added taxes. All power projects will pay an environmental certification levy equivalent to 0.01% of the project cost. It is also anticipated that with the effecting of the new constitution, royalties may be levied on projects by county governments in the future.

3. SENSITIVITY ANALYSIS AND RELATIONSHIP

3.1 Financial model

An analysis of the cost factors show interrelation between the various factors as well as the levelized and installation costs. The fixed cost and in particular the infrastructure cost is seen to be significant for a smaller sized project. However, as the project size increases, the impact of the fixed cost reduces and eventually become negligible. Further, well output is interrelated to the capital cost. As the well output increase the capital cost reduces. This also reduces cost of capital and if fixed financial leverage has been employed, the reduction further reduces the interest which intern reduces the tax shield and price advantage. It will also be noted that increase in the interest on debt have a double effect of increasing equity and additional debt requirement to cater for interest during construction. Increase in interest further improves the tax shield, hence reducing tax effect. Just like the fixed cost, the impact of the cost of drilling to the levelized generation cost reduces as the well output increases and with further increase in well output it becomes negligible. Because of these observations, it is most appropriate to investigate the relationships and sensitivity of the levelized and installation costs to the various cost factors by use of a model.

Pandey (Financial Management, ninth edition) states that investors or shareholders invest in order to increase their wealth. The objective of shareholders' of wealth maximization is an appropriate and operational feasible criterion to choose among the alternative financial actions. It provides an unambiguous measure of what financial management should seek to maximize in making investment and financial decisions on behalf of shareholders. The shareholders' wealth maximization is the net present value of cash flows (after tax) arising from an investment. This definition is consistent with the industrial calculation of the levelized cost of power generation except that it takes tax into consideration. This concept forms the basis of the model used to evaluate the relationship and sensitivity of the levelized and installation costs to the various cost factors.

Table1 enumerates the parameters chosen for the model. The model assumes a plant size of 100 MW and a fixed infrastructure cost. It ignores economic factors and changes in working capital.

4.1 Sensitivity and relationship

Figures 3 to 10 show a graphical representation of results of runs made from the model by varying one or several cost factors at a go while holding the rest constant. Table 2 is a more comprehensive representation of results of key runs undertaken for this paper. The results show that that the various cost factors related either directly or inversely to the levelized and installation costs. Well output, payback period, project size, financial leverage and loan tenure are inversely related to the levelized cost while interest on debt, drilling cost, return on equity, plant capital cost and operation and maintenance cost are directly related to the levelized cost. However, all the cost factors have varying degree of significance in their relationship to the levelized cost. The well output, payback period, project size, financial leverage, loan tenure, interest on debt, drilling cost, return on equity and plant capital cost are observed to have the highest degree of sensitivity to the levelized cost. Further observation of the graphical figures reveals that some cost factors do not have a constant relative change with the levelized cost but relative change changes with change of the cost factor. It is also observed that the various cost factors have also a direct and indirect relationship to the cost of installation even though some don't show any relationship.

A general analysis of the structure of the levelized cost (Figure 11) indicate that return on investment comprise the most significant component of the levelized cost followed by corporate income tax and depreciation respectively.

TABLE 1: Model input data

DEVELOPMENT PARAMETERS			
POWER PLANT		DEBT	
Plant size (MWe)	100	Interest	1.00%
Projected well output (MWe)	5	Grace period	7
Drilling Success Rate		Term	25
Exploration wells	50%	Arrangement fee	0.50%
Appraisal wells	75%	Commitment fee	0.50%
Production wells	90%	Pay-back period	17
Re-injection wells		Debt ratio/equity	70%
Ratio to production wells	1/5		2/7
Unsuccessful wells used for reinjection	30%	TAX	
Ratio of wellhead main plant	0%	Corporate tax rate	30%
GENERATION PARAMETERS		INFLATION AND EXCHANGE RATE	
Excess steam at startup	10%		
Steam decline rate	3%	SALES	
Plant capacity factor	90%		
Economic life (yr)	25	UNIT PRICE	0.1076
Service life (yr)	25	O&M COSTS	0.007
Operational hours per day	24	PLANT SIZE	100.00
Operational days per year	365	Ratio of production/injection wells	1/5
Parasitic load	3%	% steam wells used for reinjection	30%
EQUITY RATE OF RETURN		Estimated well output (MWe)	5.00
Expected rate of return on equity	15%	Drilling cost (US$)	3,500,000
		Drill pad cost (Kshs)	10,000,000
		Exchange rate (Kshs to US$)	85.00
		PIPELINE COST (US$/MW)	400,000
		PLANT COST (US$/MW)	1,500,000
		Well testing cost	30%

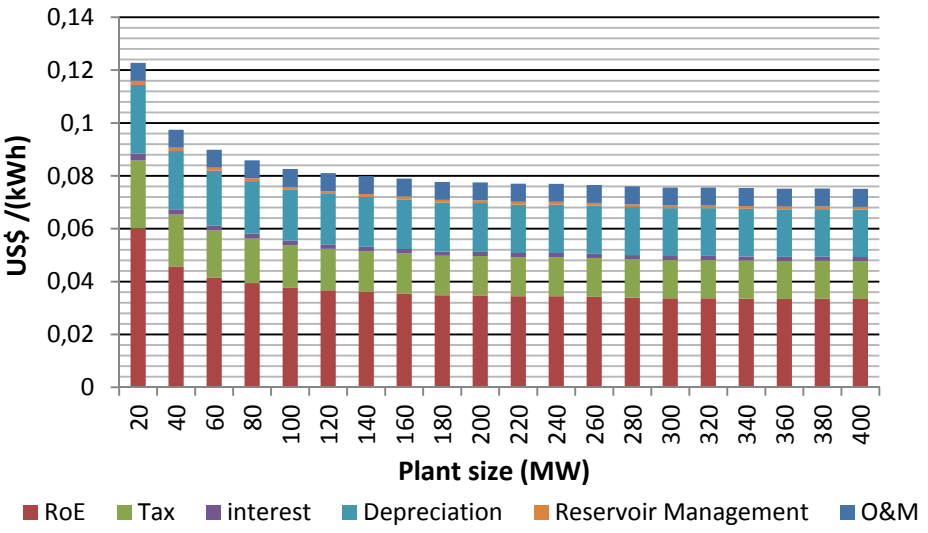

FIGURE 3: Levelized cost at various drilling cost and well output

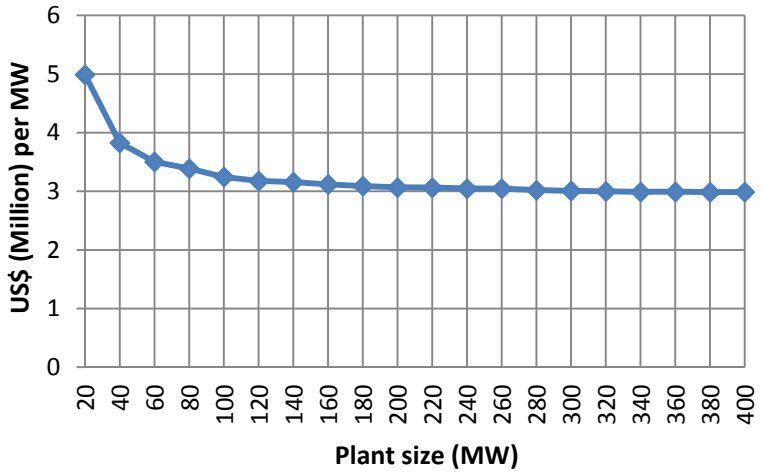

FIGURE 4: Installation cost at various plant sizes

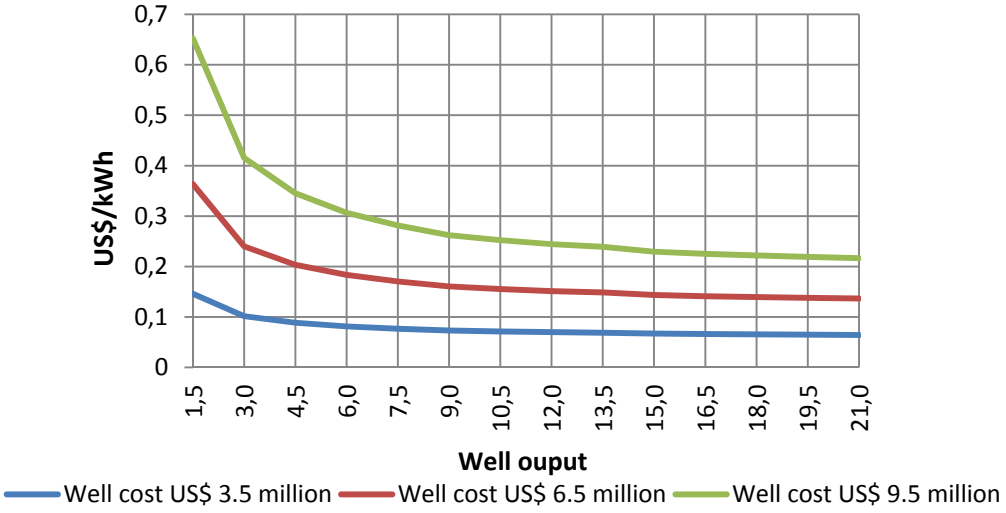

FIGURE 5: Levelized cost at various well outputs and drilling costs

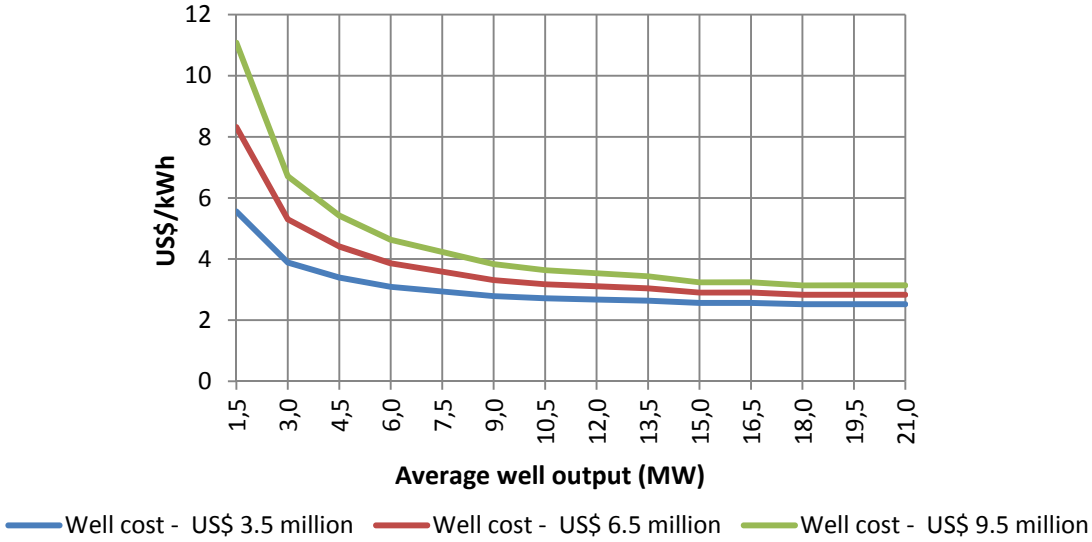

FIGURE 6: Installation cost at various well outputs and drilling costs

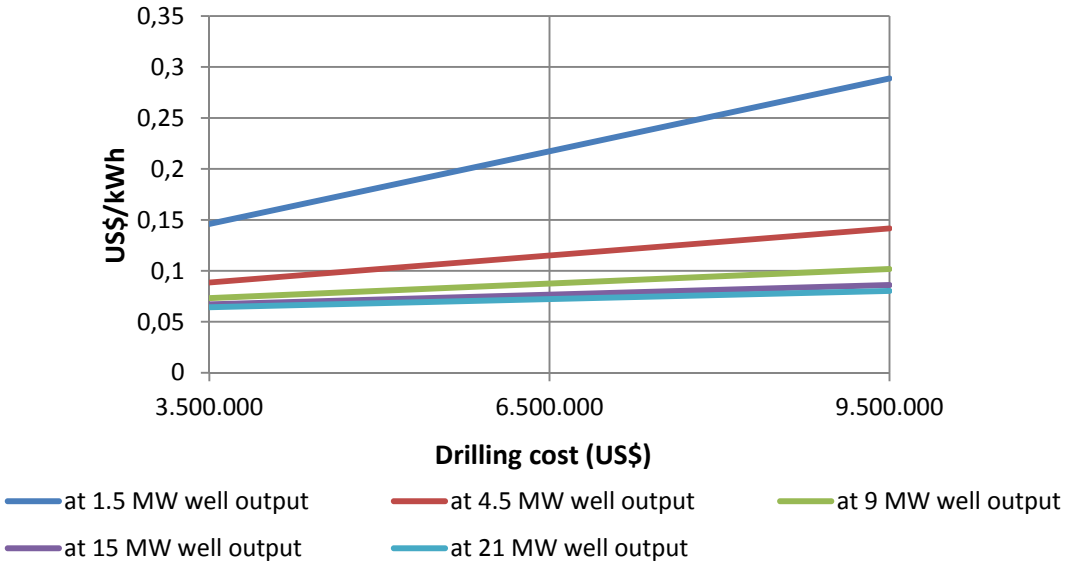

FIGURE 7: Levelized cost at various drilling cost and well output

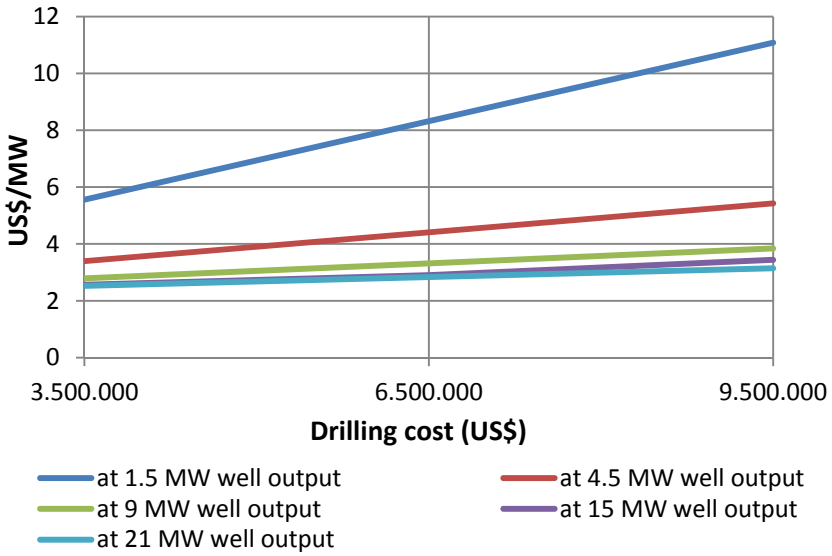

FIGURE 8: Installation cost at various drilling cost and well output

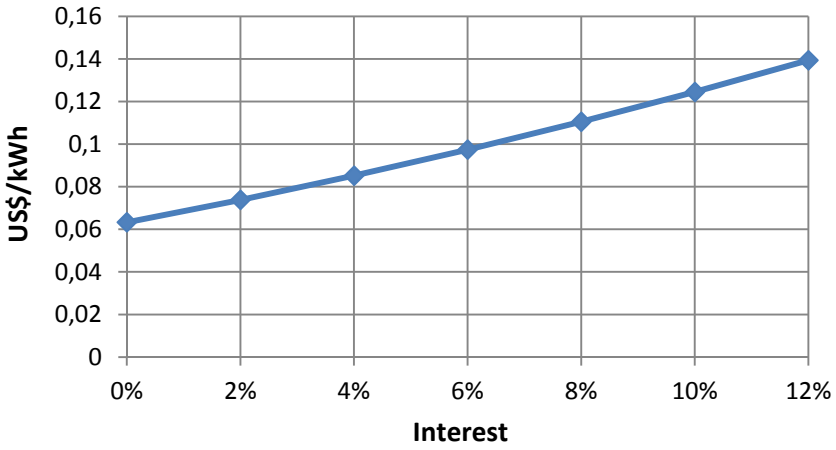

FIGURE 9: Levelized cost at various debt interest rates

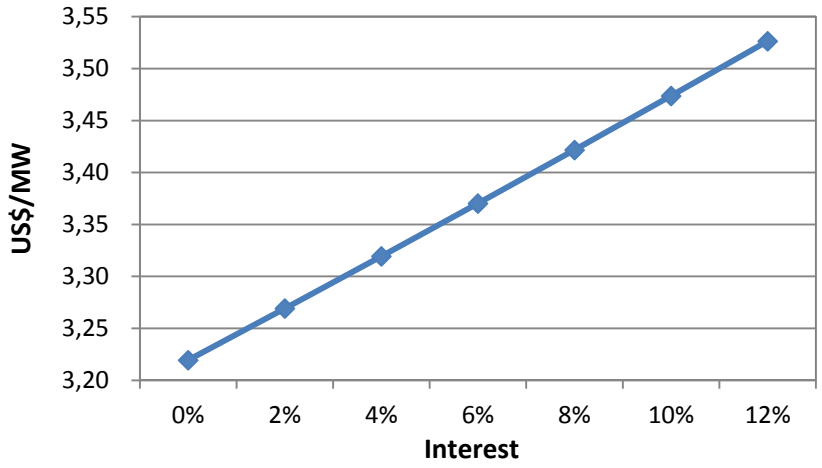

FIGURE 10: Installation costs at various debt interest rates

TABLE 2: Comprehensive result of model runs for various cost factors

Cost factor	**Relationship to generation cost**		**Relationship to investment cost**	
	Relative change	Relationship	Relative change	Relationship
Well output (1.5-21 MW)	55.7%	inverse	54.6%	inverse
Debt interest (0-12%)	54.6%	direct	8.7%	direct
Payback period (5-12 years)	50.9%	inverse	0%	
Drilling cost (US$ 3.5 -9.5 million at 1.5 MW)	49.4%	direct	49.8	direct
Project size/fix costs (20-400 MW)	35%	inverse	40%	inverse
Leverage (40-80%)	29%	inverse	0.4%	direct
Return on equity (12% - 22%)	29%	direct	0	
Plant capital cost (US$ 1.5 -3 million)	27%	direct	31.4%	direct
Loan term (7 -25 years)	25%	inverse	0%	
Early generation (wellhead, 0-60% of designated plant size)	18.8%	inverse	32%	inverse
Operation & Maintenance cost (US$ 0.005 – 0.009)	4.6%	direct	0%	
Steam decline (0-3%)	0.5%	direct	0%	

5. OPTIMIZATION

Given the behaviour of the cost factors (direct and inverse relationship), by proper selection of various cost factors a least cost factor combination can be realized. The project manager should seek to enhance the cost factor with an inverse relationship to the levelized and installation costs while limiting those with direct relationship. Further, managers may seek to minimize capital expenditure and tax while holding return

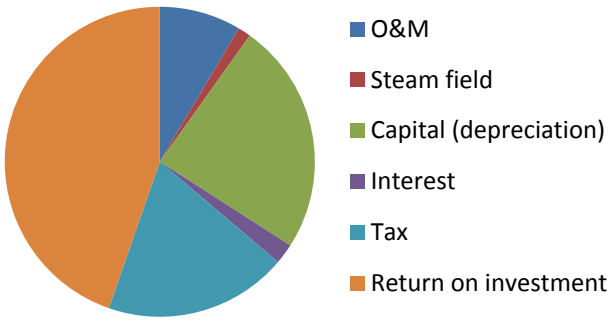

FIGURE 11: A general analysis of the structure of the levelized cost

on equity to the minimum for low levelized cost of power. Further, managers may design their projects to incorporate early power generation which has a major impact in reducing both levelized and installation capital requirement.

6. CONCLUDING REMARKS

i. The industrial practice it to use the levelized cost of power generation to express the cost of power. The levelized cost of power is a very useful tool for alternative power options. It is on the levelized cost that geothermal projects are evaluated for investment, approval and financing by prospective investors, governments, consumers or regulators and bankers or credit providers.

ii. The levelized cost is premised on the net present value of cash flows arising from a power project. However, different variants of its application exists some authors including taxes and depreciation while others don't. Investors engage in power projects to increase their wealth. The application that considers tax and depreciation provides better basis for investment decision.

iii. The levelized cost of power is project specific and must therefore be established for each individual project. Published data indicate an upper limit of about 13 US cents per kWh for geothermal projects.

iv. There are many cost factors which may influence the levelized cost. The key among them are project size, well output, wells and plant costs, operation and maintenance costs, interest on debt, loan tenure, payback period and financial leverage. These factors may be categorized as installation or initial invest cost, operation and maintenance costs, capital and financing costs, economic factors costs and legal and regulatory costs.

v. Sensitivity analysis carried out using a generic financial model indicate that project size, well output, payback period, loan tenure and financial leverage have an inverse relationship with the levelized costs while all direct cost and interest on debt have a direct relationship. It is further observed that the overall inverse relationship is predominant.

vi. The level of sensitivity is not cost but varies with most cost factors. From the model developed, project size, well output, payback, interest on debt may have the most significant impact on the levelized cost.

vii. The direct and inverse relationship of the various factors to the levelized cost means that the levelized cost can be optimized by undertaking informed cost factor selection so as to obtain the least cost factor combination.

viii. Often times the installation or initial investment has been used to give an indication of what geothermal would cost. This figure only represents the financial requirement and may not represent true reflection of what the levelized cost of power would be.

ix. The installation cost is also affected the by the various cost factors and relates with them both directly and inversely.

x. Published data indicates that installation costs ranges between 2.5 to 6.5 million US$ per MW.

xi. Use of early generation can greatly reduce the installation cost as well as reduce the levelized cost of a project. They can aptly be incorporated in a project to achieve optimization.

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PLANNING OF GEOTHERMAL PROJECTS IN KENYA

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ABSTRACT

The project cycle for the geothermal projects as implemented by KenGen comprises four phases and nine steps. The phases are resource exploration, resource assessment, plant construction and operation phases. The exploration phase is further subdivided to three development steps: existing data review, detailed surface exploration and exploration drilling. The resource assessment phase is divided into two steps: appraisal drilling and feasibility study. The construction phase comprise two steps; production drilling and construction of the steam gathering pipe network, power plant and transmission line construction. The work plans developed are used by the execution team as a road map to power plant commissioning which is the ultimate development objective and are also used for soliciting for funds from funding institutions. The planning entails scheduling of the various activities comprising the project activities and how they interrelate. The activities comprise the legal or regulatory requirements, procurement processes that include seeking for KenGen's and funding institution approvals, activities of the funding institutions leading to credit award and the actual site works. The planning aims at optimizing time, cost and procurement of human capacity not resident within KenGen's staff within the legal, regulatory and policy framework existing for each specific project. Project planning computer programs are used particularly Microsoft Project and the key planning outputs are Gantt charts, procurement plans, budgets, cash flow plans and progress reports.

1. INTRODUCTION

1.1 Definitions of work plans

Work plans may be defined as a series of interrelated tasks and activities which when implemented successfully will realize the goals and objectives of a specific project.

1.2 Why project plan

Project planning is an aspect of project management. Project management, a professional discipline, may be defined as "the overall planning, coordination and control of a project from inception to completion aimed at meeting a Client's requirements in order to produce a functionally and financially viable project that will be completed on time within authorized cost and to the required quality standard" (Pearson Education Limited, 1999).

The above definition is more applicable to perspective of the appointed project manager. However, the project plans serve various purposes to various parties involved with the project.

1.2.1 Project owner

Geothermal projects require colossal sums of money to implement. Very few individual institutions and third world governments can implement a sizable geothermal project from internal resource without resulting to soliciting for external funding. Therefore a project plan provides the owner with total project cost, project development period where the project will not make money, cash inflows and outflows and likely profitability. These data is very important for the owner as they approach prospective financiers.

1.2.2 Financiers

Banks are very willing to loan out funds. However, they are averse to adverse risk exposure. They will evaluate a long list of potential risks and in particular administration risks and projected profitability as a basis for servicing of the loan to be advanced. Often times, bilateral and multilateral financial agencies have required engagement of consultants to enhance project management functions. A well packaged project plan assures the banks of a capable project management team. The project plans also provides the banks with an instrument for economic and financial project evaluation. The work plans act as a basis for owner's contractual obligations with the bank and a reference for project progress evaluation and monitoring.

1.2.3 Project execution management team

To the execution team, the work plans are the road map for the project implementation. They capture the projects concepts, requirements, identifies what needs to be done, assigns responsibility to those who will do what needs to be done, defines how it will be done and identifies and assigns the requirements to enable the work to be done. In many times they also identify the authorities and approval to be sought in the process of the project implementation.

The work plans further highlights the milestones that must be achieved and thereby identify the critical aspects of the project. They also act as instruments of communication. In addition, they serve as instruments of performance measurement and control. Regularly the project implementation progress is assessed against the set out milestones in the work plan and where discrepancies occur adjustments are made. On the other hand costs are monitored to ensure that the project has sufficient funding and to address any budget overruns.

1.2.4 Resource persons

They are a reference for level of performance requirement and additional departmental planning.

1.3 Project cycle

A project is time-bound, with definite start and a finish date. A project cycle can be thought as a sequence of logically linked activities in which each is necessary and is a prerequisite for the next stage in the cycle. Project generally grouped into five distinct categories (Figure 1).

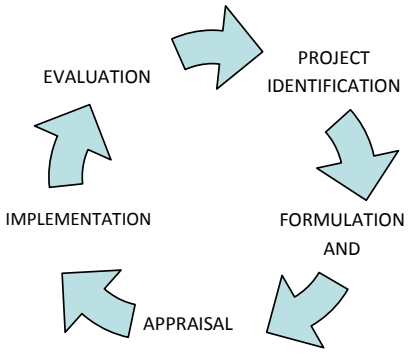

FIGURE 1: Project Cycle

1.3.1 Project identification

Identification is the very beginning of the project cycle. At this point the project is defined in very general terms. In many times, at this step, there more questions than answers.

1.3.2 Project formulation and preparation

This stage includes pre-feasibility and feasibility stages. It involves a consideration of all aspects namely; technical, financial, economic, social, cultural, managerial and political aspects. The basic rational of the project is thus examined at this stage especially to identify obvious reasons why the project may not or is unlikely to go on.

1.3.3 Appraisal

Appraisal stage is when detailed project is undertaken especially, where donors are involved, they will involved there technical team, internal staff or consultants, and the resulting plan will be implemented.

1.3.4 Implementation

This entails the execution of the agreed works plan.

1.3.5 Evaluation

Where donors are involved, project evaluation is carried to identify lessons learned. In particular the evaluation will refer back to the project objectives and the work plans and establish whether the objectives were met and if the work plan were appropriate.

The work plans are a result of the work done during project formulation and preparation and the appraisal. It is prudent to note that the works plans provide value to the entire project phases.

1.4 Project parameters

During a projects life, management focuses on three basic parameters; quality, cost and time (Figure 2). However, for those working in donor funded and government owned projects must in addition factor in the law, policy, rule and regulations which can derail the project if not observed. These parameters must be specified in detail during the planning of the project and are to be adhered to during implementations. These parameters are addressed through specifications, budgets, time schedules and the various policies, rules and regulations applicable to a specific project.

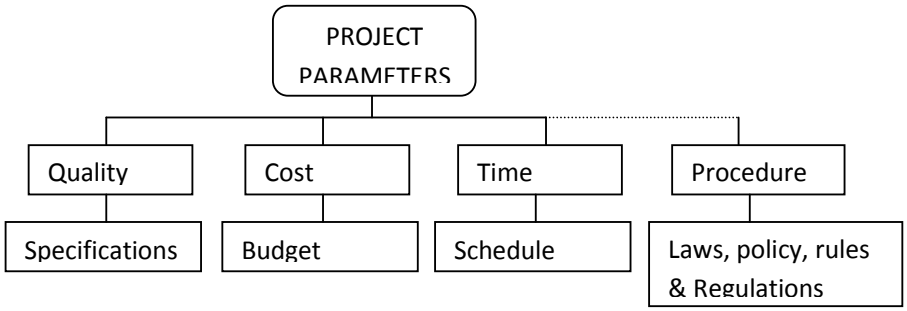

FIGURE 2: Basic Project Elements

1.5 Key project inputs

Projects use specific inputs (resources) to produce particular outputs over a specified time period in order to meet an identified development need of clearly identified target group. The key project

resources are people, equipment and materials. The work plans identify, plans for, costs and optimizes the use of each of the resources.

1.6 Planning process

The crucial phase involves the breaking down of the various activities and tasks required to complete the project along the three basic parameters while taking to consideration of the law, policy, rules and regulations. The steps involved in planning include:

- Establish the project objectives
- Choose a basic strategy for achievement of the objectives
- Break the project down into subunits of task and activities
- Determine the performance standards for each subunits
- Determine how much time is required to complete each subunit
- Determine the proper sequence for completing the subunits and aggregate this information into a schedule for the total project
- Determine the cost of each subunit and aggregate costs into the project budget
- Determine the staff organization, including the number and kind of position and the duties and responsibilities of each
- Determine what training, if any is required for project team members
- Identify the applicable laws, policy, rules and regulations

2. REVIEW OF THE DEVELOPMENT PHASES

Mwangi (Mwangi, 2007) has reviewed the planning concept used in geothermal project planning in Kenya. The entire geothermal project cycle can be summarized as shown in Figure 3 (Price Water House Coopers, 2007). There are four major phases and nine key steps in the development of geothermal project.

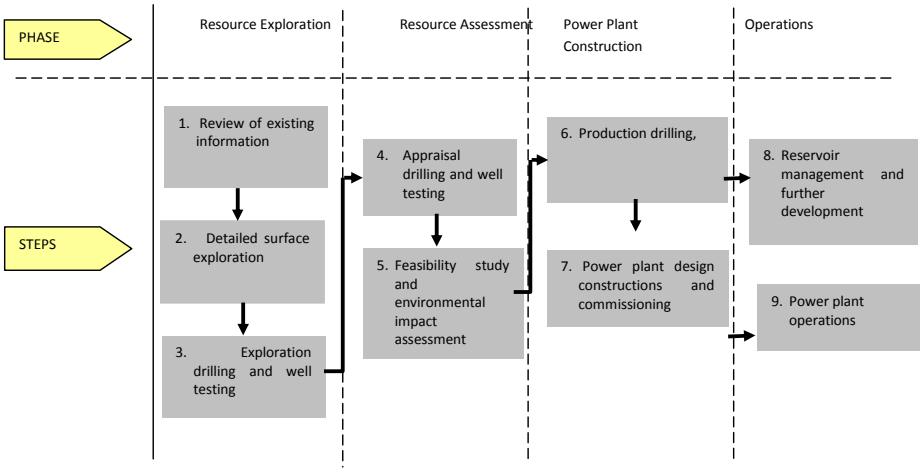

FIGURE 3: Geothermal development phases

PHASE 1: RESOURCE EXPLORATION

Step 1: Review of Existing Data

Objective: The objective is to collate available data gathered overtime by various agencies involved in studies and research with the aim of identifying gaps on the information base and strategizing on further works.

Scope of work: This entails a desktop review and analysis of existing data by various disciplines of earth sciences (geology, geophysics and geochemistry) and engineering (surface heat measurement).

Duration: The duration for this step may only be a month. Various disciplines would be involved.
Organization: KenGen has an in-house capacity and carries out this exercise
Output: An inception report would result detailing the information gap and the detailed program for undertaking surface exploration.
Costs: The cost is negligible

Step 2: Detailed surface exploration

Objective: The objective is to define the resource by its key system characteristic namely: existence of a heat source in the form of hot magmatic body near earth surface, existence of hydrological system, its characteristics (i.e. flow direction) and geological structures controlling it and area extent of the prospect.
Scope of works: This entails field measurements, sample collections, laboratory tests, studies and analysis by various disciplines of earth sciences (geology, geophysics and geochemistry) and engineering (surface heat measurement). In addition, baseline environmental studies are undertaken.
Organization: KenGen has internal capacity that carries out this step. It also engages consultants to offer peer review services.
Duration: For most fields, surface works takes about three months.
Out Put: The main output from this step is a conceptual model of the geothermal system and siting of the discovery (exploration) wells.
Cost: The budget for this step has been within US$ 0.5 million per prospect.

Step 3: Exploration drilling

Objectives: The main objective is to prove the resource inferred by the geoscientific studies by drilling a discovery well at the best point according to the conceptual model and confirm the results with one or two additional wells.
Scope of work: This step marks the beginning of the physical development on any prospect. The key activities in this step include:

- Main access road and drill pad construction
- Establishment of drilling water and pumping installation. The pumping may be powered by diesel driven generators or electricity where economically accessible.
- Acquisition of land entry rights through negotiation for compensation or purchase
- Other logistical requirements e.g. accommodation, storage, security, offices etc.
- Drilling and testing of three exploration wells.
- Acquisition of environmental license.

Organization: For short distances of access roads, KenGen has internal capacity and undertake the civil works. For long stretches of access road, KenGen contracts out the earth works. The water installation works are also contracted out except operating and maintenance of the plants, which is done in-house. The drilling works can either be contracted or carried out internally depending on rig availability. The application for environmental clearance is done in-house.
However, KenGen engages consultants for peer review.
Output: Resource discovery by discharging wells and most importantly a go or no go decision for further development.
Duration: One year is allowed to undertake the initial logistical requirements. These include opening the area up by construction of roads, establish water supply system from surface sources or drilling of borehole and the related pipeline , pumping system

and power sources. The time allows acquisition of land access rights and the compensation processes. Drilling requires storage facilities and security systems e.g. fencing, store house or containerized storage. Within the same period, procurement of overseas materials is carried out and contracts for provision of local materials made. The materials may require some advance preparation e.g. slotting. Six months is allowed for the actual drilling.

Cost: For the advance logistical requirements, a budget figure of US$ 5.2 million is allowed. The well cost are estimated at US$ 4.3 million per well using KenGen rigs. However, the actual cost for this step varies from one prospect to another.

PHASE 2: RESOURCE ASSESSMENT

Step 4: Appraisal drilling and well testing

Objective: Appraisal drilling follows a successful drilling exploration program. It is aimed at:

- Sizing the resource in terms of possible output necessary for power plant sizing;
- Determining well productivity characteristics (average fluid output per well and steam fraction) necessary for determining cost of investments and drilling requirements.
- Determining the reservoir fluids characteristics in particular, pressure at the surface (wellhead), dissolved solids that may lead to deposition and dissolved gas content which impact power plant designs and performance.
- Proving a certain fraction of required steam for a plant as a precondition for funding

Scope of work: The standard practice for KenGen is to drill and test six appraisal wells and may increase this number to nine if necessary.

Output: All the above data is obtained in preparation of feasibility study. Data and go or no go decision

Organization: The drilling is carried out in-house if KenGen has an available rig but KenGen may contract a rig but manage the drilling process. KenGen has in recent past contracted drilling consultancy and supervision to beef up its capacity. The additional civil works are carried out in-house. Where earth moving equipment shortages are encountered, these are hired on short contracts.

Duration: The total duration takes about 15 months. Drilling takes about 12 months while testing of the last well is allowed 3months to heat up and be flow tested.

Costs: The well costs is estimated at about US$ 4.3 per well including the civil works. Testing is estimated at US$ 40, 000 per well

Step 5: Feasibility study

Objective: The main objectives of the feasibility studies are:

- Matching existing power plant technologies to resource characteristics and establish a preliminary design
- Carrying out a financial and economic analysis to establish project viability
- Identifying resource management issues that will arise during exploitation and how to mitigate them
- Undertaking environmental impact study scoping

Scope of work: This is mainly a desktop study. It essentially collates all the data so far accumulated and relates it to the proposed power project. One key aspects taken to consideration

is simulation studies establish sustainable resource exploitation and coming up with the preliminary design parameters

Output: Bankable feasibility study which KenGen and funding institutions would use for funding purpose. In addition the feasibility study proposes the appropriate technology to be used to optimize the resource.

Organization: This step has been contracted to consultants especially because of the comfort of the lending institutions. However, both KenGen's Board of Consultants and KenGen staff would review the reports.

Duration: The feasibility study is allowed a six months period.

Costs: This may take up to US 2 million depending on the scope of the project.

PHASE 3: POWER PLANT DEVELOPMENT

Step 6: Production drilling

Objective: At this stage of development, a decision to construct a plant is already made. The drilling is therefore to provide sufficient steam to run the plant. Additional wells are drilled for reinjection purpose. One reinjection well is required for every 4 production wells.

Scope of works: There would be additional civil works to provide additional access roads and site construction. Wells would be drilled to provide sufficient steam plus about 10% excess at start-up. The wells would be tested. Procurement activities would continue in this step.

Organization: All civil works would be carried out in-house. Drilling would be carried out both in-house and through contracts depending on rigs availability. Well testing would be carried out in-house. A drilling consultancy and supervision may be considered to offer support to the existing drilling management staff.

Duration: Allows 60 days per well and is subject to the number of wells to be drilled. For estimation purpose, we assume exploration will be 50% successful, appraisal 75% successful and production wells 90% successful. For 140 MW plant allowing 10% excess steam at start-up we require 25 production wells. The duration will be 4 years using one rig and 2yrs with two rigs.

Costs: The well costs is estimated at about US$ 4.3 per well including the civil works. Testing is estimated at US$ 40, 000 per well.

Step 7: Power plant design, construction and commissioning

Objective: Detailed design, procure and construct the steam gathering system, power plant substation and transmission lines

Scope of works: Design, procure, construct, commission the plant and undertaking a comprehensive environmental impact studies.

Organization: KenGen appoints a project team. The project team contracts a consultant to supervise the construction contractor. KenGen and the consultants tender, shortlist and contract a contractor(s). The contractor designs, procures and install the plants and its accessories. KenGen would carry out the full EIA.

Duration: It takes about 30 months to construct the power house, manufacture and ship the turbine and their accessories. The steam field and the transmission lines will be constructed in parallel.

Cost: The power plant including the power house and all that goes into the power plant are estimated at US$ 2.5 million per MW for plants less than 50 MW, US$2.3 million those between 50 and 100 MW and US1.8 Million for plants size larger than 100 MW. The steam pipeline cost is estimated at US$ 25 million for a 70 MW plant and US$ 37.5 million for a 140 MW plant.

Step 8: Reservoir management

Objectives: Monitoring to ensure steam availability to the plant, monitor pressure drawdown and scaling problems.
Scope of Work: Entails regular measurement of well productivity, wellhead pressure and chemical composition of the well effluent. It may involve tracer injection and cold re-injection activities.
Organization: This is carried out internally.
Duration: Will be carried out for the entire operation period of the plant.
Cost: Will greatly vary. This is operations and maintenance cost.

Step 9: Operations

Objective: This entails the operations and maintenances of the power plant to ensure continuous generation.
Scope of works: This will include operation of the plant on a 24hr basis, regular maintenance and scheduled overhauls over the plant life.
Organization: It is carried out internally. The staff requires to be trained for the plant operations.
Duration: Plant life
Cost: Operation and maintenance cost

3. LAW, RULES AND REGULATIONS

3.1 Geothermal Act, 1982

The act provides:

- For the purpose of exploration, the Minister of Energy authority in writing is required whose life is one year and may be renewable (Part II, Clauses 6).
- Reasonable notice of the intention to enter upon any land shall be given to the owner or occupier of the land.
- One needs to apply for geothermal license for the purpose of exploitation. The application to be accompanied by a fee. The life of the license is not greater than 30 years (Part II, Clause 7).
- The land owners shall be compensated for the losses incurred pursuant to geothermal development (Part IV, Clauses 18 – 23).

3.2 Environmental management and co-ordination act, 1999

The act provides:

- No project will commence without submission of a project report.
- The National Environmental Management Authority (NEMA) will evaluate the report and if in their opinion it will have major impact, the project owner will be required to carry out an environmental impact assessment study (EIA).
- The report is submitted back to NEMA with a fee.
- The Authority shall respond to the application within three months without which the applicant may proceed.
- Upon receipt of the EIA document, NEMA shall cause a notice to be published in the official government news print, the Kenya Gazette including a local newspaper.
- Nema will allow the public sixty days perusing and objecting to the proposed project. This period may be extended if an individual applies for extension.

- Only when the public and the Authority is satisfied, will the Authority issue an EIA licences

3.3 The public procurement and disposal act, 2005

(LEGAL NOTICE No. 174, Kenya Gazette Supplement No. 92, 29th December, 2006, Legislative Supplement No. 53)

This Act applies to any body in which the Government has a controlling interest. In summary the act requires that:

- All international tendering will be allowed 30 days to prepare tender. If one was to use pre-qualifications one has to allow at least 14 days to prepare the prequalification documents. This require advertisement in the local and where possible international journal etc.
- National tendering requires bidders to be allowed at least 21 days to prepare their bid. In addition if the projected cost is estimated over Kshs 6 million (US 0.75 million) for goods and works and US$ 0.375 million for services will require to be advertised in the local newspapers.
- The tender documents are evaluated by a committee and approved by an official tender committee.
- The contract cannot be signed before 14 days after award to allow for complaints and appeal to the award.

3.4 Funding institution rules and regulations

3.4.1 Funding cycle

Receiving funding from donors follow a process that take about a year and may last longer. The process begins with project identification, formulation and appraisal. The funding for the project would then be presented for approval. The approving board meets once every about 4 to 6 months. After the approval, it still takes time to carry out financial negotiation

3.4.2 Procurement regulations

Prior to publication or invitation to pre-qualify or tender, the following documents are often time submitted to the funding institution for a approval without which the process may not be funded under the credit. These are:

- Invitation to tender
- Selection criteria for qualification (in detailed form)
- Tender documents, including specimen contract
- Draft notice specifying the fees for the purchase of the tender documents and their utilization, as well as list of the media in which the notice is to be published

In processes with pre-qualification, the following documents have to be submitted to the funding institution for comment prior to the invitation to tender:

- The evaluation report of the qualification, including the certificate or opinion of the consultant
- The recommendation on the list of bidders to be invited to tender

In processes with post-qualification, the following documents have to be submitted to funding institution for comment prior to the opening of the bids:

- The *evaluation report* of the qualification, including the certificate or opinion of the consultant

- The recommendation on the list of bidders whose financial bids are to be opened.

Prior to the award of the contract, the following documents are to submitted the funding institution for comment:

- The signed record of the bid opening
- The *evaluation report*
- The recommendation on the award
- The certificate or opinion of the consultant on the recommendation of the award
- If applicable, an explanation why the *binding period* could not be observed
- At the request of funding institution, if applicable, all or specific bids.

In addition the funding institutions require that the bidders be allowed at least 30 days to prepare pre-qualification bids and at least about 45 days to prepare actual bids.

3.5 The water act

The water act provides that authority is required for abstraction of water whether from surface bodies or underground. Geothermal projects require water for the drilling process and also the mining of the geothermal fluids falls within this categorization. This process requires an application to be made. A regional board would then consider the application and grant approval. This can take over six months.

4. SCHEDULING

As stated above a project has a specific start and finish date. The above information is generic and needs to be customized for a specific project. This activity is called scheduling. The steps involved in scheduling are:

- Enter the project phases, milestones and tasks into table on a paper, white board, a spreadsheet, or word processor. You may also enter the data into a Gantt chart or network diagram
- The next aspects is to calculate dates, start and finish for each activity and enter them in the table
- Link tasks with their appropriate relationships to one another. Note that some tasks cannot begin until certain previous undertaken task has been completed. Again certain tasks compete for resources hence a certain task may not begin until a limited resource is available.
- Review the program so as to take care of any deadlines and other date constraints
- Assign resources to the various tasks and optimize the resources so as not to over allocate resource thereby creating conflict or under allocate resources which leads to higher project costs
- Establish the budget for the project;
- It is increasing becoming a requirement to have a separate procurement plan. Hence one would extract the aspects of procurement from the main plan.

For a simple project, working with a paper or white board may be adequate. However, geothermal projects take many years and have very many interrelated tasks. In addition, optimization of the project plan requires working forward and backwards and can be very taxing. Several computer programs exist that aid the planners in the optimization of the work plans. The programs in particular aid the planners to:

- Calculate the start and finish dates
- Indicate whether assigned resources are actually available

- Inform you if the assigned resources are under allocated or overworked
- Alert you if you have an upcoming deadline
- Calculated the budget for you once the cost have been included in the program
- Help you to manage and control the project by highlighting activities that have not started after their start date and those that are delayed
- The programs enable the planners to get customized reports in different views e.g. Gantt, network diagram and table

Examples of the project planning computer programs are:

- Microsoft project
- Primavera
- Smart Draw

There are many others that could be found in the internet. In KenGen, Microsoft Project Software is widely use and in limited cases Primavera. The key outputs of interest to KenGen have been Gantt charts, procurement plans, budgets, cash flow plan and progress reports. A typical plan is shown in the appendix.

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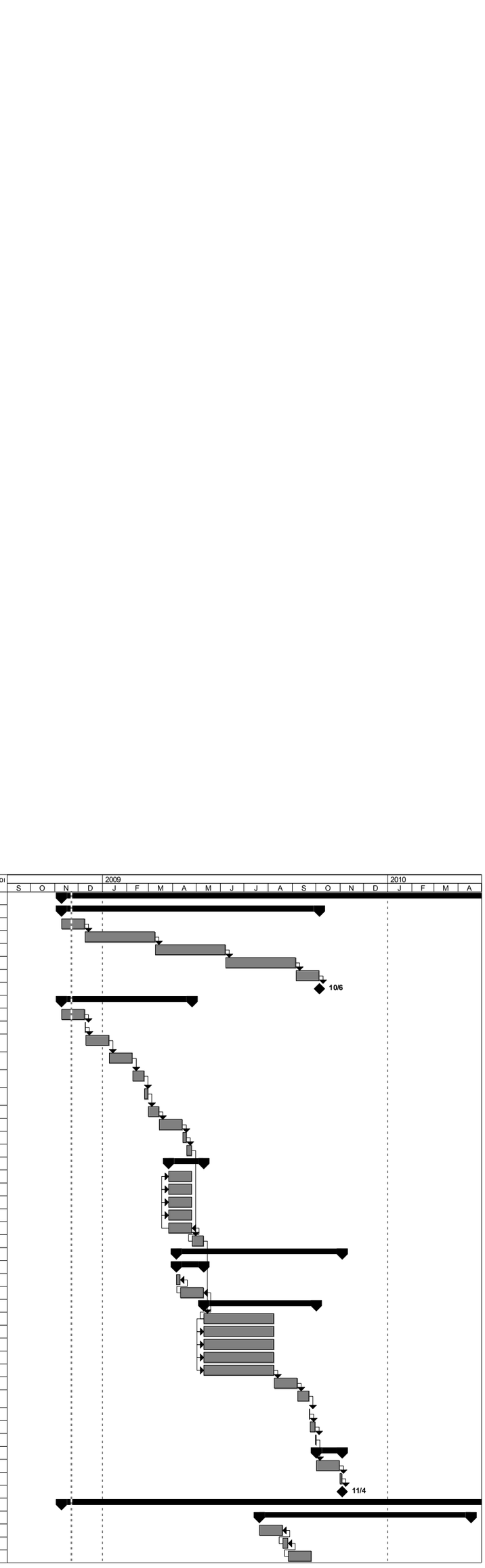
Pearson Education Limited, 1999: *Code of practice for project management for construction and development* (2nd ed.). Edinburgh Gate, Harlow, England, 217 pp

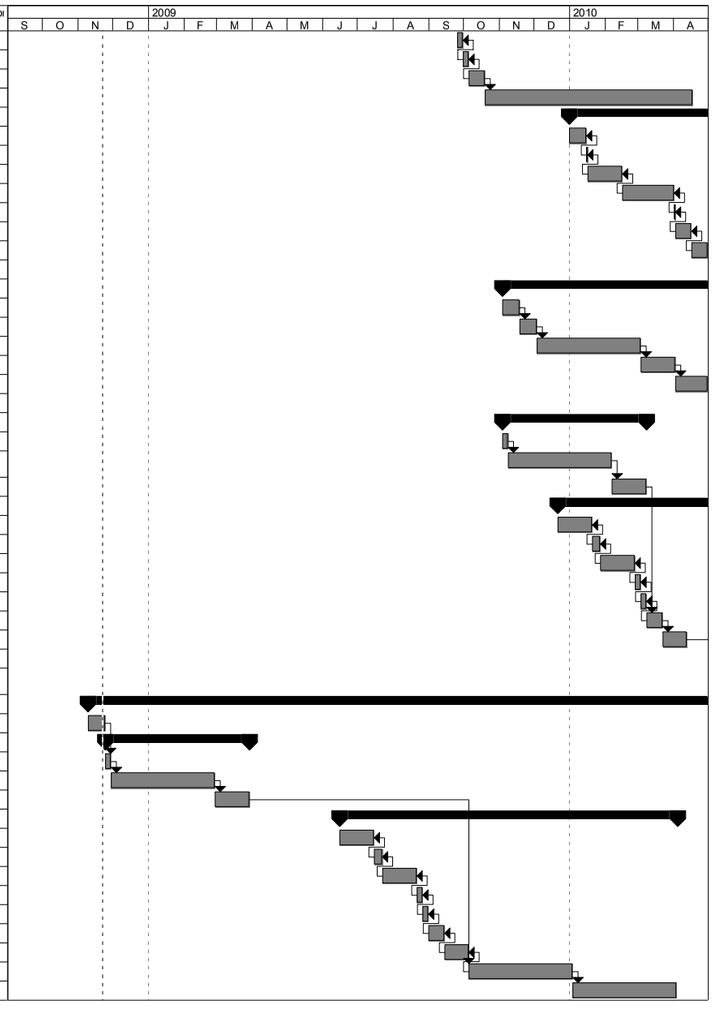
PriceWater House Coopers, 2007: *Establishment of a geothermal development company*. Draft Master and Business Plan, Nairobi, Kenya, July 2007.

APPENDIX

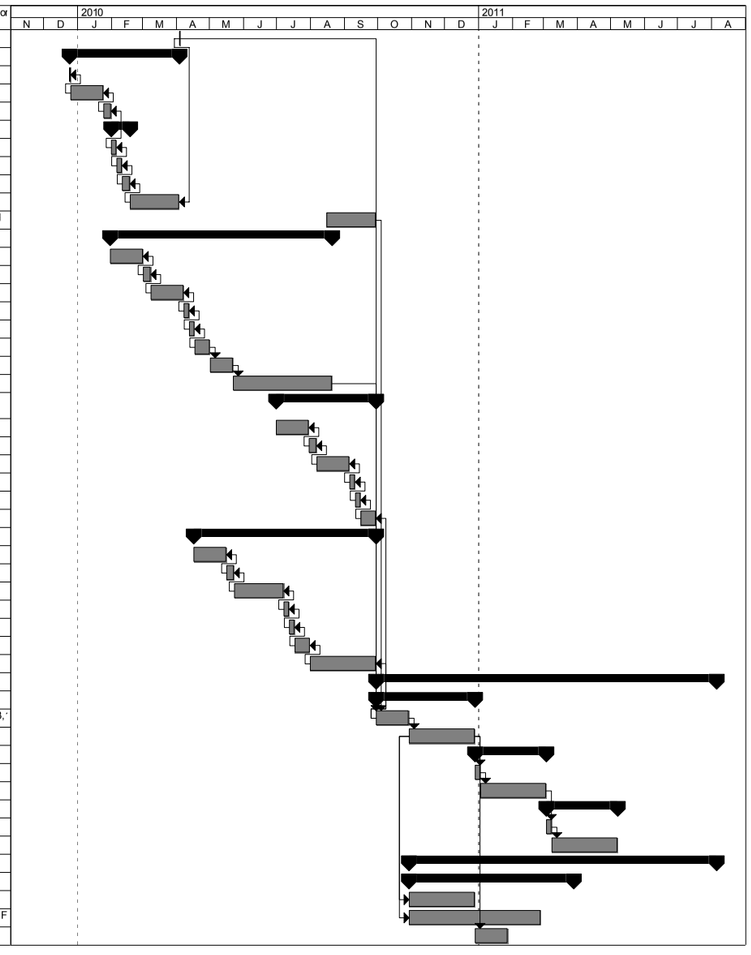
ID	Task Name	Duration	Start	Finish	Predecessor
1	**RESOURCE EXPLORATION**	**1071 d?**	**11/10/08**	**10/17/11**	
2	**Funding Application**	**330 d**	**11/10/08**	**10/6/09**	
3	Project Identification	30 d	11/10/08	12/10/08	
4	Project Formulation and Preparation	90 d	12/10/08	3/10/09	3
5	Appraisal	90 d	3/10/09	6/8/09	4
6	Funding institution Approval	90 d	6/8/09	9/6/09	5
7	Fianacial Agreements Negotiation	30 d	9/6/09	10/6/09	6
8	**Credit Effectiveness**	**0 d**	**10/6/09**	**10/6/09**	**7**
9	**Budgets Approval**	**167 d**	**11/10/08**	**4/26/09**	
10	Budget preparation	30 d	11/10/08	12/10/08	
11	Draft Submission	1 d	12/10/08	12/11/08	10
12	In-house Discussion and Review	30 d	12/11/08	1/10/09	11
13	Executive Presentation and Review	30 d	1/10/09	2/9/09	12
14	Presentation to Board of directors	15 d	2/9/09	2/24/09	13
15	Submission To Ministry Of Energy	5 d	2/24/09	3/1/09	14
16	Transmission to Treasurery	14 d	3/1/09	3/15/09	15
17	Treasurery's Approval	30 d	3/15/09	4/14/09	16
18	**Preparation of Works Orders**	**5 d**	**4/14/09**	**4/19/09**	**17**
19	**Prvovision of Works Orders**	**7 d**	**4/19/09**	**4/26/09**	**18**
20	**DATA REVIEW**	**45 d**	**3/27/09**	**5/11/09**	
21	Geology	30 d	3/27/09	4/26/09	22SS
22	Geochemistry	30 d	3/27/09	4/26/09	23SS
23	Geophysics	30 d	3/27/09	4/26/09	24SS
24	Heat Flux Data	30 d	3/27/09	4/26/09	25SS
25	Environmental Baseline Data	30 d	3/27/09	4/26/09	26SF
26	Inception Report	15 d	4/26/09	5/11/09	19
27	**SURFACE RECONNAISSANCE**	**212 d**	**4/6/09**	**11/4/09**	
28	**Obtain Survey Permit**	**35 d**	**4/6/09**	**5/11/09**	
29	Draft Application Letter and obtain signature	5 d	4/6/09	4/11/09	30SF
30	Minister's Permit (1yr)	30 d	4/11/09	5/11/09	32SF
31	**Actual Work**	**144 d**	**5/11/09**	**10/2/09**	
32	Geology	90 d	5/11/09	8/9/09	26
33	Geochemistry	90 d	5/11/09	8/9/09	32SS
34	Geophysics	90 d	5/11/09	8/9/09	33SS
35	Heat Flux Data	90 d	5/11/09	8/9/09	34SS
36	Environmental Baseline Data	90 d	5/11/09	8/9/09	35SS
37	Reports Individual Disciplines	30 d	8/9/09	9/8/09	36
38	Combined report- Conceptual Model	15 d	9/8/09	9/23/09	37
39	Presentation	1 d	9/23/09	9/24/09	38
40	In-house Review	7 d	9/24/09	10/1/09	39
41	Submission of Final Draft	1 d	10/1/09	10/2/09	40
42	**BOC Review**	**33 d**	**10/2/09**	**11/4/09**	
43	Post Reports	30 d	10/2/09	11/1/09	41
44	Actual Meetings	3 d	11/1/09	11/4/09	43
45	Go or No Go	0 d	11/4/09	11/4/09	44
46	**Exploration Drilling**	**1071 d?**	**11/10/08**	**10/17/11**	
47	**Overseas Procurement**	**271 d**	**7/21/09**	**4/18/10**	
48	Prepare tender	30 d	7/21/09	8/20/09	49SF
49	Advertise	7 d	8/20/09	8/27/09	50SF
50	Tender Period	30 d	8/27/09	9/26/09	51SF



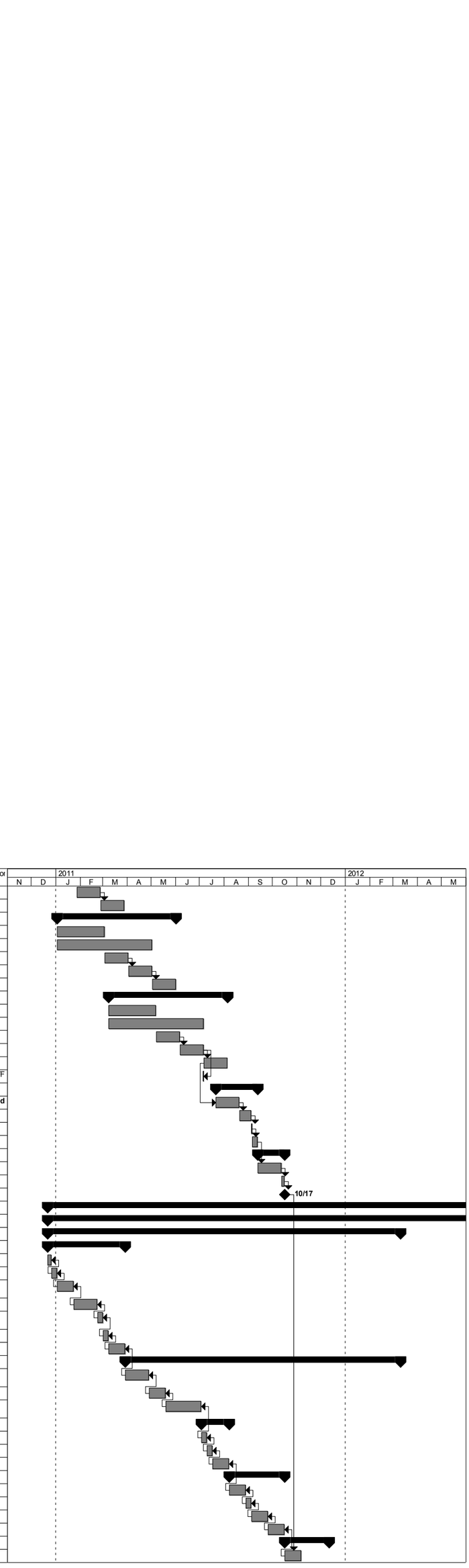
ID	Task Name	Duration	Start	Finish	Predecessor
51	Evaluation	5 d	9/26/09	10/1/09	52SF
52	Approval	5 d	10/1/09	10/6/09	53SF
53	Award & Appeal Period	14 d	10/6/09	10/20/09	8
54	Delivery	180 d	10/20/09	4/18/10	53
55	**EIA License acquisition**	**167 d?**	**1/1/10**	**6/17/10**	
56	Prepartion of Project Report	15 d	1/1/10	1/16/10	57SF
57	Submission of Project report	1 d?	1/16/10	1/17/10	58SF
58	Review By NEMA	30 d	1/17/10	2/16/10	59SF
59	Undertake EIA	45 d	2/16/10	4/2/10	60SF
60	Submit	1 d?	4/2/10	4/3/10	61SF
61	Advertise	14 d	4/3/10	4/17/10	62SF
62	Public Review	60 d	4/17/10	6/16/10	63SF
63	Obtain Licence	1 d?	6/16/10	6/17/10	83SF
64	**Acquisition of Land Rights**	**225 d**	**11/4/09**	**6/17/10**	
65	Identification of Owners	15 d	11/4/09	11/19/09	45
66	Approaching the Owners	15 d	11/19/09	12/4/09	65
67	Engage Owners into negotiations	90 d	12/4/09	3/4/10	66
68	Apply for approval	30 d	3/4/10	4/3/10	67
69	Enter into agreements	45 d	4/3/10	5/18/10	68
70	Pay Compensations	30 d	5/18/10	6/17/10	69
71	**Water Abstraction License**	**125 d**	**11/4/09**	**3/9/10**	
72	Compile Application	5 d	11/4/09	11/9/09	45
73	Review by WaterManagement Board	90 d	11/9/09	2/7/10	72
74	Obtain License	30 d	2/7/10	3/9/10	73
75	**Contract Earth Works**	**297 d**	**12/22/09**	**10/15/10**	
76	Prepare tender	30 d	12/22/09	1/21/10	77SF
77	Advertise	7 d	1/21/10	1/28/10	78SF
78	Tender Period	30 d	1/28/10	2/27/10	79SF
79	Evaluation	5 d	2/27/10	3/4/10	80SF
80	Approval	5 d	3/4/10	3/9/10	81SF
81	Award & Appeal Period	14 d	3/9/10	3/23/10	74
82	Mobilization	21 d	3/23/10	4/13/10	81
83	Road and Site Costruction	90 d	6/17/10	9/15/10	82,70
84	Construct storage facilities and temporary offices	90 d	7/17/10	10/15/10	83SS+30 d
85	**Establish Water Supply System**	**689 d?**	**11/10/08**	**9/30/10**	
86	Survey Sources of Water	15 d	11/10/08	11/25/08	
87	**Water Abstraction License**	**125 d**	**11/25/08**	**3/30/09**	
88	Compile Application	5 d	11/25/08	11/30/08	86
89	Review by WaterManagement Board	90 d	11/30/08	2/28/09	88
90	Obtain License	30 d	2/28/09	3/30/09	89
91	**Drilling Of Water Bore holes**	**293 d?**	**6/16/09**	**4/5/10**	
92	Prepare tender	30 d	6/16/09	7/16/09	93SF
93	Advertise	7 d	7/16/09	7/23/09	94SF
94	Tender Period	30 d	7/23/09	8/22/09	95SF
95	Evaluation	5 d	8/22/09	8/27/09	96SF
96	Approval	5 d	8/27/09	9/1/09	97SF
97	Award & Appeal Period	14 d	9/1/09	9/15/09	98SF
98	Mobilization	21 d	9/15/09	10/6/09	99SF
99	Actual Drilling	90 d	10/6/09	1/4/10	90,8
100	Water Works Construction	90 d	1/4/10	4/4/10	99



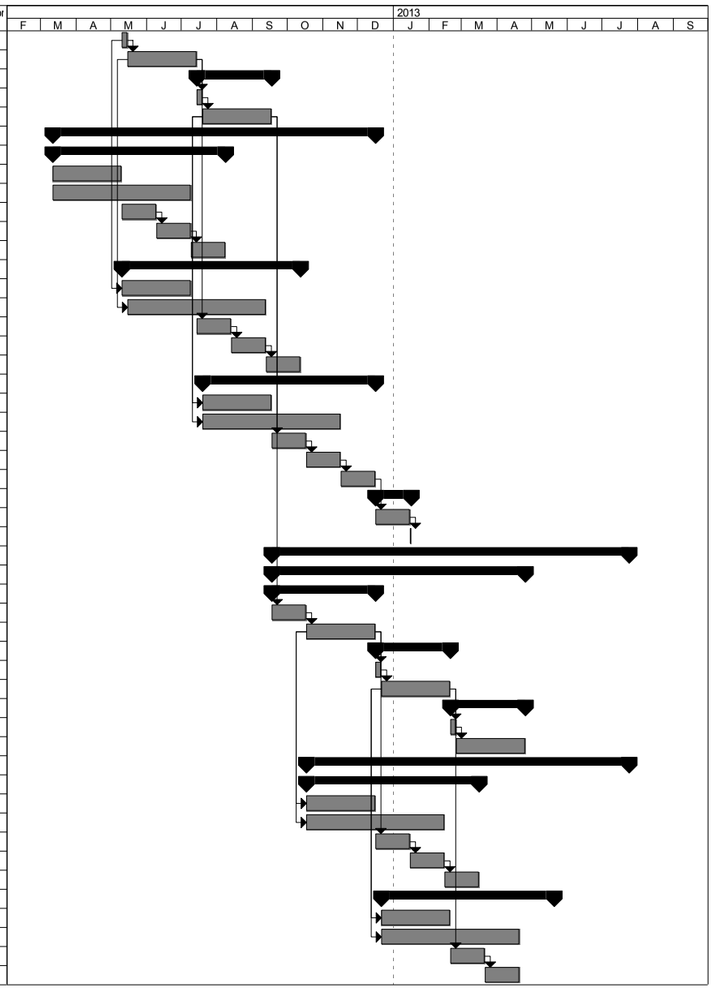
ID	Task Name	Duration	Start	Finish	Predecessor
101	Commissioning	1 d?	4/4/10	4/5/10	100
102	**Apply For Electricity Supply to Boreholes**	**100 d?**	**12/25/09**	**4/4/10**	
103	Compile Application	1 d?	12/25/09	12/26/09	104SF
104	Assessment	30 d	12/26/09	1/25/10	105SF
105	Quotation	7 d	1/25/10	2/1/10	107SF
106	**Payment**	**17 d**	**2/1/10**	**2/18/10**	
107	Prepare Request for Approval	5 d	2/1/10	2/6/10	108SF
108	Approval	5 d	2/6/10	2/11/10	109SF
109	payment	7 d	2/11/10	2/18/10	110SF
110	Design & Costruction	45 d	2/18/10	4/4/10	101SF
111	Laying Of Water Line	45 d	8/16/10	9/30/10	83SS+60 d
112	**Slotting of Liners**	**202 d**	**1/31/10**	**8/21/10**	
113	Prepare tender	30 d	1/31/10	3/2/10	114SF
114	Advertise	7 d	3/2/10	3/9/10	115SF
115	Tender Period	30 d	3/9/10	4/8/10	116SF
116	Evaluation	5 d	4/8/10	4/13/10	117SF
117	Approval	5 d	4/13/10	4/18/10	118SF
118	Award & Appeal Period	14 d	4/18/10	5/2/10	54
119	Mobilization	21 d	5/2/10	5/23/10	118
120	Actual Works	90 d	5/23/10	8/21/10	119
121	**Contract for Bulk Cement & Diesel Fuel**	**91 d**	**7/1/10**	**9/30/10**	
122	Prepare tender	30 d	7/1/10	7/31/10	123SF
123	Advertise	7 d	7/31/10	8/7/10	124SF
124	Tender Period	30 d	8/7/10	9/6/10	125SF
125	Evaluation	5 d	9/6/10	9/11/10	126SF
126	Approval	5 d	9/11/10	9/16/10	127SF
127	Award & Appeal Period	14 d	9/16/10	9/30/10	138SF
128	**Contract Cementing Services**	**166 d**	**4/17/10**	**9/30/10**	
129	Prepare tender	30 d	4/17/10	5/17/10	130SF
130	Advertise	7 d	5/17/10	5/24/10	131SF
131	Tender Period	45 d	5/24/10	7/8/10	132SF
132	Evaluation	5 d	7/8/10	7/13/10	133SF
133	Approval	5 d	7/13/10	7/18/10	134SF
134	Award & Appeal Period	14 d	7/18/10	8/1/10	135SF
135	Mobilization	60 d	8/1/10	9/30/10	138SF
136	**Drilling**	**310 d**	**9/30/10**	**8/6/11**	
137	**Well 1**	**90 d**	**9/30/10**	**12/29/10**	
138	Rig Mobilization	30 d	9/30/10	10/30/10	120,111,83,7
139	Actual Drilling	60 d	10/30/10	12/29/10	138
140	**Well 2**	**65 d**	**12/29/10**	**3/4/11**	
141	Rig Mobilization	5 d	12/29/10	1/3/11	139
142	Actual Drilling	60 d	1/3/11	3/4/11	141
143	**Well 3**	**65 d**	**3/4/11**	**5/8/11**	
144	Rig Mobilization	5 d	3/4/11	3/9/11	142
145	Actual Drilling	60 d	3/9/11	5/8/11	144
146	**Testing**	**280 d**	**10/30/10**	**8/6/11**	
147	**Well 1**	**150 d**	**10/30/10**	**3/29/11**	
148	Geology	60 d	10/30/10	12/29/10	139SS
149	Geochemistry	120 d	10/30/10	2/27/11	139SS,151F
150	Heat up	30 d	12/29/10	1/28/11	139



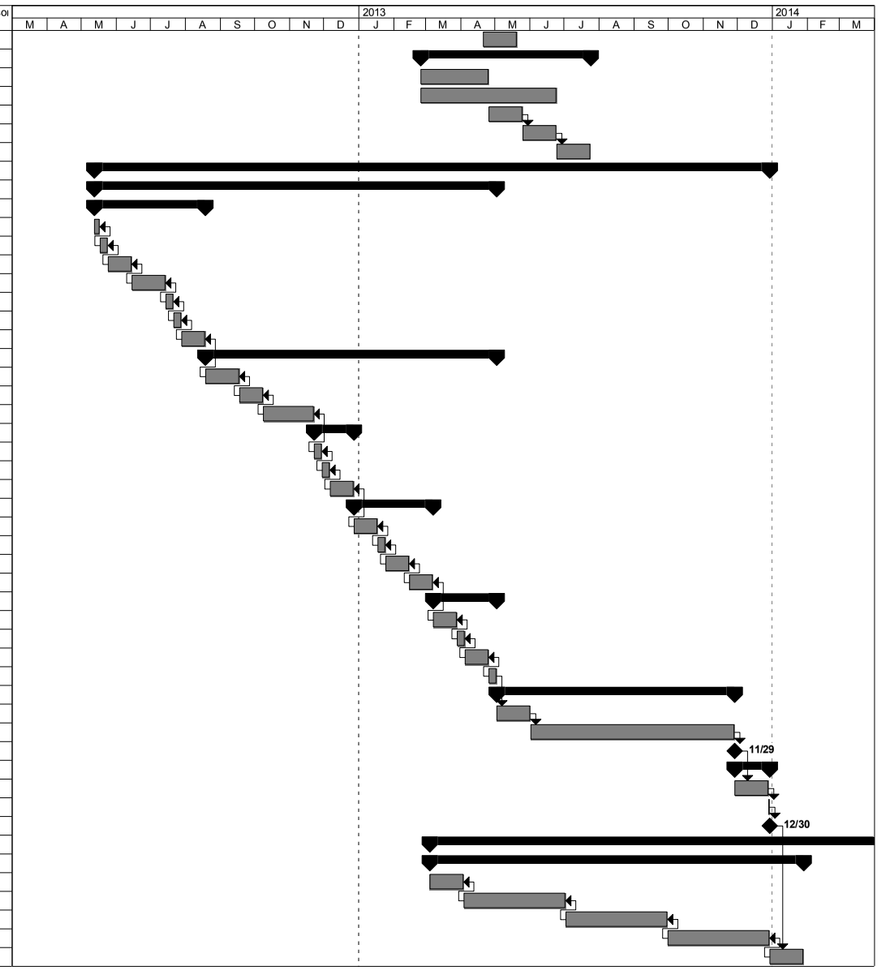
ID	Task Name	Duration	Start	Finish	Predecessor
151	Flow testing	30 d	1/28/11	2/27/11	150
152	Reports	30 d	2/27/11	3/29/11	151
153	**Well 2**	**150 d**	**1/3/11**	**6/2/11**	
154	Geology	60 d	1/3/11	3/4/11	142SS
155	Geochemistry	120 d	1/3/11	5/3/11	142SS
156	Heat up	30 d	3/4/11	4/3/11	142
157	Flow testing	30 d	4/3/11	5/3/11	156
158	Reports	30 d	5/3/11	6/2/11	157
159	**Well 3**	**150 d**	**3/9/11**	**8/6/11**	
160	Geology	60 d	3/9/11	5/8/11	145SS
161	Geochemistry	120 d	3/9/11	7/7/11	145SS
162	Heat up	30 d	5/8/11	6/7/11	145
163	Flow testing	30 d	6/7/11	7/7/11	162
164	Reports	30 d	7/7/11	8/6/11	163
165	Environment Management	1 d?	7/6/11	7/7/11	83SS,163FF
166	**In-house Reviews**	**53 d?**	**7/22/11**	**9/13/11**	
167	**Collation of data and reports**	**30 d**	**7/22/11**	**8/21/11**	**164SS+15 d**
168	Review initial Conceptual Model	15 d	8/21/11	9/5/11	167
169	Presentation	1 d?	9/5/11	9/6/11	168
170	Modification	7 d	9/6/11	9/13/11	169
171	**BOC Review**	**34 d**	**9/13/11**	**10/17/11**	
172	Posting of reports	30 d	9/13/11	10/13/11	170
173	Actual meetings	4 d	10/13/11	10/17/11	172
174	**Go or No Go**	**0 d**	**10/17/11**	**10/17/11**	**173**
175	**RESOURCE ASSESSMENT**	**1104 d**	**12/22/10**	**12/30/13**	
176	**Appraisal Program**	**946 d**	**12/22/10**	**7/25/13**	
177	**Rig Hire**	**445 d**	**12/22/10**	**3/11/12**	
178	**Pre-Qualification**	**98 d**	**12/22/10**	**3/30/11**	
179	Prepation of Expression of Interest	5 d	12/22/10	12/27/10	180SF
180	Obtain Banks No objection	7 d	12/27/10	1/3/11	181SF
181	Advertise (local media and international)	21 d	1/3/11	1/24/11	182SF
182	Bidding Period	30 d	1/24/11	2/23/11	183SF
183	Evaluation & Shortlist Report Preparation	7 d	2/23/11	3/2/11	184SF
184	KenGen's Approval	7 d	3/2/11	3/9/11	185SF
185	Obtain Banks No objection	21 d	3/9/11	3/30/11	187SF
186	**Tendering**	**347 d**	**3/30/11**	**3/11/12**	
187	Preparation of bidding Documents	30 d	3/30/11	4/29/11	188SF
188	Obtain Banks' no objection	21 d	4/29/11	5/20/11	189SF
189	Issue bid documents + tendering	45 d	5/20/11	7/4/11	191SF
190	**Technical Evaluation**	**35 d**	**7/4/11**	**8/8/11**	
191	Evaluation	7 d	7/4/11	7/11/11	192SF
192	KenGen Approval	7 d	7/11/11	7/18/11	193SF
193	Obtain Bank's no objection	21 d	7/18/11	8/8/11	195SF
194	**Commercial Evaluation**	**70 d**	**8/8/11**	**10/17/11**	
195	Invite bidders for tender openining	21 d	8/8/11	8/29/11	196SF
196	Evaluation	7 d	8/29/11	9/5/11	197SF
197	KenGen Approval & Appeal	21 d	9/5/11	9/26/11	198SF
198	Obtain Bank's no objection	21 d	9/26/11	10/17/11	200SF
199	**Contract Negotaition**	**56 d**	**10/17/11**	**12/12/11**	
200	Invite bidders for Negotiation	21 d	10/17/11	11/7/11	174



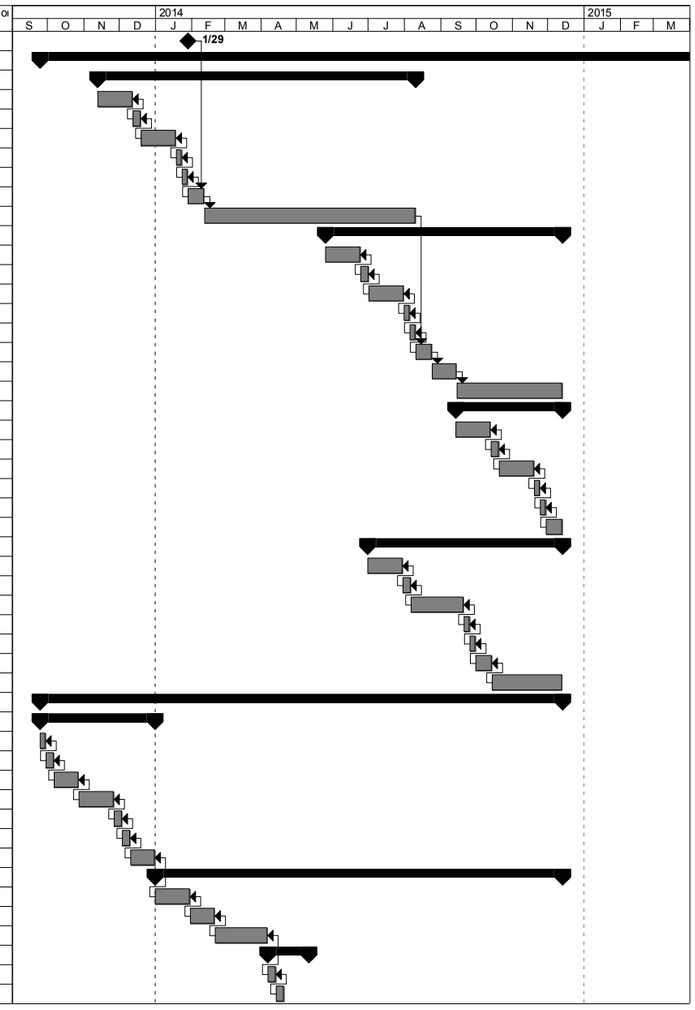
ID	Task Name	Duration	Start	Finish	Predecessor
251	Rig Mobilization	5 d	5/11/12	5/16/12	249
252	Actual Drilling	60 d	5/16/12	7/15/12	251
253	**Well 6**	**65 d**	**7/15/12**	**9/18/12**	
254	Rig Mobilization	5 d	7/15/12	7/20/12	252
255	Actual Drilling	60 d	7/20/12	9/18/12	254
256	**Testing First Three wells**	**280 d**	**3/12/12**	**12/17/12**	
257	**Well 4**	**150 d**	**3/12/12**	**8/9/12**	
258	Geology	60 d	3/12/12	5/11/12	249SS
259	Geochemistry	120 d	3/12/12	7/10/12	249SS
260	Heat up	30 d	5/11/12	6/10/12	249
261	Flow testing	30 d	6/10/12	7/10/12	260
262	Reports	30 d	7/10/12	8/9/12	261
263	**Well 5**	**155 d**	**5/11/12**	**10/13/12**	
264	Geology	60 d	5/11/12	7/10/12	251SS
265	Geochemistry	120 d	5/16/12	9/13/12	252SS
266	Heat up	30 d	7/15/12	8/14/12	252
267	Flow testing	30 d	8/14/12	9/13/12	266
268	Reports	30 d	9/13/12	10/13/12	267
269	**Well 6**	**150 d**	**7/20/12**	**12/17/12**	
270	Geology	60 d	7/20/12	9/18/12	255SS
271	Geochemistry	120 d	7/20/12	11/17/12	255SS
272	Heat up	30 d	9/18/12	10/18/12	255
273	Flow testing	30 d	10/18/12	11/17/12	272
274	Reports	30 d	11/17/12	12/17/12	273
275	**Exploration Strategy review**	**31 d**	**12/17/12**	**1/17/13**	
276	Data Collation	30 d	12/17/12	1/16/13	274
277	Presentation and Review	1 d	1/16/13	1/17/13	276
278	**Drilling of Remaining Three wells**	**310 d**	**9/18/12**	**7/25/13**	
279	**Drilling**	**220 d**	**9/18/12**	**4/26/13**	
280	**Well 7**	**90 d**	**9/18/12**	**12/17/12**	
281	Rig Mobilization	30 d	9/18/12	10/18/12	255
282	Actual Drilling	60 d	10/18/12	12/17/12	281
283	**Well 8**	**65 d**	**12/17/12**	**2/20/13**	
284	Rig Mobilization	5 d	12/17/12	12/22/12	282
285	Actual Drilling	60 d	12/22/12	2/20/13	284
286	**Well 9**	**65 d**	**2/20/13**	**4/26/13**	
287	Rig Mobilization	5 d	2/20/13	2/25/13	285
288	Actual Drilling	60 d	2/25/13	4/26/13	287
289	**Testing Remaining Three wells**	**280 d**	**10/18/12**	**7/25/13**	
290	**Well 7**	**150 d**	**10/18/12**	**3/17/13**	
291	Geology	60 d	10/18/12	12/17/12	282SS
292	Geochemistry	120 d	10/18/12	2/15/13	282SS
293	Heat up	30 d	12/17/12	1/16/13	282
294	Flow testing	30 d	1/16/13	2/15/13	293
295	Reports	30 d	2/15/13	3/17/13	294
296	**Well 8**	**150 d**	**12/22/12**	**5/21/13**	
297	Geology	60 d	12/22/12	2/20/13	285SS
298	Geochemistry	120 d	12/22/12	4/21/13	285SS
299	Heat up	30 d	2/20/13	3/22/13	285
300	Flow testing	30 d	3/22/13	4/21/13	299



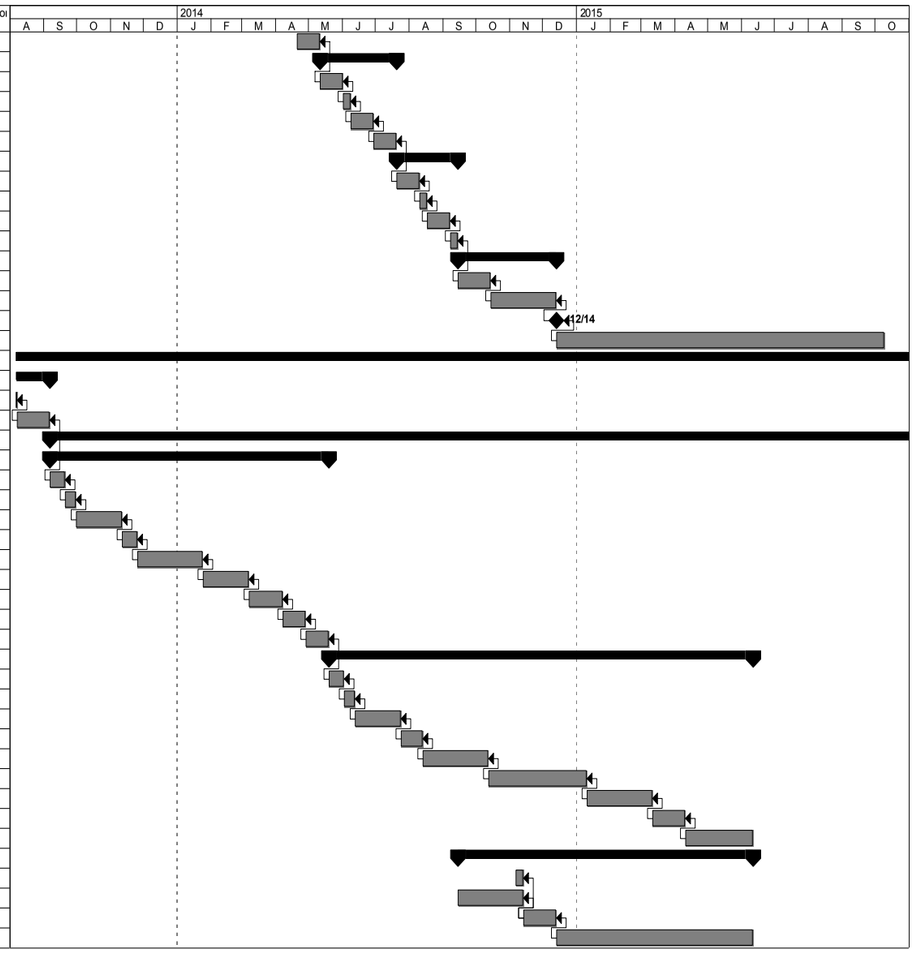
ID	Task Name	Duration	Start	Finish	Predecessor
301	Reports	30 d	4/21/13	5/21/13	300
302	**Well 9**	**150 d**	**2/25/13**	**7/25/13**	
303	Geology	60 d	2/25/13	4/26/13	288SS
304	Geochemistry	120 d	2/25/13	6/25/13	288SS
305	Heat up	30 d	4/26/13	5/26/13	288
306	Flow testing	30 d	5/26/13	6/25/13	305
307	Reports	30 d	6/25/13	7/25/13	306
308	**Feasibility Study**	**596 d**	**5/13/12**	**12/30/13**	
309	**Hire of Consultants**	**355 d**	**5/13/12**	**5/3/13**	
310	**Pre-Qualification**	**98 d**	**5/13/12**	**8/19/12**	
311	Prepation of Expression of Interest	5 d	5/13/12	5/18/12	312SF
312	Obtain Banks No objection	7 d	5/18/12	5/25/12	313SF
313	Advertise (local media and international)	21 d	5/25/12	6/15/12	314SF
314	Bidding Period	30 d	6/15/12	7/15/12	315SF
315	Evaluation & Shortlist Report Preparation	7 d	7/15/12	7/22/12	316SF
316	KenGen's Approval	7 d	7/22/12	7/29/12	317SF
317	Obtain Banks No objection	21 d	7/29/12	8/19/12	319SF
318	**Tendering**	**257 d**	**8/19/12**	**5/3/13**	
319	Preparation of bidding Documents	30 d	8/19/12	9/18/12	320SF
320	Obtain Banks' no objection	21 d	9/18/12	10/9/12	321SF
321	Issue bid documents + tendering	45 d	10/9/12	11/23/12	323SF
322	**Technical Evaluation**	**35 d**	**11/23/12**	**12/28/12**	
323	Evaluation	7 d	11/23/12	11/30/12	324SF
324	KenGen Approval	7 d	11/30/12	12/7/12	325SF
325	Obtain Bank's no objection	21 d	12/7/12	12/28/12	327SF
326	**Commercial Evaluation**	**70 d**	**12/28/12**	**3/8/13**	
327	Invite bidders for tender openining	21 d	12/28/12	1/18/13	328SF
328	Evaluation	7 d	1/18/13	1/25/13	329SF
329	KenGen Approval & Appeal	21 d	1/25/13	2/15/13	330SF
330	Obtain Bank's no objection	21 d	2/15/13	3/8/13	332SF
331	**Contract Negotaition**	**56 d**	**3/8/13**	**5/3/13**	
332	Invite bidders for Negotiation	21 d	3/8/13	3/29/13	333SF
333	Negotiation & Drafting of contract	7 d	3/29/13	4/5/13	334SF
334	Obtain Bank's no objection	21 d	4/5/13	4/26/13	335SF
335	Signing of contracts	7 d	4/26/13	5/3/13	288
336	**Contract Performance**	**210 d**	**5/3/13**	**11/29/13**	
337	Advance Payment	30 d	5/3/13	6/2/13	335
338	Study	180 d	6/2/13	11/29/13	337
339	Submission of Bankable report	0 d	11/29/13	11/29/13	338
340	**BOC Review Meeting**	**31 d**	**11/29/13**	**12/30/13**	
341	Data Collation	30 d	11/29/13	12/29/13	339
342	Presentation and Review	1 d	12/29/13	12/30/13	341
343	Go or No Go	0 d	12/30/13	12/30/13	342
344	**CONSTRUCTION PHASE**	**1921 d**	**3/5/13**	**6/8/18**	
345	**Funding Application**	**330 d**	**3/5/13**	**1/29/14**	
346	Project Identification	30 d	3/5/13	4/4/13	347SF
347	Project Formulation and Preparation	90 d	4/4/13	7/3/13	348SF
348	Appraisal	90 d	7/3/13	10/1/13	349SF
349	Funding institution Approval	90 d	10/1/13	12/30/13	350SF
350	Fianacial Agreements Negotiation	30 d	12/30/13	1/29/14	343



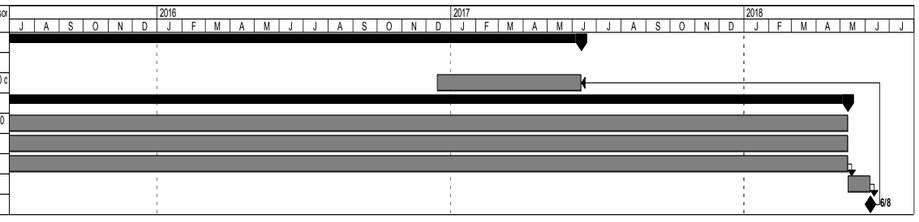
ID	Task Name	Duration	Start	Finish	Predecessor
351	Credit Effectiveness	0 d	1/29/14	1/29/14	350
352	**Production Drilling**	**745 d**	**9/25/13**	**10/10/15**	
353	**Overseas Procurement**	**271 d**	**11/13/13**	**8/11/14**	
354	Prepare tender	30 d	11/13/13	12/13/13	355SF
355	Advertise	7 d	12/13/13	12/20/13	356SF
356	Tender Period	30 d	12/20/13	1/19/14	357SF
357	Evaluation	5 d	1/19/14	1/24/14	358SF
358	Approval	5 d	1/24/14	1/29/14	359SF
359	Award & Appeal Period	14 d	1/29/14	2/12/14	351
360	Delivery	180 d	2/12/14	8/11/14	359
361	**Slotting of Liners**	**202 d**	**5/26/14**	**12/14/14**	
362	Prepare tender	30 d	5/26/14	6/25/14	363SF
363	Advertise	7 d	6/25/14	7/2/14	364SF
364	Tender Period	30 d	7/2/14	8/1/14	365SF
365	Evaluation	5 d	8/1/14	8/6/14	366SF
366	Approval	5 d	8/6/14	8/11/14	367SF
367	Award & Appeal Period	14 d	8/11/14	8/25/14	360
368	Mobilization	21 d	8/25/14	9/15/14	367
369	Actual Works	90 d	9/15/14	12/14/14	368
370	**Contract for Bulk Cement & Diesel Fuel**	**91 d**	**9/14/14**	**12/14/14**	
371	Prepare tender	30 d	9/14/14	10/14/14	372SF
372	Advertise	7 d	10/14/14	10/21/14	373SF
373	Tender Period	30 d	10/21/14	11/20/14	374SF
374	Evaluation	5 d	11/20/14	11/25/14	375SF
375	Approval	5 d	11/25/14	11/30/14	376SF
376	Award & Appeal Period	14 d	11/30/14	12/14/14	416SF
377	**Contract Cementing Services**	**166 d**	**7/1/14**	**12/14/14**	
378	Prepare tender	30 d	7/1/14	7/31/14	379SF
379	Advertise	7 d	7/31/14	8/7/14	380SF
380	Tender Period	45 d	8/7/14	9/21/14	381SF
381	Evaluation	5 d	9/21/14	9/26/14	382SF
382	Approval	5 d	9/26/14	10/1/14	383SF
383	Award & Appeal Period	14 d	10/1/14	10/15/14	384SF
384	Mobilization	60 d	10/15/14	12/14/14	416SF
385	**Hire of Second Rig**	**445 d**	**9/25/13**	**12/14/14**	
386	**Pre-Qualification**	**98 d**	**9/25/13**	**1/1/14**	
387	Prepation of Expression of Interest	5 d	9/25/13	9/30/13	388SF
388	Obtain Banks No objection	7 d	9/30/13	10/7/13	389SF
389	Advertise (local media and international)	21 d	10/7/13	10/28/13	390SF
390	Bidding Period	30 d	10/28/13	11/27/13	391SF
391	Evaluation & Shortlist Report Preparation	7 d	11/27/13	12/4/13	392SF
392	KenGen's Approval	7 d	12/4/13	12/11/13	393SF
393	Obtain Banks No objection	21 d	12/11/13	1/1/14	395SF
394	**Tendering**	**347 d**	**1/1/14**	**12/14/14**	
395	Preparation of bidding Documents	30 d	1/1/14	1/31/14	396SF
396	Obtain Banks' no objection	21 d	1/31/14	2/21/14	397SF
397	Issue bid documents + tendering	45 d	2/21/14	4/7/14	399SF
398	**Technical Evaluation**	**35 d**	**4/7/14**	**5/12/14**	
399	Evaluation	7 d	4/7/14	4/14/14	400SF
400	KenGen Approval	7 d	4/14/14	4/21/14	401SF



ID	Task Name	Duration	Start	Finish	Predecessor
401	Obtain Bank's no objection	21 d	4/21/14	5/12/14	403SF
402	**Commercial Evaluation**	**70 d**	**5/12/14**	**7/21/14**	
403	Invite bidders for tender openining	21 d	5/12/14	6/2/14	404SF
404	Evaluation	7 d	6/2/14	6/9/14	405SF
405	KenGen Approval & Appeal	21 d	6/9/14	6/30/14	406SF
406	Obtain Bank's no objection	21 d	6/30/14	7/21/14	408SF
407	**Contract Negotaition**	**56 d**	**7/21/14**	**9/15/14**	
408	Invite bidders for Negotiation	21 d	7/21/14	8/11/14	409SF
409	Negotiation & Drafting of contract	7 d	8/11/14	8/18/14	410SF
410	Obtain Bank's no objection	21 d	8/18/14	9/8/14	411SF
411	Signing of contracts	7 d	9/8/14	9/15/14	413SF
412	**Contract Performance**	**90 d**	**9/15/14**	**12/14/14**	
413	Advance Payment	30 d	9/15/14	10/15/14	414SF
414	Mobilization	60 d	10/15/14	12/14/14	415SF
415	Onsite	0 d	12/14/14	12/14/14	416SF
416	Drilling and Testing	300 d	12/14/14	10/10/15	369
417	**Custruction Phase**	**1766 d**	**8/7/13**	**6/8/18**	
418	**Interfacing with KPLC**	**31 d**	**8/7/13**	**9/7/13**	
419	Contact KPLC	1 d	8/7/13	8/8/13	420SF
420	Obtain counterpart Staff	30 d	8/8/13	9/7/13	423SF
421	**Power Plant Construction and Commissioning**	**1707 d**	**9/7/13**	**5/11/18**	
422	**Procure Consultants**	**255 d**	**9/7/13**	**5/20/14**	
423	Prepare expression of interest	14 d	9/7/13	9/21/13	424SF
424	Advertise	10 d	9/21/13	10/1/13	425SF
425	Tender period	42 d	10/1/13	11/12/13	426SF
426	Pre-qualify Consultants	14 d	11/12/13	11/26/13	427SF
427	Tender Documents	60 d	11/26/13	1/25/14	428SF
428	Tendering Process	42 d	1/25/14	3/8/14	429SF
429	Complete Tender Evaluation and Approval (two enve	31 d	3/8/14	4/8/14	430SF
430	Complete Aw ard, Negotion and Contract signing	21 d	4/8/14	4/29/14	431SF
431	Advance Payment and LC	21 d	4/29/14	5/20/14	433SF
432	**Procure Contractor**	**388 d**	**5/20/14**	**6/12/15**	
433	Prepare expression of interest	14 d	5/20/14	6/3/14	434SF
434	Advertise	10 d	6/3/14	6/13/14	435SF
435	Tender period	42 d	6/13/14	7/25/14	436SF
436	Pre-qualify Contractors	20 d	7/25/14	8/14/14	437SF
437	Tender Documents and Conceptual design	60 d	8/14/14	10/13/14	438SF
438	Tendering Process	90 d	10/13/14	1/11/15	439SF
439	Complete Tender Evaluation and Approval	60 d	1/11/15	3/12/15	440SF
440	Complete Aw ard, Negotion and Contract signing	30 d	3/12/15	4/11/15	441SF
441	Advance Payment and LC	62 d	4/11/15	6/12/15	451SF
442	**Construct Service Power line**	**270 d**	**9/15/14**	**6/12/15**	
443	Make Application	7 d	11/7/14	11/14/14	445SF
444	KPLC quotation Period	60 d	9/15/14	11/14/14	445SF
445	Make payment	30 d	11/14/14	12/14/14	446SF
446	Line Construction	180 d	12/14/14	6/12/15	451SF



ID	Task Name	Duration	Start	Finish	Predecessor
447	**Acquire Staff**	**1141 d**	**4/29/14**	**6/13/17**	
448	Acquire counterpart staff from Generation	30 d	4/29/14	5/29/14	431SS
449	Acquire operation Staff	180 d	12/15/16	6/13/17	455FF-360 d
450	**Complete Construction -Key Milestone**	**1064 d**	**6/12/15**	**5/11/18**	
451	Power plant and accessories	1064 d	6/12/15	5/11/18	416SS+180
452	Steamfield Surface equipment	1064 d	6/12/15	5/11/18	451SS
453	Transmission and Substation	1064 d	6/12/15	5/11/18	452SS
454	Commissioning of Plant	4 wks	5/11/18	6/8/18	453
455	Commencement of commercial operation	0 d	6/8/18	6/8/18	454



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PLANNING OF GEOTHERMAL PROJECTS IN ICELAND

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ABSTRACT

Geothermal energy supplies about 65% of the primary energy used in Iceland. The most important use is for space heating but geothermal power production is increasing rapidly. Exploration and development of the geothermal fields are divided into several phases starting with preliminary studies and continuing with appraisal study, project design, construction and operation of a power plant. Earlier the development strategy was to fully utilize the generating capacity of each field in one"large" power plant. This meant that the generating capacity of the field had to be known prior to the decision on the installed capacity of the power plant to be built. This strategy required an immense effort in exploration and testing to determine the optimum generating capacity of a field, requiring a large investment in exploration, drilling, reservoir testing and monitoring. A multi-step strategy is considered more suitable and more cost-effective for geothermal development than one large (full) step strategy. Stepwise development means that the geothermal field is developed in relatively small (20-50 MW_e) steps. The response of the reservoir to this production is then monitored and evaluated and used for deciding if and when the next development step is taken. In this way, the power plant is in operation (and earning money for its owners) while the field is being tested. Stepwise development of geothermal resources has been applied in Iceland during the last 15-20 years.

1. INTROUCTION

Iceland is a volcanic island that lies astride the Mid Atlantic Ridge, the rift zone along the constructive boundary between the American and the Eurasian tectonic plates which move apart at an average rate of 2 cm per year. The presently active zone of rifting and volcanism crosses Iceland from southwest to northeast.

Iceland is rich in geothermal resources due to the volcanic activity, and heat flow through the crust is several times higher than world average. Traditionally the geothermal fields are divided into *high temperature fields,* in which temperatures above 200°C are found at 1 km depth and *low-temperature fields,*in which temperatures are lower than 150°C in the uppermost kilometre. Some 30 high temperature fields have been described in Iceland, all within the active volcanic zone (Figure 1). The low temperature activity is highest on the flanks of the volcanic zones but low temperature resources are found in most parts of the country (Figure 1).

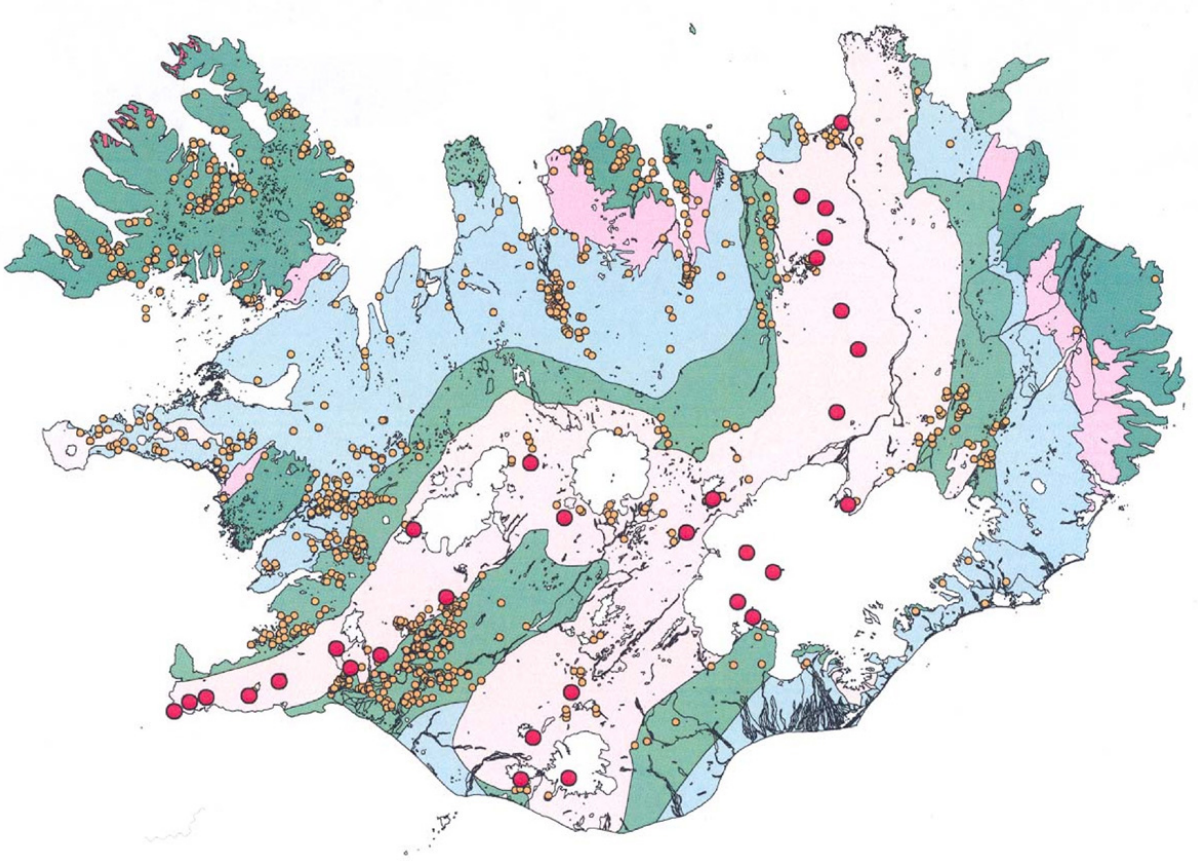

FIGURE 1: Geothermal map of Iceland. High temperature fields inside the active volcanic zone are shown as red circles, and hot and warm springs as yellow circles

2. GEOTHERMAL UTILIZATION

Through the centuries there was little utilization of geothermal energy in Iceland. Hot water from warm springs was, however, used locally in some areas for bathing, cooking and washing and sulphur was mined from a few of the high temperature areas and exported. Large scale utilization started initially with the utilization of low temperature resources for space heating. Later utilization of high temperature resources for electrical generation, space heating and some industrial uses followed. Cascaded use of geothermal water became common in the late 20th century.

Large scale utilization of geothermal resources in Iceland began in 1930 when a district heating system started operating in Reykjavik supplying hot water to a hospital, a school, a swimming pool and some 70 homes. The extent of utilization grew over the next decades (Figure 2). During the energy crisis in the 1970´s, an effort was made to abandon the use of oil for space heating and replace it with geothermal energy. Today almost 90% of houses in Iceland are heated by geothermal energy and electricity serves the remaining 10%. Now (2008) the installed geothermal power capacity is 500 MW_e. Geothermal energy has become the main source of energy in Iceland supplying about 65% of the primary energy used in the country (Figure 3). The most important uses are still for space heating, but electricity generation is growing rapidly and amounts to more than 20% of the utilization. Figure 4 shows a pie chart on how the geothermal energy was utilized in Iceland in 2007.

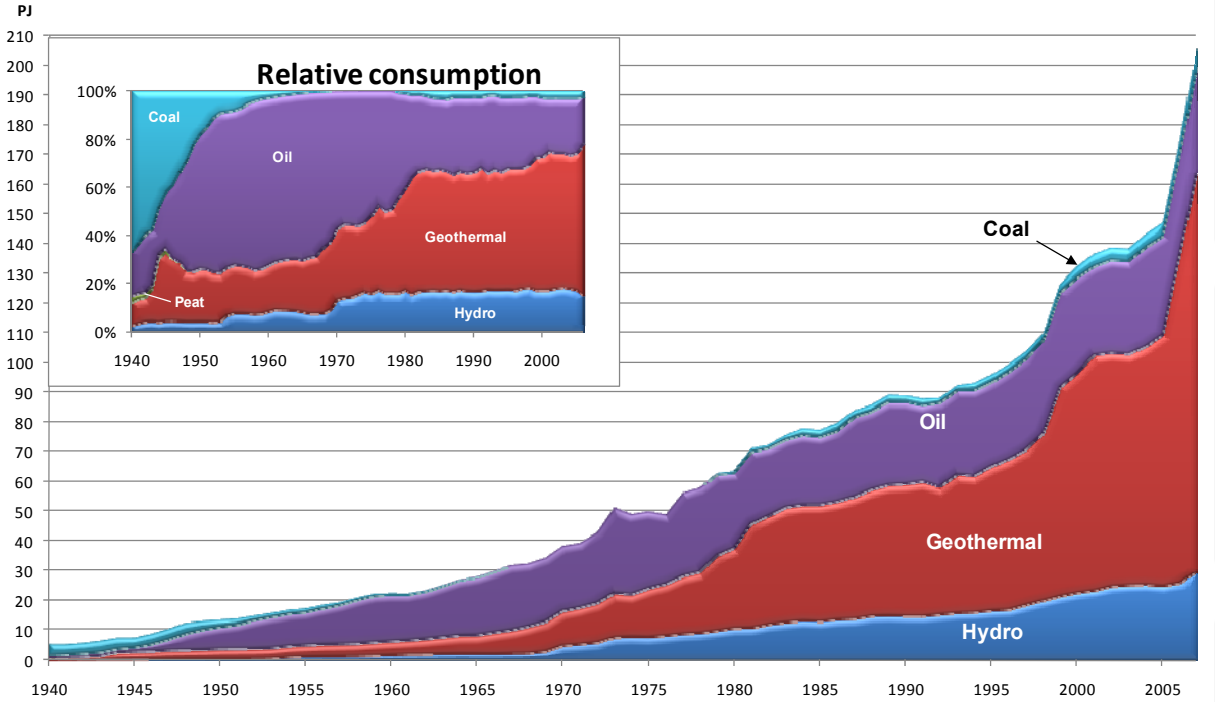

FIGURE 2: Primary energy consumption in Iceland 1940-2007. Source: Orkustofnun (National Energy Authority)

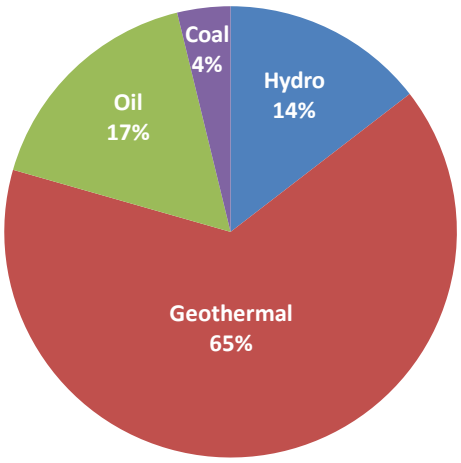

FIGURE 3: Sources of energy used in Iceland in 2007. Source: Orkustofnun (National EnergyAuthority)

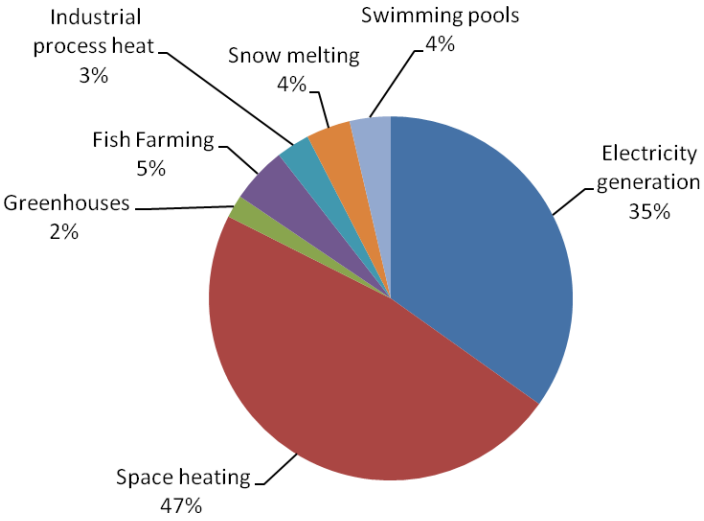

FIGURE 4: Geothermal energy uses in Iceland in 2007. Source: Orkustofnun (National Energy Authority)

3. GEOTHERMAL PROJECT STRATEGY

3.1 Exploration programme of 1969

Methodology of the exploration of Icelandic geothermal areas has been under discussion and development since their utilization started. It was soon evident that the geothermal areas were an

important source of energy for the nation. It was also clear that a considerable effort of costly exploration, drilling and testing of wells had to be carried out for years before it was possible to evaluate the feasibility of utilizing the geothermal fields, in particular the high temperature fields.

The first exploration programme, for development of the geothermal fields, was proposed by Orkustofnun (the National Energy Authority) in 1969.To organize and accelerate the utilization of the fields exploration was divided into three phases (Björnsson 1970):

- Regional Survey, during which all relevant methods of geology, geochemistry and geophysics should be applied to obtain a conceptual model of the geothermal field and locate production sites.
- Exploratory Drilling to obtain information on the geological structure, temperature and pressure distribution and fluid characteristics of the geothermal reservoir and use it to modify the conceptual model of the field, to design production wells and to carry out a preliminary plant design and a pre-feasibility study of the field.
- Production Drilling and Testing; carried out in steps to test the production capacity of the field if the results of the pre-feasibility are promising.

In the time frame for the exploration it was estimated that the regional survey could be completed in 1-3 years, the exploration drilling would take 1-2 years and the production drilling 1-3 years. The exploration of each area would therefore take up to 8 years before the capacity of the field would be confirmed and the feasibility of a utilization project could be determined.

The development strategy of the 1969 program was used as a guideline for the exploration of several high temperature areas in Iceland in 1960-1980, including the Reykjanes, Námafjall, Svartsengi, and Krafla fields.

The Krafla power plant is an example of a project originally planned in accordance with the 1969 Exploration Programme but its development was subject to interferences due to management and natural causes. Surface exploration was carried out in accordance with the programme 1970-1973. At that time a hydropower project in nearby River Laxá was reduced in scale due to local opposition and there was concern about dearth in power supply in North Iceland and therefore it was decided to speed up operations in Krafla. Two relatively shallow exploration wells were drilled in 1974 and based on the results for these and the known character of the nearby Námafjall geothermal system (where 9 relatively shallow wells had been drilled) the decision was made to purchase two 30 MW double flash turbines to be on line in 1977. In 1975 a volcanic eruption started in the neighbourhood causing excess gas in the fluid and the clogging up of wells due to deposition. In 1978 the first turbine was started but the steam available was only sufficient for 7 MW_e production. Another well was drilled in 1978 but its steam caused problems and the increase in production was small and it was decided to put a halt to drilling. Fumarole gas was investigated and the existence of steam producing areas where volcanic influence was absent proved. In 1980 drilling was resumed and in 1984 the first turbine was producing 30 MW_e. The volcanic activity lasted till 1984 and the second turbine was put in storage for the time being. As most of the later wells were high enthalpy wells a problem arose as there was not sufficient steam for the low pressure part of the double flash turbine and two low enthalpy make up wells were drilled as well as two exploratory wells until 1997 when it was decided to drill for steam to supply the second 30 MW_e turbine which was commissioned in 1999 when 8 more wells had been drilled. Thus it had taken nearly 30 years to get full production from the Krafla power plant.

3.2 Systematic exploration programme of 1982

The Parliament of Iceland made a resolution in 1981 that the government, should set up and implement an exploration program for the high temperature areas in such a way that the feasibility study for utilization of two areas should be carried out within five years and five more areas within ten years. In late 1981 the Ministry of Energy and Industry asked Orkustofnun to set up a systematic

exploration programme for the high temperature fields according to the goals of the resolution. A task force of six geothermal specialists was allocated the job and completed it in a year (Stefansson et al., 1982). The programme was never executed due to lack of funding in the following years. However the strategy for exploring high temperature fields was analysed and a generic plan put forward for the development of geothermal fields. (Figure 5) in five phases: *Preliminary study* starting with a reconnaissance study of the field, an *appraisal study*, followed by *project design*, a *construction phase,* and finally the *operation* of a geothermal plant. A time frame was estimated for the development according to which a decision can be made on how the field should be utilized after 10 years of exploration.

Surface exploration of the Hengill geothermal area started in the 1940s but seriously in Nesjavellir in 1964 when Reykjavík Heating Company (now Reykjavík Energy) acquired the Nesjavellir land. Exploratory drilling was carried out and a pilot plant run until 1982 when a full scale development plan for hot water production for the Reykjavík area using heat exchangers was put into action in accordance with the 1982 Systematic Exploration Programme. Several appraisal wells were drilled from 1982 to 1986 when a decision to build a 100 MW_{th} heating plant was made. This plant was commissioned in 1990 and expanded to 150 MW_{th} in 1992. In 1996 a decision was made to build a 60 MW_e power plant and expand the heating plant to 200 MW_{th} and this addtion was commissioned in 1998. The plant was further expanded to 90 MW_e/290 MW_{th} in 200 and to 120 MW_e in 2005.

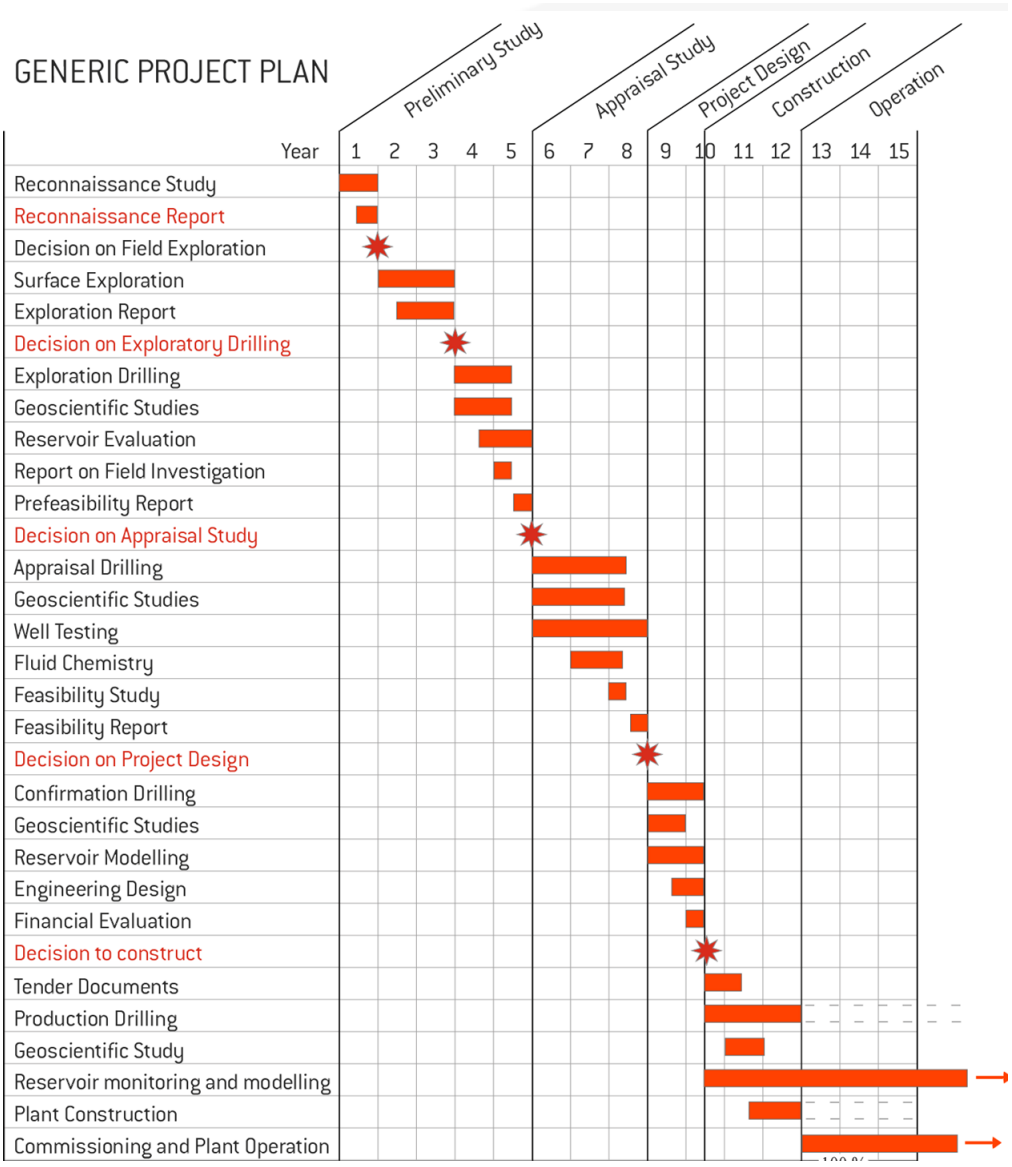

FIGURE 5: Generic phase plan of 1982 for geothermal development

3.3 Stepwise development strategy

The development strategies described above assume that the production capacity of the geothermal field is known when a decision is made regarding utilization. A generating capacity of the power plant is subsequently selected to fully match the field potential. This strategy is borrowed from hydropower development for which the determination of production capacity is rather easy and is known at a relatively early stage in the exploration programme. This is, however, not the case for the geothermal areas for which reliable knowledge on the generating capacity can only be obtained through detailed exploration of the field, drilling and monitoring the of response of the geothermal reservoir to production lasting for some years. In the generic plan of 1982, it is after 10 years of intensive exploration, drilling and testing that a decision is made on whether to go ahead with the power plant.

Stefansson (1992) discussed several examples of geothermal projects worldwide and pointed out that a stepwise development strategy for geothermal resources has considerable economic benefits compared to full utilization of the field capacity in one large power plant. By following the generic plan of Figure 5 but selecting a relatively small (20-50 MW_e) power plant as a first step, the time scale can be reduced and the plant commissioned and put into operation much earlier than for a "full" size plant (Stefansson, 2002). Monitoring of the field response to the first development step is then used to determine if and when the next step can be taken and so on until the total reservoir capacity is reached. Thus the generating capacity is first known when the field is fully utilized, whereas in the one step strategy the production capacity is determined before the power plant is constructed. A comparison of these two strategies is shown in Figure 6.

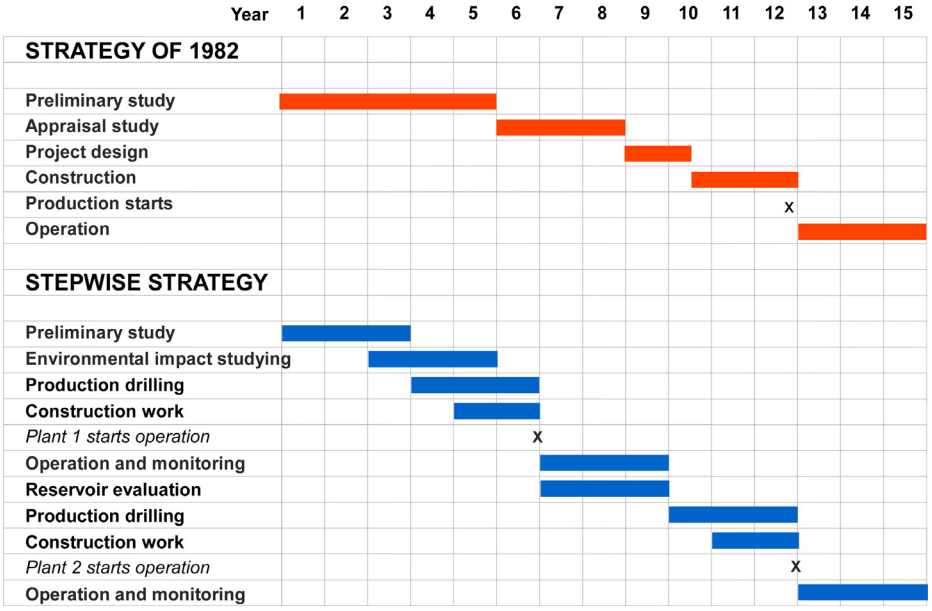

FIGURE 6: Comparison of the stepwise development strategy (lower part of the figure) and the conventional development strategy (upper part of the figure)

As mentioned above exploration of the Hengill area started in the 1940s. Exploratory wells were drilled in the Hellisheiði area in 1985 and 1994, but a concerted exploration effort was started in 2001 and 5 exploration wells were drilled 2001-2002 the results of which provided grounds for the decision to build a power plant in stages. In 2006 2 45 MW_e units were commissioned, a 30 MW_e low pressure turbine in 2007 and two more 45 MW_e units in 2008 and a hot water plant is planned for 2009. The estimated production potential is 300 MW_e and 400 MW_{th}.

A modification of the stepwise development strategy is the 5 MW_e portable power unit of Kaldara plc (www.kaldara.com) which may be a condensation or a binary power plant placed at the wellhead of a particular well whose steam is utilised. Such turbines can be started after 2 years of exploration and can thus give some return on investment much earlier than conventional turbines. One possibility is preliminary production during the construction of a power plant. An example is the procurement of such a unit for the Bjarnarflag power plant where steam acquisition is now underway and about half

the steam for a 90 MW_e power plant has been obtained. The use of this unit is planned for 3.5 years or until the power plant has been built. Then it is planned to move the unit to Theistareykir where steam is being acquired for another power plant and use it there until that plant is commissioned. And so on.

3.4 Research permits

Before a project proponent can obtain a Research Permit for a geothermal area he is interested in developing from the Ministry of Industry he needs to present a detailed research plan describing the objective of the project, the areal extent, the time plan, possible effects on neighbouring areas, previous research in the area and research and operations plans. Orkustofnun (www.os.is/page/ald_leidb) has published guidelines for applications for research permits.

3.5 Environmental impact studies

Project proponents are subject to restrictions due to planning decisions that have been made for the area to be developed. Recently Act No. 105/2006 on Strategic Environmental Assessment (SEA) was passed in Iceland. SEA is carried out at the planning stage and is described as a set of processes, documents and analyses that help the public administration to reach its environmental goals. To this purpose scientific data, data on environmental issues, local and national policies, and information about international laws and regulations are consulted.

According to the Act on Environmental Impact Assessment No. 106/2000, the Act on Changes to the Act on Environmental Impact Assessment 74/2005, and the Act on Planning and Building No. 73/1997, all projects, which may have a significant effect on the environment, natural resources or community, shall be subject to an Environmental Impact Assessment (EIA). Skipulagsstofnun (the Planning Agency) monitors the application of laws and regulations on planning, building and Environmental Impact Assessment. The Minister for the Environment has the supreme control of planning and building under the Planning and Building Act and EIA programmes under the Act on Environmental Impact Assessment. The assessment must be a part of the planning process.

Appendix 1 to a regulation supplementing the environmental act states which projects are compulsory for an EIA. Other projects, which may or may not be subjected to an assessment, depending on their magnitude, are listed in Appendix 2 of the regulation. These include "*drilling of production wells and research wells in high enthalpy fields*", and "*plants for production of electricity, steam and hot water, hydropower plants with installed capacity of 100 kW or more or geothermal exploitation of 2500 kW or more*". Initial drilling thus falls under projects listed in Appendix 2. In such cases the executing party prepares a report, the Environmental Impact Statement, to inform the Planning Agency of the intended project. The report must include a detailed description of the proposed project, in accordance with the procedure outlined in the regulations. After evaluation the Agency makes a decision on whether the project is exempted from EIA.

Figure 7 shows the progress of a project from proposal to EIA. If EIA is required the developer prepares an action plan for the EIA, which requires the approval of the Planning Agency. Figure 8 shows the progress of an EIA and the time required. The whole process from the time when the Planning Agency is handed the Environmental Impact Statement to a final decision of the EIA can be a minimum of 4 weeks if the

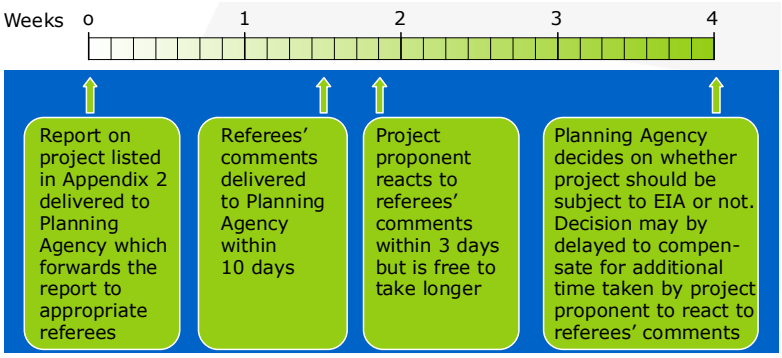

FIGURE 7: Procedure for projects listed in Appendix 2 of regulation to the Act on Environmental Impact Assessment, No. 106/2000

reports are found to be sufficient and no verdict is disputed. The time required by the developer to prepare the reports is not included here, and the time required varies, depending on the size and complexity of the proposed project.

The EIA process itself is depicted in Figure 8 and will take more than 32 weeks and considerably longer if the verdict is disputed. Power production or a large scale industrial project would fall under Appendix 1 of the Act and EIA is thus compulsory.

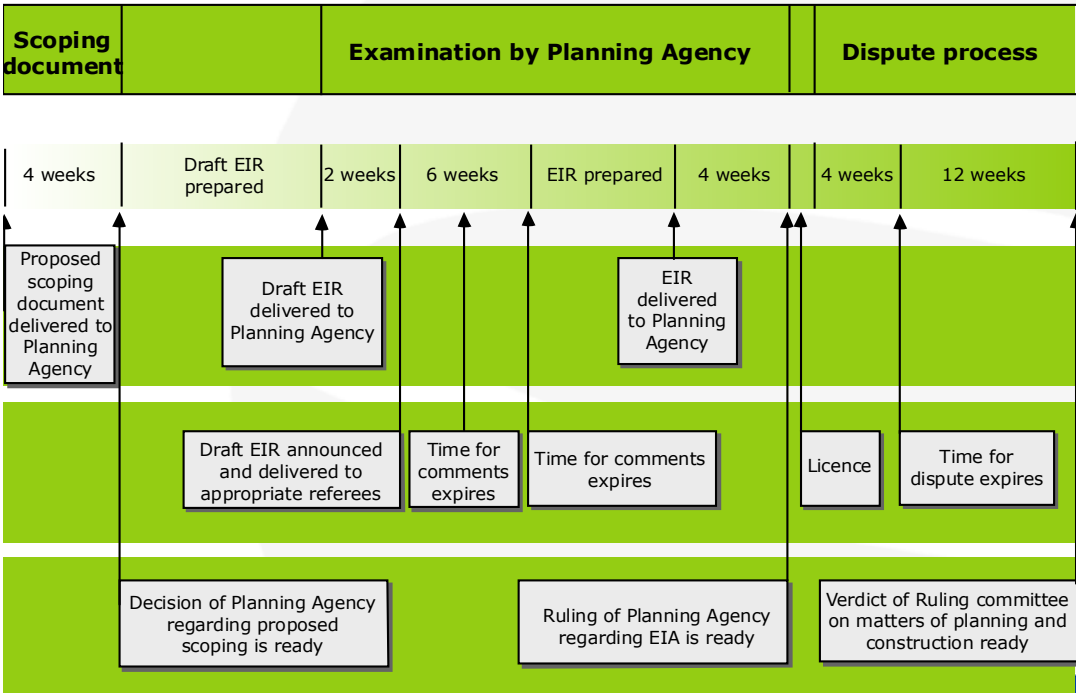

FIGURE 8: The EIA process

3.6 Master Plan for utilization of renewable energy resources

The Government of Iceland decided in 1999 to develop a Master plan for utilization of hydropower and geothermal resources. The Master Plan should be based on the best scientific information available and its development should be open to democratic involvement.

In the first phase of the Master Plan, a large number of proposed power projects were to be evaluated. The evaluation should involve the impact of the project on the environment, nature and wildlife, landscape, cultural heritage and ancient monuments, grazing and other traditional land use, outdoor life, fishing and hunting. The implications for employment and regional development were also to be accounted for. Finally the proposed projects should be categorized on the basis of efficiency and economic profitability, as well as how they will benefit the economy as a whole (The Minister for Industry, 1999). A more detailed description of the Master Plan was presented by Steingrímsson et al. (2008) and a special website, www.landvernd.is/natturuafl, was set up, for the project.

The Ministry of Industry, in co-operation with the Ministry of the Environment, established in April 1999 a special Steering Committee for the project. . In its function the Steering Committee was supported by about 50 experts working in four different working groups for the first phase:

- **Working Group I** was to evaluate what impact proposed power projects will have on nature, i.e. landscape, geological formations, vegetative cover, flora and fauna, as well as on cultural heritage and ancient monuments.

- **Working Group II** was to evaluate the impact on outdoor life, agriculture, revegetation, fishing in rivers and lakes, and hunting.
- **Working Group III** was to evaluate the impact proposed power projects can have on economic activity, employment and regional development.
- **Working Group IV** was to identify potential power projects, both hydropower and geothermal energy, and carry out technical as well as economic evaluation of the projects.

During the development of the Master Plan Orkustofnun and/or power companies compile reports on project proposals they wish to have evaluated by the Steering Committee. These reports are made public, and as a first step of the process, the public and interested organisations will have an opportunity to review the reports and offer comments.

It is expected that a total of about 100 project proposals will be evaluated by the Working Groups and the Steering Committee. A report on the first phase of the work, comparing 19 hydropower projects with an energy potential of 16.600 GWh/a and 24 geothermal projects with an energy potential of 18.000 GWh/a, was issued in November 2003 (The Board for the Master Plan for the Use of Hydropower and Geothermal Energy, 2003). The hydropower projects were mainly in glacial rivers in the central highlands whereas most of the geothermal projects were in geothermal fields near to inhabited lowlands.

The second phase of the Master Plan began in 2005 and now the focus is on scientific exploration of the active geothermal systems in the central highlands of Iceland but also on the environmental impact and sustainability of energy development. The second phase is expected to be completed in 2009. The third phase is expected to include exploration of recoverable geothermal energy outside the active geothermal areas.

4. DISCUSSION AND CONCLUSIONS

Geothermal utilization on a large scale began less than 80 years ago in Iceland. Today, geothermal energy amounts to about 65% of the primary energy used in the country. The techniques and strategies on how to explore and utilize geothermal fields have been developed during these years as the knowledge of the geothermal fields and the geothermal processes has improved. It has proved useful to divide geothermal exploration and development into sequential phases, the first phase being a preliminary study of the geothermal field to be explored and the last being the operation of a geothermal installation in the field, as shown schematically in Figures 5 and 6.

The general structure of the generic plan of 1982 is still valid after more than twenty years. Increased environmental awareness and new law from the Icelandic Parliament on environmental impact studies have added various environmental studies and monitoring to the tasks in all the development phases. In 1982 the strategy was to develop the geothermal fields in one big step. In recent years it is generally accepted by the geothermal industry in Iceland that a stepwise development is more economical and better suited to the geothermal fields. It has been the policy of the Icelandic Government to promote the uses of geothermal resources in order to minimize import of oil. A governmental institution, Orkustofnun (The National Energy Authority), has been a major investigating agent in exploring the geothermal resources since their utilization began, separately or in partnership with the municipal or governmental energy companies. Orkustofnun also acted as a consultant to the energy companies until 2003 when the institute was divided into two; Orkustofnun (OS) and Iceland GeoSurvey (ISOR). Orkustofnun is now mainly an administrative and regulating agency whereas ISOR is the former geothermal specialist group of OS and carries out geothermal exploration consultant work for OS, the Icelandic energy companies and others. The role of the Icelandic state in the geothermal development in Iceland has gradually decreased with time. The energy companies are, however, still to a large extent owned by the state and/or the municipalities. The government initiated a few years ago the development of a Master Plan for the utilization of both

hydropower and geothermal resources. This is in a way a pioneering work which calls for research in methodology in order to base decisions on scientific knowledge. The Steering Committee of the Master Plan project have supported several new research projects in order to evaluate the proposed energy projects. Examples of such research projects include:

- Methods to evaluate the conservation value of wilderness areas
- Tourism and the value of an area for outdoor recreation
- Methods to evaluate landscape
- The economic efficiency of power projects and their potential socio-economic impact

The government has recently decided to participate with the energy companies in a large geothermal research project. The project is called the Iceland Deep drilling Project (IDDP) and aims at a better understanding of the geothermal resources below the relatively well known upper 3 km of the crustm (Fridleifsson and Elders, 2005). At 4-5 km depth within the volcanic systems it is expected to find fluids at supercritical pressure and temperature. Such deep unconventional geothermal resources are expected to produce super high enthalpy fluid at surface and result in a more efficient utilization of the high temperature areas.

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GEOTHERMAL EXPLORATION AND DEVELOPMENT OF THE OLKARIA GEOTHERMAL FIELD

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ABSTRACT

Several geothermal prospect areas have been identified in Kenya and are mainly located within the Kenyan Rift System. Olkaria prospect was the first to be explored and developed as Olkaria geothermal field, which is approximately 80 km^2. Due to its large size, it was found prudent to segment Olkaria geothermal field into seven sectors for ease of development. The sectors include Olkaria East, Olkaria North East, Olkaria Central, Olkaria South West, Olkaria North West, Olkaria South East and Olkaria Domes. Due to poor technology at the time, exploration work took over two decades before development of the first sector, which is Olkaria East. Olkaria reservoir produces two-phase mixture of steam and water in general proportion of 85% steam and 15% water and hence the resource is suitable for electrical power generation. Two types of power generation plants operate in Olkaria namely, the Ormat binary plants and the Mitsubishi geothermal condensing steam plants. A total of five power plants have been installed, two owned by KenGen, one by Ormat International and two by Oserian Development Company Ltd. The total installed power generation capacity of the four plants is 131.5 MW_e. Thus geothermal power installation constitutes about 12% of the national power installation and the plants operate as base load. Geothermal energy in Olkaria has mainly been utilized for electrical power production. Direct use has received little attention though recently Oserian Development Company Ltd leased a well from KenGen for direct use in horticultural farming. There are wells in Olkaria with extreme cyclic discharge characteristics and hence cannot operate with the other wells supplying steam to the power plants. Such wells, in the past, have either been turned to re-injection wells or simply rendered useless and yet are capable of supplying a lot of geothermal power for direct use. KenGen is looking at the possibility of economically selling geothermal energy from such wells to direct users either for recreational purposes or space heating.

1. INTRODUCTION

Several geothermal prospect areas have been identified in Kenya and are mainly located within the Kenyan Rift system. Olkaria prospect was the first to be explored and developed and became Olkaria geothermal field, located 125 km North West of Nairobi (Figures 1).

After extensive geo-scientific surveys in the early seventies, exploration drilling started in 1974 and continued through 1977. Following evaluation of the initial drilling results, a feasibility report was produced in 1977. The following year 1978, production drilling commenced and continued until 1983. Sufficient resource capacity was confirmed for installation of the first power plant of 45 MW_e at Olkaria between 1981 and 1985.

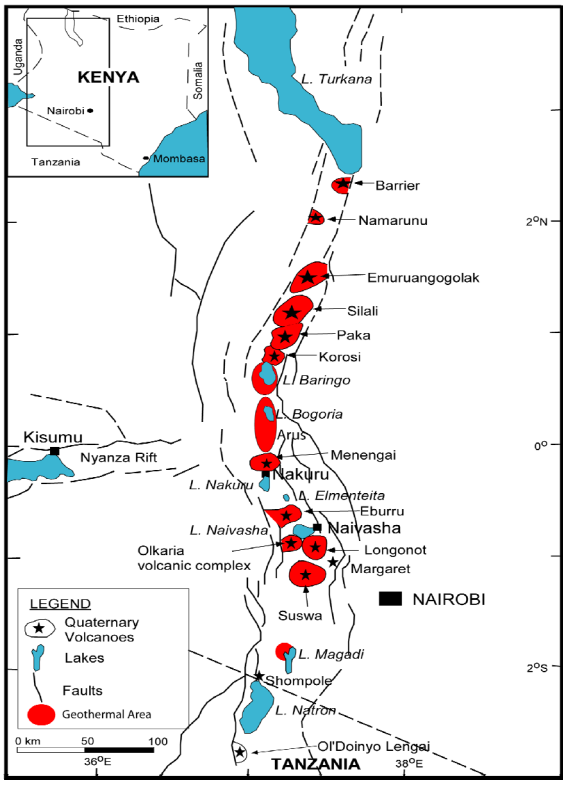

FIGURE 1: Location of Olkaria field

Further exploration continued in Olkaria and additional resource capacity was confirmed and the field size approximated to be about 80 km^2. It was therefore found prudent to segment Olkaria geothermal field into seven sectors for ease of development. The sectors are namely, Olkaria East, Olkaria North East, Olkaria Central, Olkaria South West, Olkaria North West, Olkaria South East and Olkaria Domes (Figure 2).

Additional power plants have been installed in Olkaria recently. These include a binary plant at Olkaria South West (Olkaria III) in 2000, with a capacity of 12 MW_e, a condensing plant at Olkaria North East (Olkaria II) in 2003, with a capacity of 70 MW_e and another binary plant with a capacity of 2.5 MW_e and condensing plant with a capacity of 2 MW_e at Olkaria North West (Oserian) in 2004 and 2007 respectively. Three exploration wells were drilled in Olkaria Domes between 1998 and 1999 and appraisal drilling is in progress to appraise this sector for installation of a 70 to 140 MW power plant.

Since commencement of exploitation of Olkaria geothermal field, performance has been encouraging and that has lead to additional installations being considered for the sectors. Although output from the production wells has been on the decline, it has been gradual and in line with the predictions of the numerical simulation studies carried out for the Olkaria reservoir (Bodvarsson and Pruess, 1981).

For instance, Olkaria I plant of capacity 45 MWe was commissioned in 1981. It has operated quite well and registered outstanding performance with the plant availability exceeding 90%. Around 2004, it was realized that the life of this plant was coming to an end and yet the Olkaria East reservoir still had great potential to supply steam. The total amount of steam available from the twenty-eight (28) wells that supplied the plant could support generation of 70 MWe, implying availability of excess steam equivalent to 25 MWe.

Similarly, Olkaria II plant of capacity 70 MWe was commissioned in 2003. It is supplied with steam from twenty (20) production wells. The total steam available from the North East production wells in 2004 could support generation of 98 MWe, implying availability of excess steam equivalent to 28 MWe. The total excess steam, which was available in the two fields, was equivalent to 53 MWe. Based on this fact, KenGen desired to install a third 35 MW unit at Olkaria II plant similar to the two units commissioned here the previous year.

However, it is known that Olkaria East, North East and Domes are interconnected. It was therefore necessary that any development in any part be considered in the light of the entire investment. Therefore in 2004, KenGen contracted West Japan Engineering Consultants, Inc. to carry out Olkaria

Optimization Study to find an optimal scheme for exploitation of Olkaria East, North East and Domes fields. The study is yet to be concluded but the results will provide a clear investment plan for KenGen now and in the future.

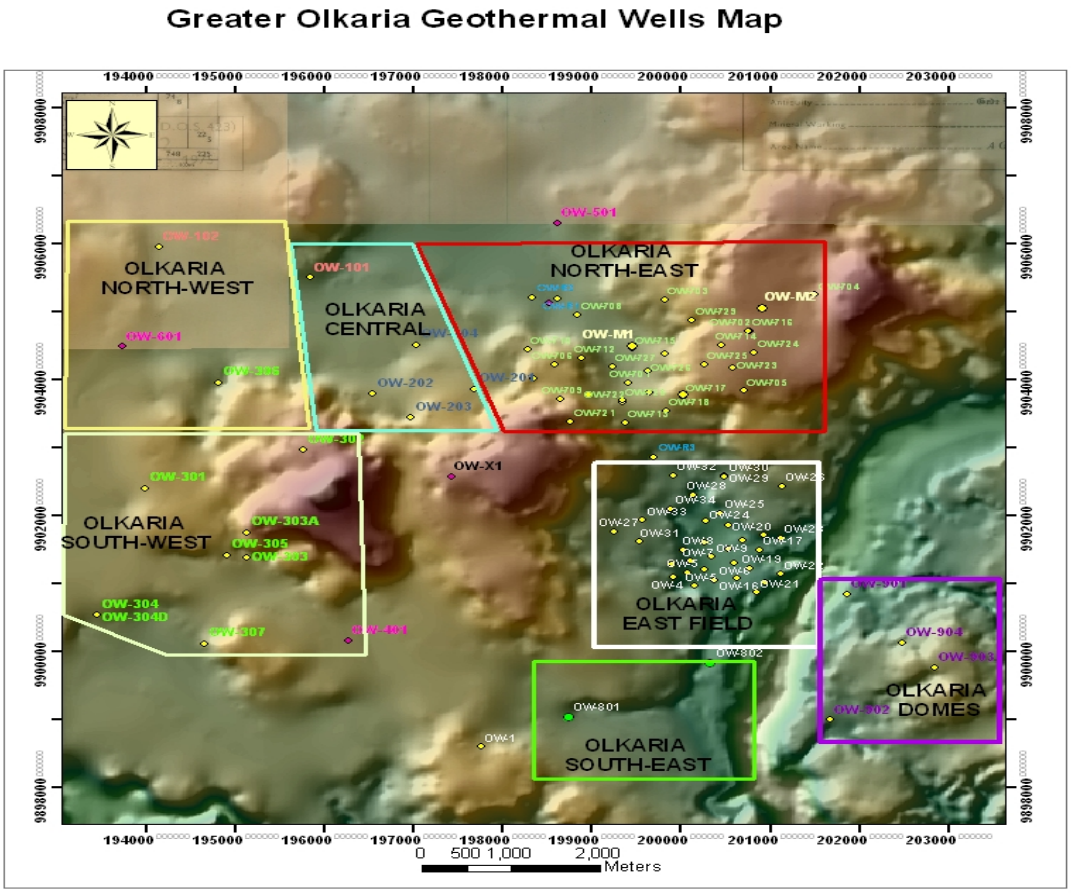

FIGURE 2: Geothermal Fields within the Greater Olkaria Geothermal Area

As part of reservoir management and assessment, Olkaria reservoir has been monitored for thermodynamic and chemical changes. Routine downhole temperature and pressure surveys have been carried out in production wells during well outages or plant shut downs. Regular output metering and geochemical sampling of the production wells have been conducted. The data collected during the above exercise is used to prepare the field bi-annual status reports on steam production. The decline in output of the wells has been compensated for jointly by drilling and connecting of make-up wells and in-field re-injection of effluent from the production wells.

The geothermal resource in Olkaria has mainly been utilized for electrical power production. Direct use has had little attention though it is well known that even after utilizing the steam part of the resource for electrical power production; a lot of energy is left in the water. Except for the binary plants in Olkaria South West and North West that utilize both steam and water, the condensing plants in Olkaria East, North East and North West only utilize the steam from the wells for electrical power production and separated water is rejected. However, there are wells with relatively lower enthalpy and produce more water than steam and hence if the energy in the water is rejected the result is very poor utilization of the resource. This paper discusses exploration and development of Olkaria geothermal field and management of the geothermal resource during exploitation.

2. EXPLORATION

Drilling of geothermal wells at Olkaria started in 1956 when shallow wells namely, X1 and X2 (Figure 3) were drilled without much success due to poor drilling experience. No information is available why the two wells were drilled at the location. Later Betty carried out some resistivity measurements in 1966 and found encouraging results of finding a geothermal resource.

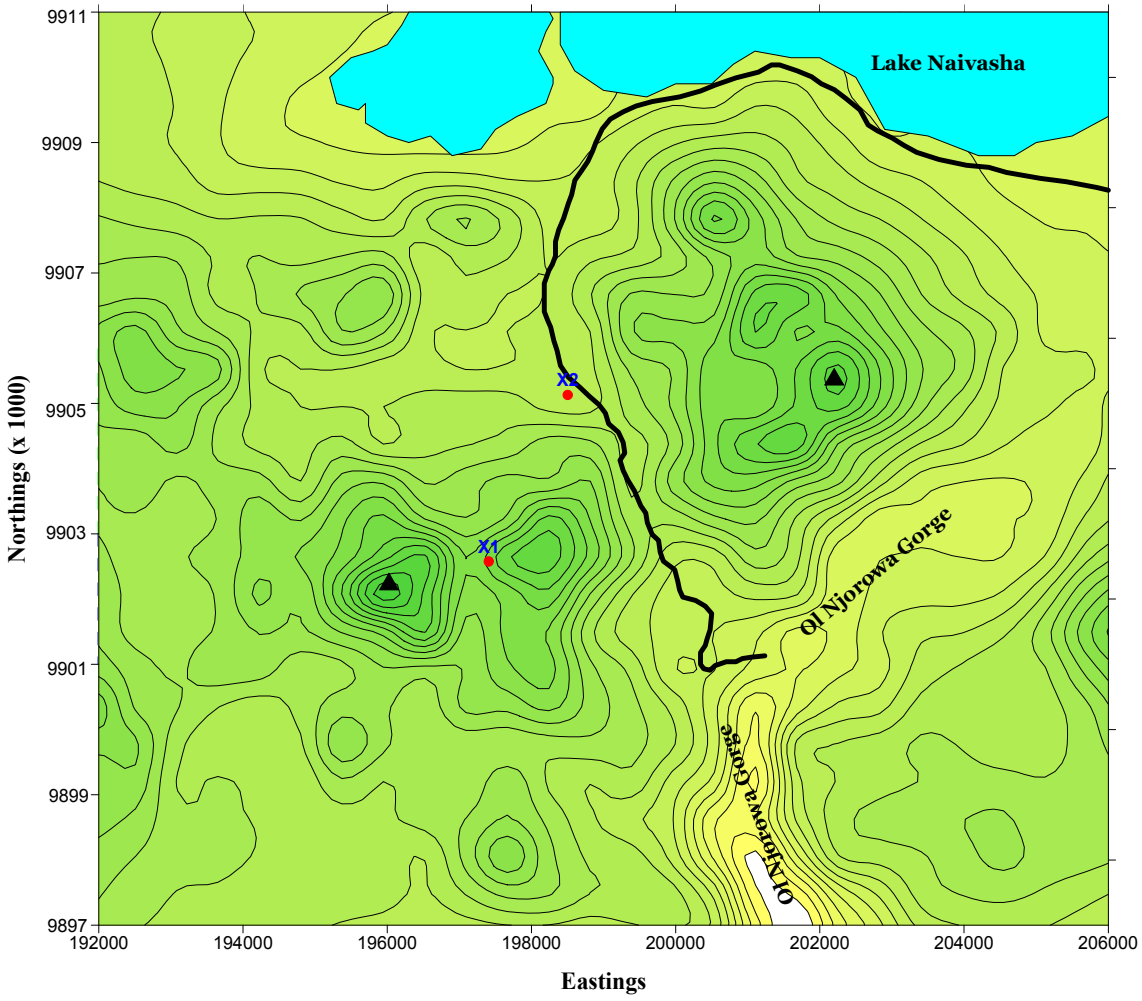

FIGURE 3: Location of OW-X1 and OW-X2

During the world oil crisis of 1970, UNDP and the Kenya Government carried out a reconnaissance survey along the Kenya rift that included Lake Magadi, Olkaria, Eburru and Lake Bogoria. Based on this reconnaissance survey more detailed work was done in Olkaria that included detailed geology, geophysics, geochemistry, heat flow measurements and hydrogeology. Although discharge of X2 was successful, it was not continuous.

Based on the scientific findings, the first well OW-1 (Figure 4) was drilled in 1973 to the south of the present Olkaria East in an area which had strong fumaroles. At 1000m, only 102 $^{\circ}$C was realized. This area is now well established to be the outflow of the Olkaria geothermal system.

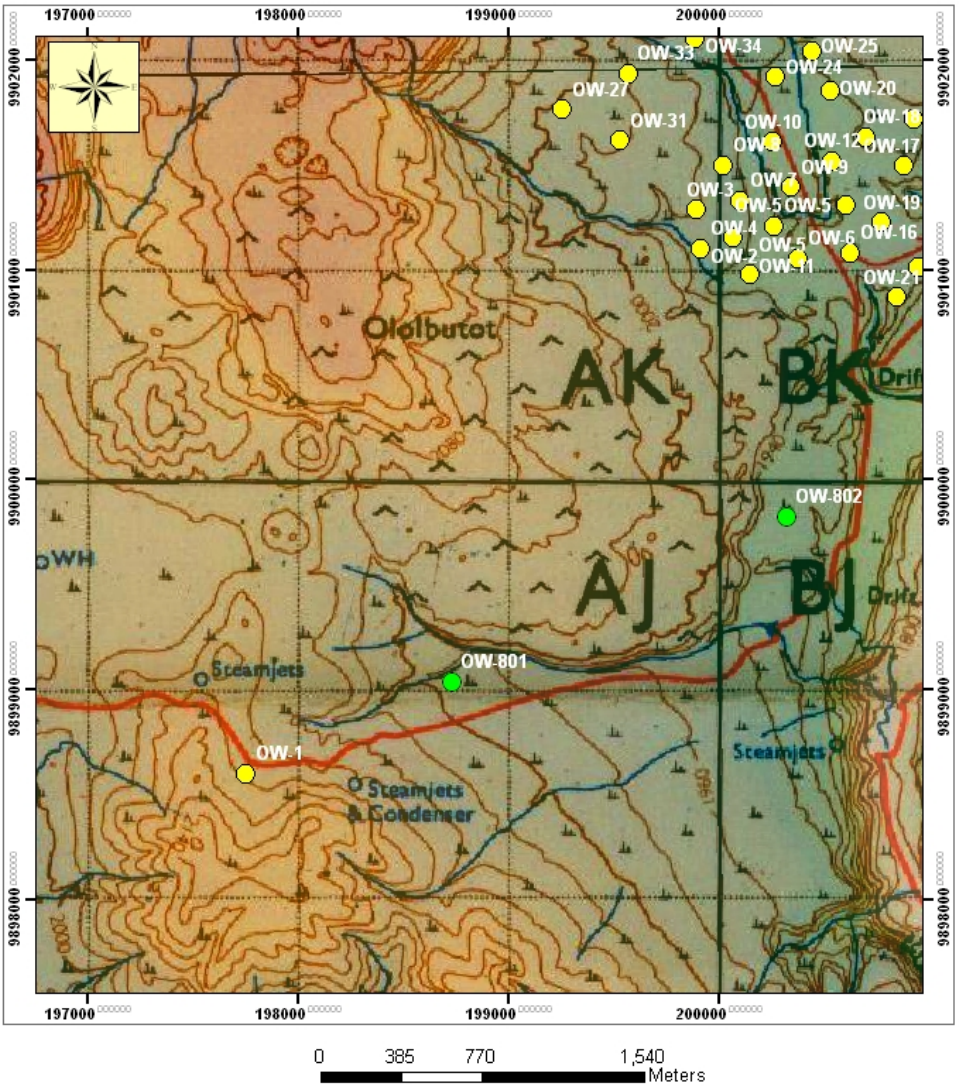

FIGURE 4: Location of OW-1 from Olkaria East sector

3. DEVELOPMENT

The scientific results were revaluated again and a decision was made to drill into the current Olkaria East area defined by a low resistivity. In 1974, OW-2 was drilled and because it proved steam, 5 other wells were drilled as step out wells by 1976. These wells proved the existence of an exploitable steam resource.

3.1 Olkaria East

Feasibility studies conducted by Virkir and Sweco (1976) recommended the development of a 2 x 15MW station. The construction of the power plant commenced in 1979 with World Bank funding and the first unit was commissioned in 1981. Production drilling was done while the power station was being constructed. By the time the second unit was commissioned in 1982, 25 wells had been drilled with more steam than the station could utilize. More knowledge of the reservoir was becoming available which indicated that the reservoir was progressively better northwards. A case was made to the World Bank and other financiers for the extension of the station by another third unit. The third unit was commissioned in 1985. The development of first power plant at Olkaria East therefore took about 15years. Performance of the reservoir in the last twenty-six years coupled with review of the

earlier scientific data has suggested that this sector can support much more electrical power generation than 45 MW. Depending on the results of Olkaria Optimization Study it may be possible to add another 70 MW installation here.

3.2 Olkaria North East

In 1980, an experts' technical review meeting was held in Nairobi to deliberate on the next development stages of the greater Olkaria field (GENZL, 1980). In this meeting, the scientific and drilling results were reviewed. Several wells spread far apart were sited to test several scientific theories. Some of these theories were that faults and fractures were the major conduits of geothermal fluids, the main ones being Ololbutot fault, Olkaria fracture and Olkaria fault.

In 1984 another scientific review meeting was held to evaluate the drilling results (KRTA, 1985). It was concluded that the western part of Olkaria had a separate geothermal system upflow with high CO_2 content and that an area north of Olkaria East existed a field with similar fluid chemistry to Olkaria East. OW-701 was then sited to prove this with much success. By 1988 five additional appraisal wells had been drilled and the field was then committed for a 2 x 30 MW development.

In 1989 a consortium of four companies carried out a feasibility study for the power plant and a full EIA was undertaken between 1990 and 1994 (Sinclair knight and RPS, 1994). By 1993, the required 33 wells for production, re-injection and monitoring had been drilled. A numerical simulation study of the field performance under exploitation was completed in 1993. Although the power station designs were done between 1991 and 1994, they could not be approved until environmental issues were fully incorporated. These included use of water from Lake Naivasha.

In 1996, donors introduced energy sector reforms in Kenya some of which became conditional for further funding for the construction phase. The designs were reviewed in 1997, financing was approved in 1998 and a new supervising consultant, different from the designing one, was appointed. The tender documents prepared earlier by the previous consultant were revised and some design aspects changed to take into account changes in technology.

Construction of Olkaria II then commenced in September 2000 and commissioned at the end of 2003 after 3 years. Olkaria II power plant therefore took about 17 years to be realized. Following from the results of Phase I of the Olkaria Optimization Study a contract has been signed between KenGen and joint venture of Mitsubishi Corporation and Mitsubishi Heavy Industries for expansion of Olkaria II through installation of a third, 35 MW unit at the station.

3.3 Olkaria West

During the time exploration wells were spread far apart in the field to test several scientific theories in Olkaria, some wells were drilled in Olkaria West. Successful drilling results were also obtained in this part of the field. In the 1984 scientific review meeting held to evaluate the drilling results (KRTA, 1985), it was concluded that the western part of Olkaria had a separate geothermal system upflow with high CO_2 content. The southern portion (Olkaria South West) was acquired by an IPP (Ormat International) who installed 13 MW binary power plant in 2000. Ormat drilled more wells in this area since 2000 and following successful results the plant is being expanded to 48 MW generation capacity.

Some of the successful exploration wells drilled in the northern portion of Olkaria West are within Oserian Development Company land. Oserian has leased two of these wells, one for direct use in heating of green houses (OW-101) and another for electrical power generation (OW-306).

3.4 Olkaria Central

The first exploration well drilled in this sector had inverted temperatures and discharged medium enthalpy fluid. Another three wells (OW-202, OW-203 and OW-204) were drilled in this sector between 1994 and 1997 and only one of them (OW-202) was able to discharge. Steam from this well is to be utilized by Oserian Development Company to operate 2 MW condensing plant which is being commissioned. Three of the wells (OW-201, OW-203 and OW-204) are re-injection wells. OW-201 and OW-204 receive cooling tower blow-down from Olkaria II power station and OW-203 will receive brine from the separator at OW-202. This part of the field is considered an outflow zone and hence utilized for cold re-injection.

3.5 Olkaria South East

As a follow-up to the poor results obtained from drilling of OW-1 more geophysical work was carried out in this sector of Olkaria and OW-801 was drilled to confirm existence of the resource to the south of Olkaria East especially to the west of Ololbutot fault. Unfortunately, this well was unsuccessful and cannot discharge. The data was reviewed and OW-802 sited in this sector but has not been drilled.

3.6 Olkaria Domes

Detailed geo-scientific investigations were carried out in this sector between 1992 and 1997 involving geology, geophysics, geochemistry and heat flow measurements. Based on the scientific review of the data gathered from the surface investigations three explorations wells OW-901, OW-902 and OW-903 were sited and drilled between 1998 and 1999. All the three wells were successful and were able to discharge. By this time more advanced geophysical techniques, with better subsurface penetration capabilities than Schlumberger soundings used earlier, namely, Magneto telluric (MT) and Transient Electromagnetic (TEM), were available. The two techniques were applied to review the results of the previous geophysical surveys resulting in the high success achieved from drilling of the three exploration wells. Additional geophysical work was carried out using MT and TEM to have even better data spread hence gather more confidence in demarcation of the boundaries of the resource area.

This plus down-hole data from the three exploration wells were reviewed and the results are the basis for siting of the six appraisal wells currently being drilled in this sector. Two of the appraisal wells (OW-904A and OW-903A) have been drilled to completion and both have encountered very high temperatures (over 300 ^{o} C). OW-904A has been able to discharge and is capable of producing steam equivalent to over 6 MW of electrical power. The geophysical anomaly (Figure 5) is indicating a large resource area in this sector and if confirmed by drilling may support installation of up to 140 MW plant. However, the optimum installation in this sector will also depend on the results of the Olkaria Optimization Study.

Figure 6 represents the status of development in all the seven sectors of the Greater Olkaria geothermal field.

4. OLKARIA RESERVOIR MODEL

Development of the conceptual reservoir model of Olkaria geothermal field was initiated by Sweko and Virkir (United Nations – Government of Kenya, 1976). Since that time the model has been reviewed several times as additional information became available (KPC, 1980, 1982, 1985, 1986, 1997; KenGen, 1999; Bodvarsson, 1980; Bodvarsson and Pruess, 1981, 1984, 1988; Ewbank Preece – Virkir, 1989 and Virkir-Orkint and Bodvarsson, 1993). Over the years, the main concepts have remained more or less the same except that with more information, it has been possible to strengthen the model and add confidence to the understanding of the production characteristics of the reservoir.

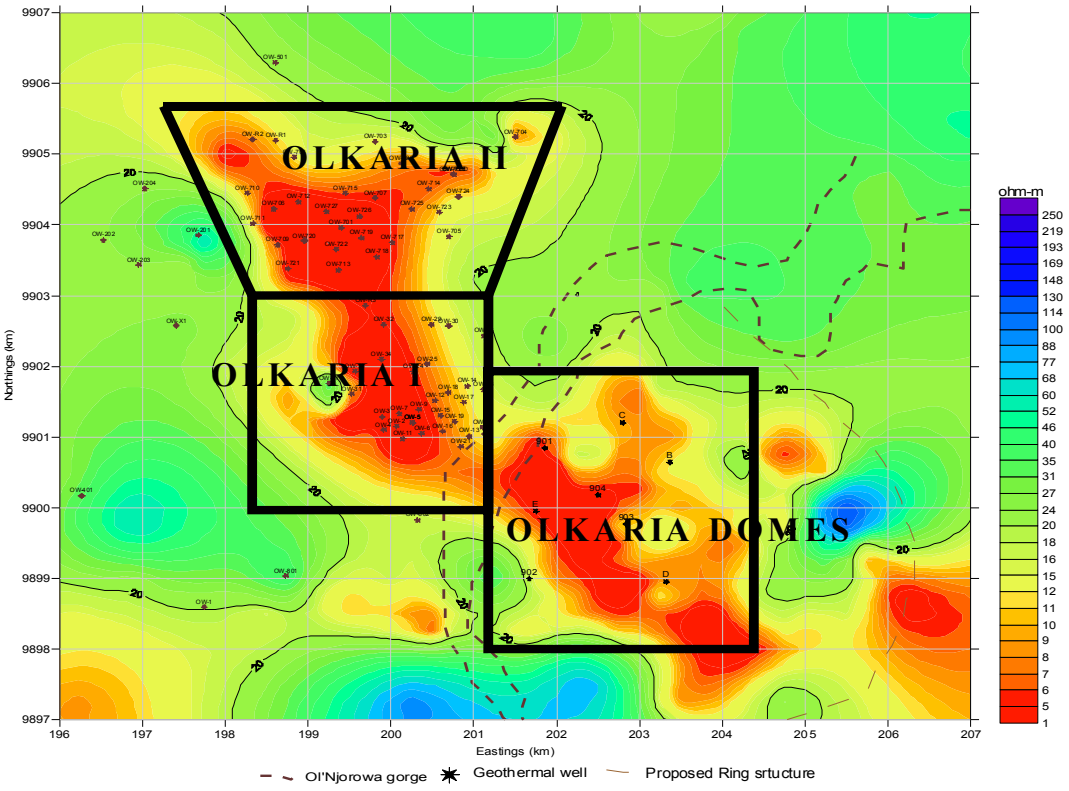

FIGURE 5: Potential resource areas for Olkaria East, North East and Domes

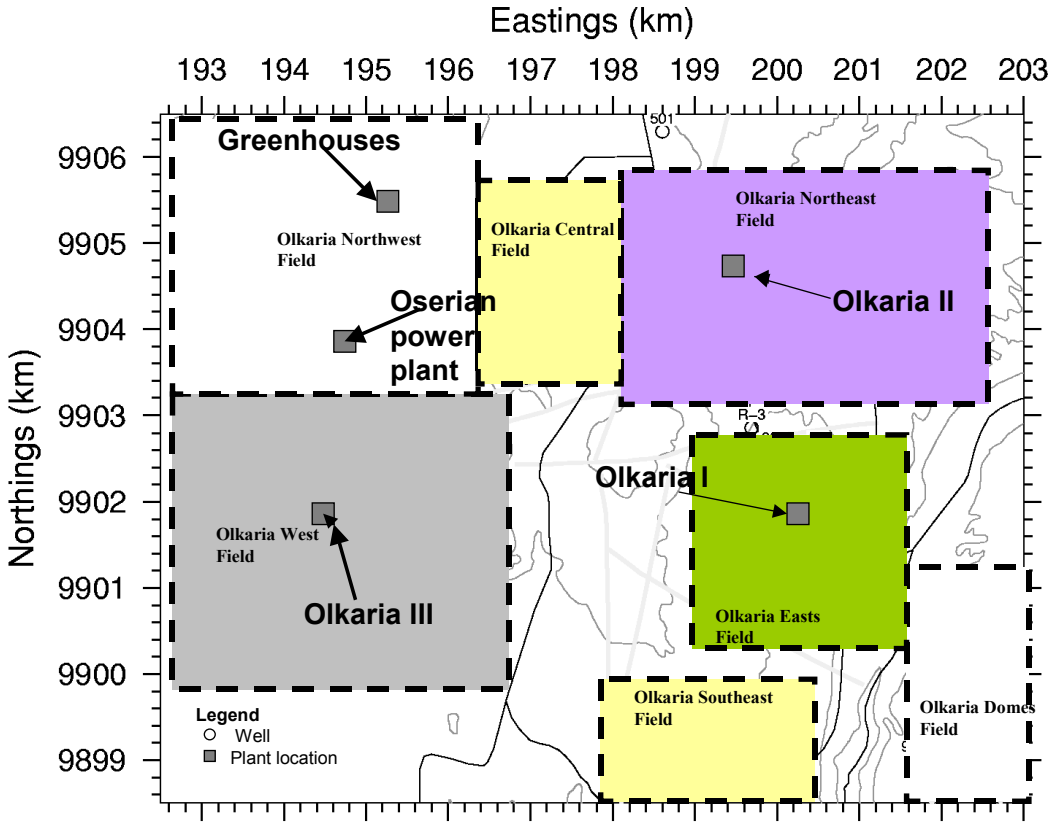

FIGURE 6: Present utilization of Olkaria Field area

The major hydrogeological features of the field, including two upflow zones of hot fluids in the general area of OW-301 and OW-716, large scale fluid movement in the field is dominated by major faults and fracture zones and large steam losses at the reservoir top, especially along the Ololbutot fault between wells OW-201 and OW-01, are established.

The Olkaria geothermal reservoir is associated with the Olkaria volcanic centre. It is considered that the reservoir is bounded by arcuate faults forming a ring or a caldera structure. The magmatic heat source is represented by intrusions at deep levels inside the ring structure. It is a two-phase liquid dominated one overlain by a thin steam dominated zone 100 to 200m thick at 240°C. This zone is widest in the south and thinnest in the north. Below the steam zone a two-phase system of boiling water exist. Above the steam zone, is a caprock that marks the top of the reservoir and is composed of impermeable basalt and trachytes, which lie 400 to 700m below the surface. The bulk of the reservoir rocks are mainly trachytic. The vertical extent of the reservoir is unestablished but it is believed to be of the order of several hundred meters (Bodvarsson, 1984). Temperatures intercepted by the wells are generally high, (250°C) with bottom hole temperature about 300°C (Figure 7).

The initial static water level varies but is between 400 and 700m. The initial pressure and temperature distribution in the field increases northwards while hydrological gradient indicated water movement was from North to South. This has been confirmed through drilling in the northern parts of the field where bottom-hole temperature in most wells exceed 310°C. The steam zone, that is present in the Olkaria East field, is replaced by a shallow two-phase zone in the Olkaria North East field (Ambusso and Ouma, 1991).

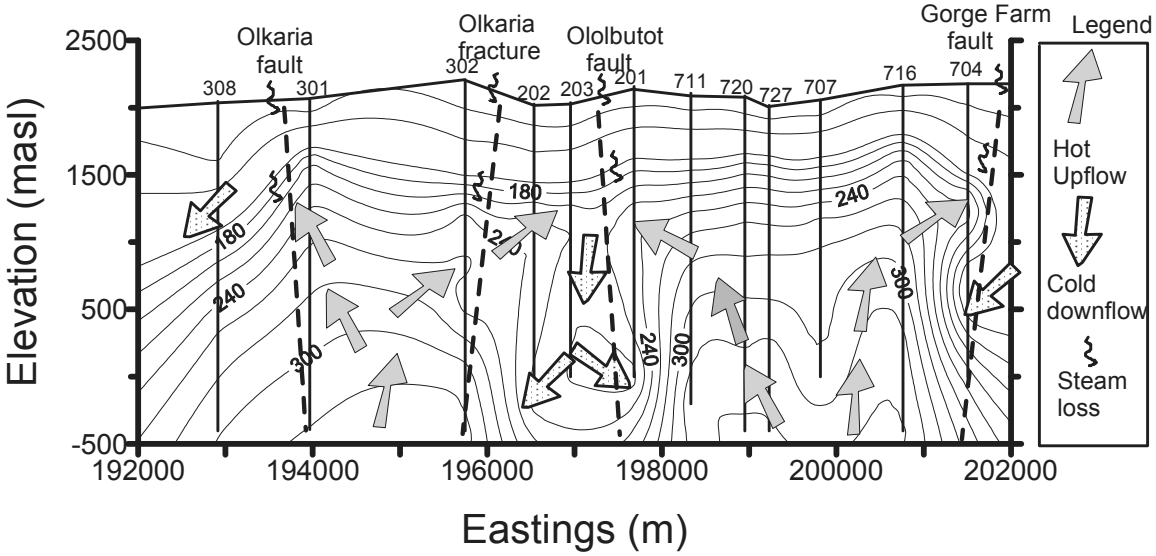

FIGURE 7: Conceptual model of Olkaria geothermal reservoir

5. RESERVOIR MANAGEMENT

The Olkaria reservoir has been under exploitation for the last twenty-six (26) years. Numerical studies of the generating capacity of Olkaria reservoir (Bodvarsson and Pruess, 1981) projected decline in deliverability of production wells with time and recommended monitoring of the production wells to determine the decline rate. The decline rate in the deliverability of the Olkaria wells would have major economical effects on the development plan for the field. However, the history match and performance predictions for Olkaria geothermal field (Bodvarsson and Pruess, 1984) indicated that injection of water into the geothermal reservoir would significantly increase the economic life time of production wells and thus save on the drilling of make-up wells. Therefore, as part of reservoir

management requirement and general performance assessment, the reservoir has regularly been monitored for thermodynamic and chemical changes.

5.1 Temperature and pressure

Routine down-hole temperature and pressure logs have been carried out in production wells during well outages or plant shutdowns. Availability of wells for down-hole logs has been very limited due to the high steam demand hence limited information is available on the changes in reservoir temperature and pressure across the field. However, from the available data, the most significant change in this field over the last twenty-six (26) years of production is pressure decline (Figure 8). The figure shows that minimal pressure drawdown of about 22 bars has occurred in the liquid reservoir. This pressure drop recovers pretty fast when production rate is decreased as seen after the year 2003 when unit I in Olkaria East was out of service for a long time for major overhaul followed by unit III.

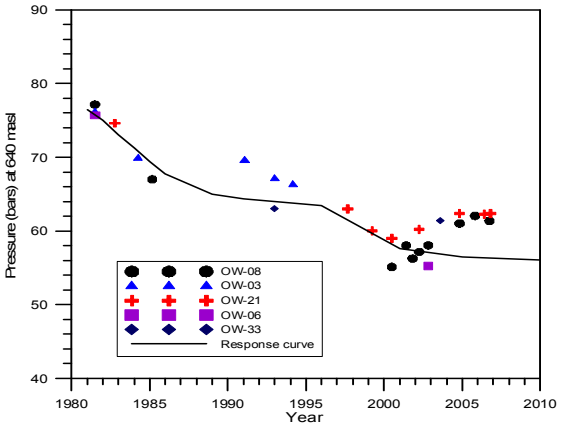

FIGURE 8: Pressure decline trends

The response curve fit suggests that the reservoir has a good recharge so that after a certain time constant (of about 7 years), it reaches a steady state. This is actually evident by the fact that we now have almost zero decline rate in output from the field. Increasing production under these circumstances will not therefore adversely affect performance of the production wells.

Downhole temperature and pressure logs show that wells located at the central and western parts of Olkaria East field are almost dry (Figures 9) while those in the south show temperature inversion at the bottom, indicating incursion of cooling fluid (Figure 10).

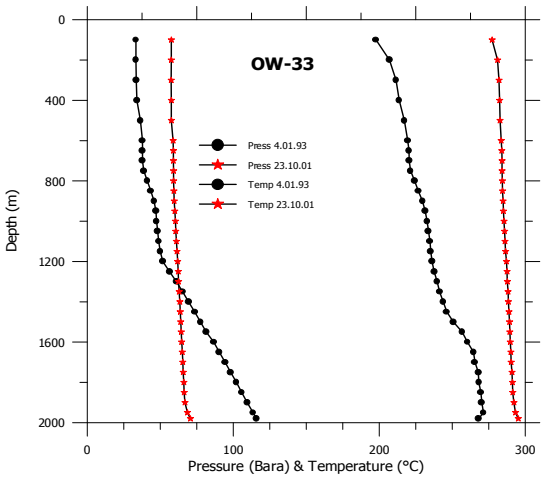

FIGURE 9: Downhole profiles in OW-33

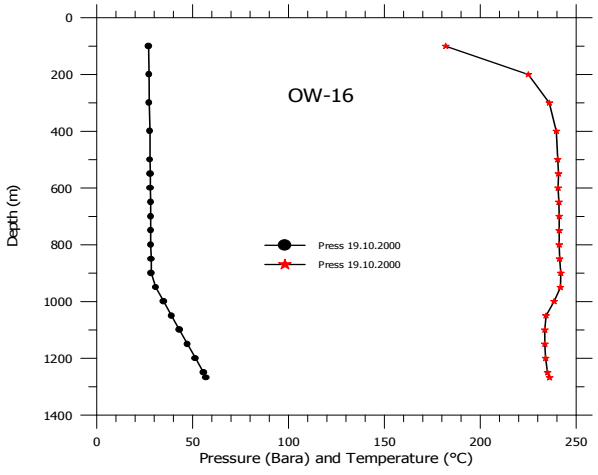

FIGURE 10: Downhole profiles in OW-16

5.2 Wells deliverability

From the time the third unit was commissioned in 1985 at Olkaria East, the field has experienced pressure drawdown and hence decline in output from the wells resulting into decline in steam supply to Olkaria I plant. The decline in pressure has also introduced severe cyclicity in some of the wells in Olkaria East (Ouma, 1992). The field has shown various regimes of annual steam decline from an

initial 5-6% decline to the current near zero. From 1981 to 1988 the average steam decline was about 5.5 % per annum (Ambusso and Karingithi, 1993). This led to the connection of OW-26 in 1986 raising the steam output by about 35 t/hr. The decline rate between 1988 and 1992 was about 4% per annum that reduced to less than 4% between 1993 and 1998 with some wells experiencing almost no decline while others experienced an increase (Ouma and Karingithi, 1998). Six make-up wells were connected between 1993 and 1998 raising the output by about 230 t/hr. In 1998, the steam decline was 4.6% (Ofwona and Wambugu, 1999) whereas between 1999 and 2000 Olkaria East field experienced steam increase of about 1% instead of a decline (Kariuki and Opondo, 2001). The trend of steam increase continued with a value of about 3.7% increase being observed in 2001. After connection of make-up wells OW-32 and OW-34, the total steam available became 730 t/hr equivalent to about 73 MW_e (Kariuki and Opondo, 2002). Except for the problem with well OW-34 (Ofwona and Opondo, 2003) the total steam available in Olkaria East field has remained at about 707 t/hr between 2002 and 2004 (Karingithi and Mburu, 2005). Generally it has been observed that steam deliverability from Olkaria East field has a significantly reduced decline rate compared to what was predicted by the numerical simulation models (Figure 11).

From 1992 to 2004, discharge enthalpy for the centrally located wells in Olkaria East field has increased with as high as 600 kJ/kg. This is mainly due to large reservoir pressure drawdown leading to drying up of wells as a result of boiling. Peripheral wells unlike the centre ones have had a decrease in discharge enthalpy (Maximum 400kJ/kg). This is caused by cold water incursion at the bottom of the wells as demonstrated by down-hole temperature logs.

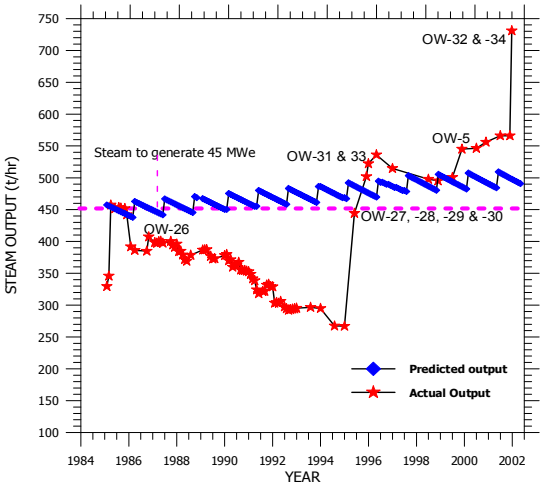

FIGURE 11: Steam decline trend at Olkaria East field

5.3 Fluid chemistry

Chemical changes in this field have been diverse and vary both in type and degree across the field. The cyclic nature of most wells and multiple production zones make the data interpretation complicated. However, for a number of wells, the extent of variation has been minimal and such wells have been used to infer the changes in the reservoir. These changes have been evaluated in terms of concentration of reservoir chloride, silica, sulphate, discharge enthalpy, calculated geothermometer temperatures and variation in gas composition of the discharge fluids. Gases considered include nitrogen, hydrogen, hydrogen sulphide and carbon dioxide in the steam. Wells located at the centre of the field have shown a gradual increase in concentration of dissolved constituent like chloride. Some peripheral wells have shown stable or decline in chloride concentration (Figures 12).

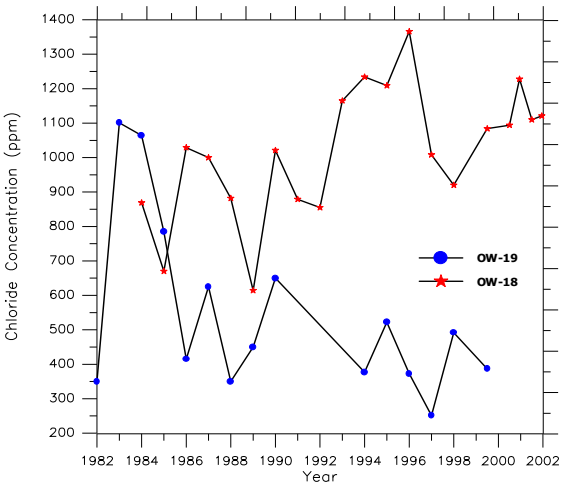

FIGURE 12: Chloride concentration for OW-18 and OW-19

5.4 Re-injection

Numerical simulation studies suggested that re-injection into this field would reduce well deliverability decline rate and hence reduce the number of make-up wells requirement (Bodvarsson and Pruess, 1984; Bodvarsson, 1993). This was considered economically favourable and hence cold and hot re-injection has been implemented in Olkaria geothermal field. Cold re-injection was carried out in OW-12 from July 1996 to August 1997 with a total of 136,886 tonnes of water being re-injected. Accompanying tracer test showed that OW-12 has hydrological communication with wells OW-15, OW-18 and OW-19. Monitoring of these wells indicated improved mass output but enthalpy drop due to cold re-injection and therefore was discontinued before the affected wells started recovering (Figure 13). Hot re-injection of separated brine from OW-27, OW-31 and OW-33 into OW-3 has been going on since May 1995. A total of 1,750,000 tonnes of brine has been re-injected into this well resulting in improved output in wells OW-2, OW-6, OW-8 and OW-11 without causing excessive decline in enthalpy (Figure 14). Currently, about 5% of the total brine generated from Olkaria East field is being re-injected hot into OW-3 and plans are underway to increase this amount. Recently cold re-injection of condensate from Olkaria I plant into OW-6 was commissioned in which about 13% of the condensate generated is re-injected.

In Olkaria North East field we have 100% re-injection of effluent generated by the production wells. Hot brine is re-injected into wells OW-R2, OW-R3, OW-703 and OW-708 whereas cold condensate is re-injected into well OW-201 or OW-204. Tracer was introduced into the re-injected fluid at OW-708 with returns reported in OW-706 and OW-712 and at OW-R3 with returns reported in OW-25 and OW-32.

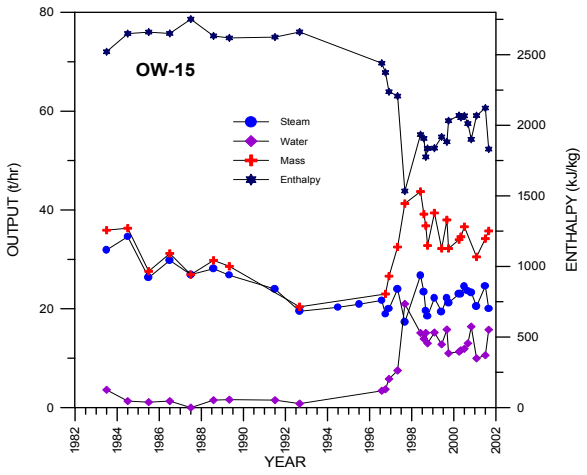

FIGURE 13: Effects of cold re-injection in well OW-15

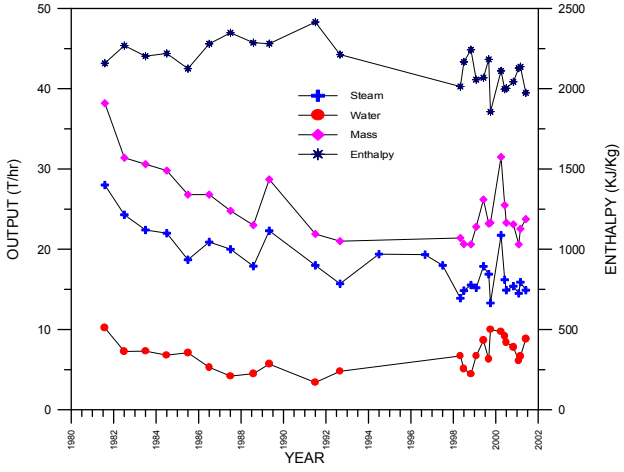

FIGURE 14: Effects of hot re-injection into well OW-2

6. POWER PRODUCTION

Olkaria reservoir produces two-phase mixture of steam and water in general proportion of 85% steam and 15% water. However, there are a few wells that produce near dry steam or mostly hot water with very little steam. Thus the resource is suitable for electrical power generation. Two types of power generation plants operate in Olkaria namely, the Ormat binary plants and the Mitsubishi condensing plants. In all there are four power plants, two owned by KenGen and one each owned by Ormat International and Oserian Development Company Ltd (ODCL). The total installed power generation capacity of the four plants is 129 MW_e. Thus geothermal power installation constitutes about 12% of the national power installation and the plants operate as base load.

6.1 Olkaria I plant

It is the oldest plant in Olkaria and has been in operation since 1981 (24 years) with an installed power generation capacity of 45 MW_e. It consists of three (3) Mitsubishi condensing units each of capacity 15 MW_e. The plant has achieved an overall load factor of 81.9% and availability factor of 92.5% and continuous operation of up to ten months in one year has been realized. The steam conversion rate has been maintained at 9.2 t/hr per MW_e (Figure 15).

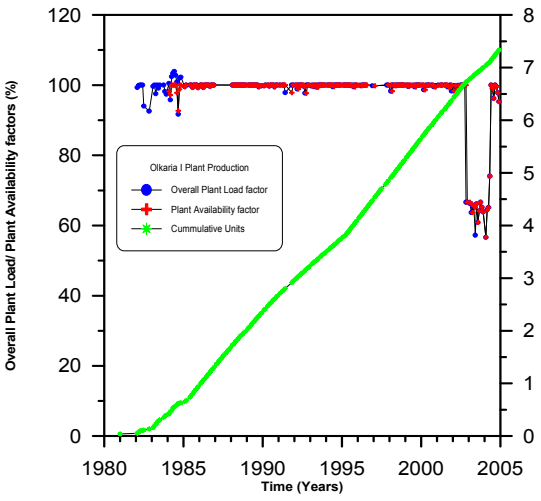

FIGURE 15: Olkaria I Plant Production

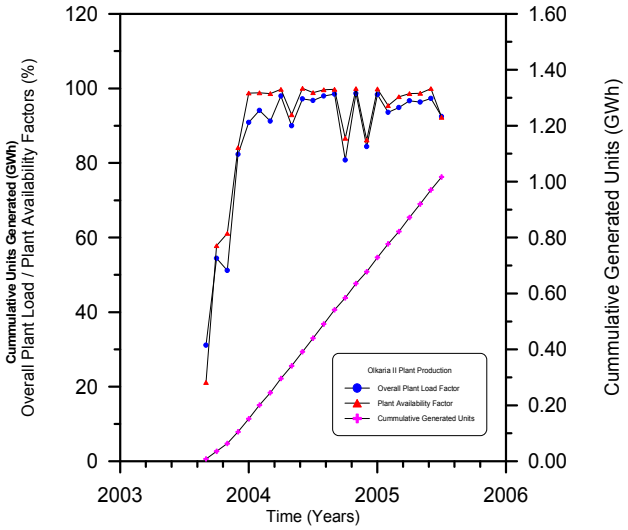

FIGURE 16: Olkaria II Plant Production

6.2 Olkaria II plant

It is the second geothermal plant installed by KenGen in Olkaria and has been in operation since October 2003 (2 years) with an installed power generation capacity of 70 MW_e. It is similar to Olkaria I plant but consists of two (2) Mitsubishi condensing turbo-generating units each of capacity 35 MW_e. The plant has achieved an overall load factor of 80% and availability factor of 83% in the last two years it has been in operation. This plant has steam conversion rate of 7.3 t/hr per MW_e, which is better than that of Olkaria I plant (Figure 16).

6.3 Ormat type binary plants

These were installed one each by Ormat International (Orpower 4) and Oserian Development Company Ltd. (ODCL) at Olkaria South and North West sectors. They utilize both steam and water phases of the discharge from the wells for electrical power generation.

The Orpower 4 plant with an installed capacity of 12 MW_e has been in operation since 2000 (5 years). It was installed as a pilot to test the performance of that sector of Olkaria reservoir, utilizing some of the exploration wells that had been drilled in the eighties plus the first drilled appraisal and production wells, ahead of the bigger plant planned for Olkaria South West.

The Oserian plant with an installed capacity of 2.0 MW_e has been in operation since 2004 (1 year). It utilizes discharge from one well (OW-306) that was drilled as an exploration well in Olkaria North West sector but which falls within the land owned by ODCL. The electrical power generated from this plant is all consumed by ODCL and supplements the electrical power supply from The Kenya Power and Lighting Company Ltd.

6.4 Energy utilization

Geothermal energy in Olkaria has mainly been utilized for electrical power production. Direct use has received little attention though it is well known that even after utilizing the energy for electrical power production, a lot of energy is still left in the water. Whereas the Ormat binary plants installed at Olkaria South and North West utilize both steam and water parts of the discharge from wells for electrical energy production, the Mitsubishi condensing plants installed by KenGen in Olkaria East and North East only utilize the steam part. Furthermore, there are wells with relatively lower enthalpy and hence produce more water than steam and if energy in the water for such wells is rejected can imply very poor energy utilization. For instance Olkaria I plant in Olkaria East field generates 45 MW of electrical power from steam but rejects 46 MW of thermal power in the water. Similarly, Olkaria II plant in Olkaria North East field generates 70 MW of electrical power from steam but rejects 142 MW of thermal power in the water.

Recently Oserian Development Company Ltd (ODCL) leased OW-101 from KenGen for direct use in horticultural farming. OW-101 is one of the exploration wells drilled in Olkaria North West in the early eighties and is capable of supporting generation of only 1 MW of electrical power. However, it has proved capable of supplying up to 10 MW of thermal power to ODCL for direct use in flower farming. With geothermal energy from OW-101 ODCL is able to heat approximately 30 Ha of green houses.

There are wells in Olkaria with extreme cyclic discharge characteristics and hence cannot operate with the other wells supplying steam to the power plants. Such wells, in the past, have either been turned to re-injection wells or simply rendered useless and yet are capable of supplying a lot of geothermal power for direct use. KenGen is looking at the possibility of economically selling geothermal energy from such wells to direct users either for recreational purposes or space heating. One such well is OW-724 drilled in Olkaria North East field. It is productive but because of its cyclic discharge characteristics, was found unsuitable to connect to the Olkaria II power plant. It was also found unsuitable for re-injection and hence so far no use has been found for it. However, this well is capable of providing 15 MW of thermal power for direct use and is being considered for supply of thermal power to interested direct users.

7. DISCUSSION

Initial scientific investigations for Olkaria geothermal field were unable to demarcate the resource accurately because limitations of the techniques used. Geophysical studies at the time did not give a good representation of the subsurface structure due to limited depth of penetration (less than 700m). The data spread was also sparse and therefore could not demarcate the boundaries of the resource area. In addition, the drilling technology was poor and that contributed to the initially low drilling success rate. With more advanced techniques applied in the later part of exploration especially geophysical techniques with more subsurface penetration capabilities, it became possible to demarcate the resource more accurately and hence the drilling success rate remarkably improved. For instance in Olkaria Domes MT and TEM were applied and the data coverage improved and that has contributed significantly in the excellent drilling success rate registered so far.

Development of Olkaria resource has been slow mainly due to funding and the best example is Olkaria North East case where funding delayed the Olkaria II plant construction by over a decade. After exploiting Olkaria East sector for twenty-six years it has been realized that this sector can support more that the 45 MW installed but decision to expand the power installation has been delayed because the financiers are insisting on the results of Olkaria Optimization Study before availing the funds. The study has already delayed the decision by three years while results from analysis of the data gathered over the twenty-six years of operating the field are strongly supporting additional installation.

The geothermal resource has mainly been used for electrical power production utilizing the steam portion of the discharge from wells. The water portion of the resource has mostly been sent to waste either through surface rejection or re-injected back into the reservoir. This has resulted into very poor utilization of the resource and KenGen is exploring the possibility of economically selling energy contained in the water part of the resource to neighbouring flower farms and hotels for direct use.

8. CONCLUSION

Improvement in technology and approach to scientific investigations has contributed to the high drilling success rate for exploration wells. Availability of funding can accelerate the development of Olkaria geothermal resource. Olkaria reservoir has performed well and should be developed further to realize its full potential. Energy utilization of the Olkaria resource will remain low unless some use is found for the energy contained in the water portion.

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Presented at *Short Course VIII on Exploration for Geothermal Resources*,
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TORFAJÖKULL, ICELAND – A RHYOLITE VOLCANO AND ITS GEOTHERMAL RESOURCE

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ABSTRACT

Torfajökull in South-Central Iceland occupies a unique position among Iceland´s volcanoes both as regards type of volcanism and structure, but the size and intensity of its geothermal activity is also exceptional. Its geothermal potential is estimated in the range of 1000 MW, two or three times higher than Hengill which comes next. The results of surface exploration carried out intermittently in the past 25 years are presented in summary. They were directed towards both the geothermal resource and the volcanology. The two fields of interest complement each other to give a fairly good conceptual model of the area.

1. GENERAL FEATURES

The Torfajökull volcano (1200 m a. sl.) forms a massive, 300–600 m higher than the surroundings. Its eastern half is heavily eroded contrary to the western half where Holocene lavas have been erupted. The eastern area offers the best exposures and allows the development of the volcano to be traced far back. Bright coloured rhyolite is almost the sole rock type there (up to 7 units in a single section) with remnants of hyaloclastite (basaltic) overlying it in places with NE-SW-feeder dykes cutting up through the rhyolite below. The western half is undulating high ground where hyaloclastite, obsidian flows and dark grey ash shed over it from neighbouring volcanoes lend the landscape a blackish hue. Local permanent snow and the fumes from countless steam vents make a contrast and green ribbons of moss along streams bring some live to the scene.

Torfajökull (Figures 1 and 2) developed as a flank zone volcano with rocks of transitional composition (intermediate between tholeiitic and alkalic). In a last stage it was overtaken by a spreading zone propagating to the SW. This change is marked by the eruption of mixed lavas of primarily transitional rhyolite and some tholeiite components.

The hot springs are a very dominant feature in the landscape (Figure 3). They concentrate in certain areas forming wide tracts of steaming ground with mud pots and roaring fumaroles. Judging from their areal distribution and intensity the core of the geothermal field is located around the eruption foci of the centrally erupted Holocene lavas. The high temperature geothermal manifestations occur within a 18 x 12 km caldera. Cold alteration extends beyond it as do tepid and hot springs to the NE and SW, some rich in carbondioxide, probably outflows. The oldest dated rocks are nearly 0.4 million years old. They are superimposed on hydrothermally altered pre-caldera rhyolite and a caldera-fill.

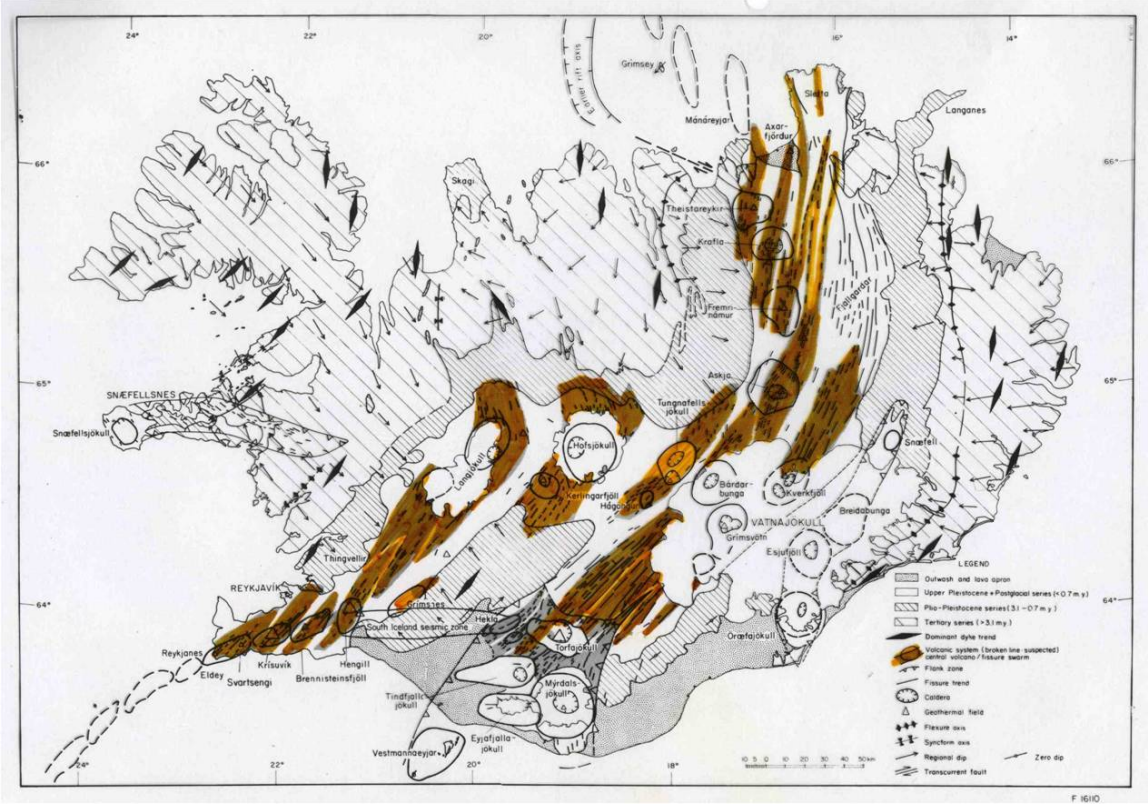

FIGURE 1: Volcanic systems of the active volcanic zones in Iceland. Torfajökull in South Central Iceland is at the intersection of a spreading zone to the north-east, the South Iceland Seismic Zone to the west and a non-rifting flank zone to the south

2. GEOLOGY

Five main groups form the Torfajökull sequence (Figure 2):

1. The oldest group forms a horseshoe shaped rim around the caldera which is open to the west. Its oldest member is less than 800 ka.
2. A caldera collapse followed. It became filled with sediment, tuff, rhyolite breccia and plugs. Resurgence (i.e. uplift of the caldera floor) and a second inner caldera subsidence occurred.
3. Domes erupted from concentric fissures within and around the caldera close to its rim are as old as 300 ka. The youngest member of the group, about 25 km³, was erupted subglacially at about 80 ka.
4. Hyaloclastite (basaltic) erupted below ice from a NE-SW dyke swarm, most intense in the NE but otherwise occurring around a volcanic shadow zone. The shadow zone is underlain by a magma chamber in the central part of the caldera. It is thought to have contracted after the 80 ka event (Figures 2 and 5).
5. Holocene rhyolite lavas, mixed with tholeiite to some degree, erupted on a NE-SW fissure swarm. The tholeiitic component of the lavas indicates that the eruptions were triggered by lateral injection via dykes from a rift zone volcano 80 km distant to the NE (Bárdarbunga in Vatnajökull Glacier) (Figure 10). Three Holocene basaltic eruption fissures transected the western part of the volcano without intersecting the magma chamber.

As to the youngest stratigraphic unit (number 5 above) there have been 8 eruptions in Holocene time (last 11,500 years). The oldest occurred about 9000 years ago, the three youngest about 2000, 1100 and 500 years ago (Figure 4). Six of them erupted rhyolite flows. Some of them had an initial plinian phase which produced widespread air fall ash layers (brown arrows). The eruptions were triggered by tholeiitic injections from the north-east.

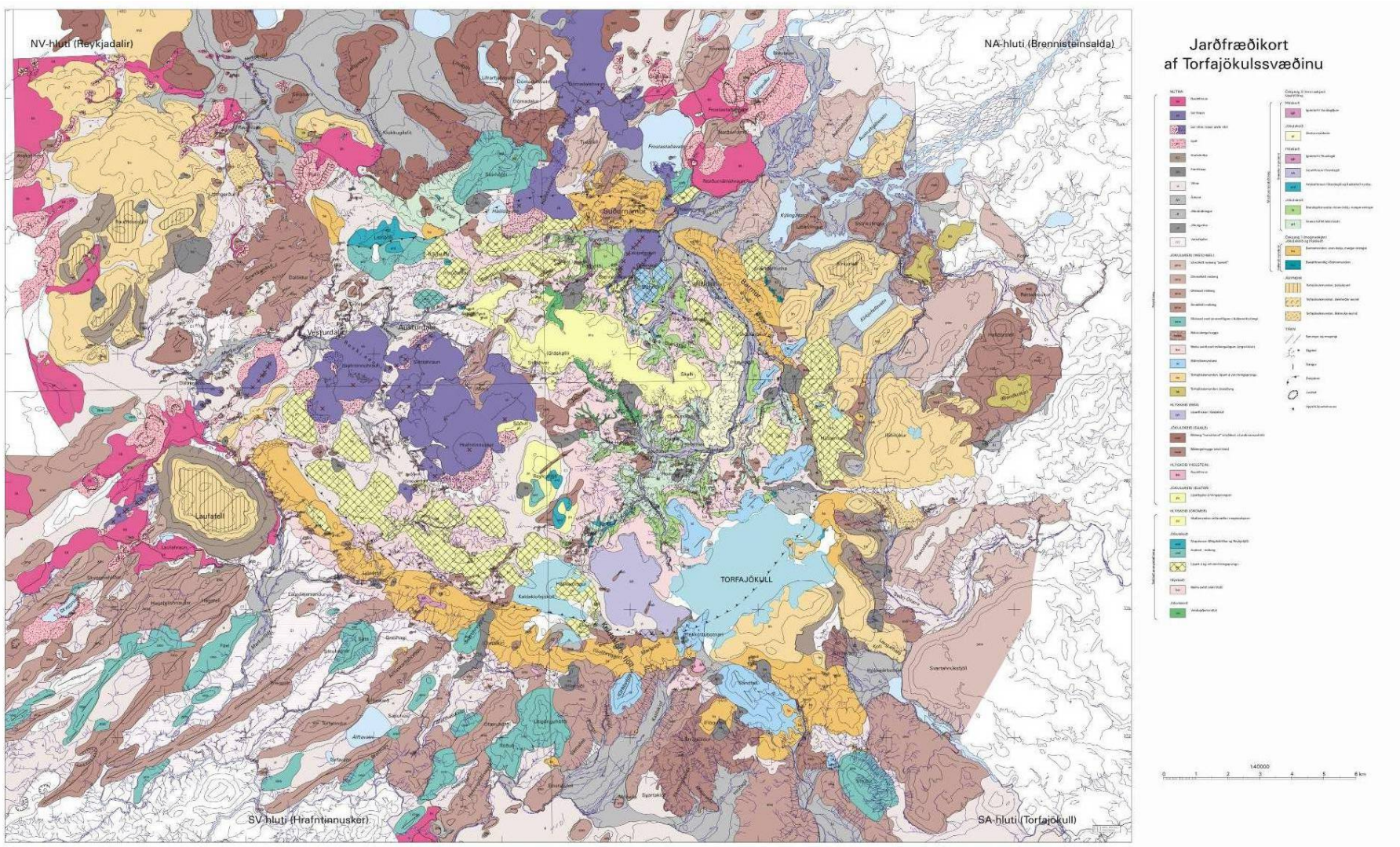

FIGURE 2: Geology of the Torfajökull volcano. The oldest unit crops out in an elliptical narrow zone which encloses the caldera. In Holocene time rhyolite lavas were erupted in the centre of the caldera and mixed lavas near its periphery. Basalt lavas were erupted from NE-SW crater rows further away. The ring fracture rhyolites are shown in pale yellow

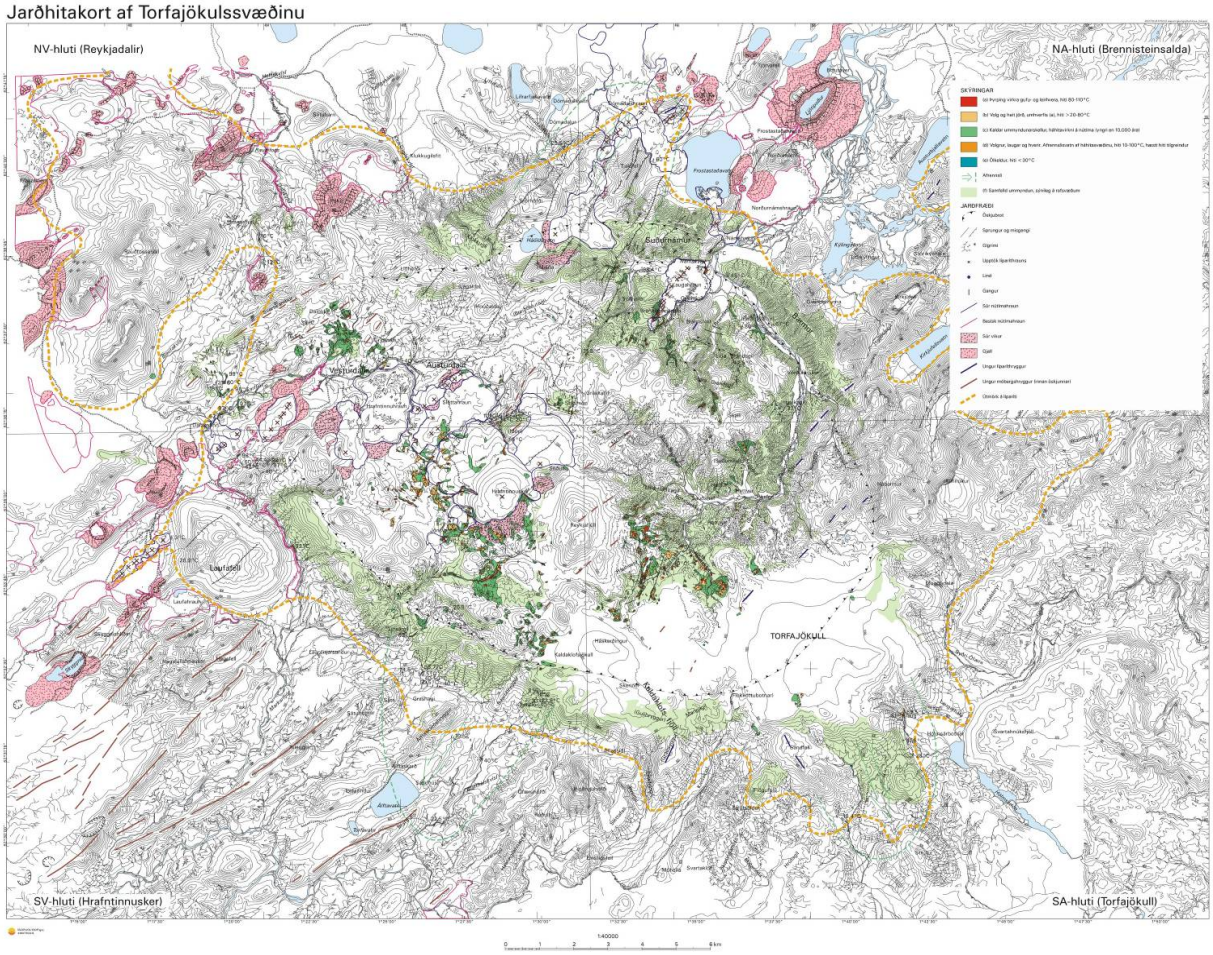

FIGURE 3: Geothermal activity is widespread, mostly as fumaroles inside the caldera. Warm and hot springs are common too around the periphery of young lavas and other permeable formations. CO_2-rich hot springs occur in the east of the caldera and to the SW of it. Alteration is pervasive in the older rock units, much of it cold (light green). Hot ground is extensive around the fumarole fields (dark green)

The most intense thermal manifestations are clearly related to faults and eruption foci of the active NE-SW fissure swarm, in particular within the shadow zone (Figures 3 and 5). There is a marked large offset (right lateral) of the fissure swarm in the SW of the caldera (Figures 2 and 4). The offset segments of the fissure swarm overlap rather than being connected by a transcurrent fault. In the eastern half of the caldera fumaroles concentrate around the youngest domes (most of which erupted under ice) and related fissures.

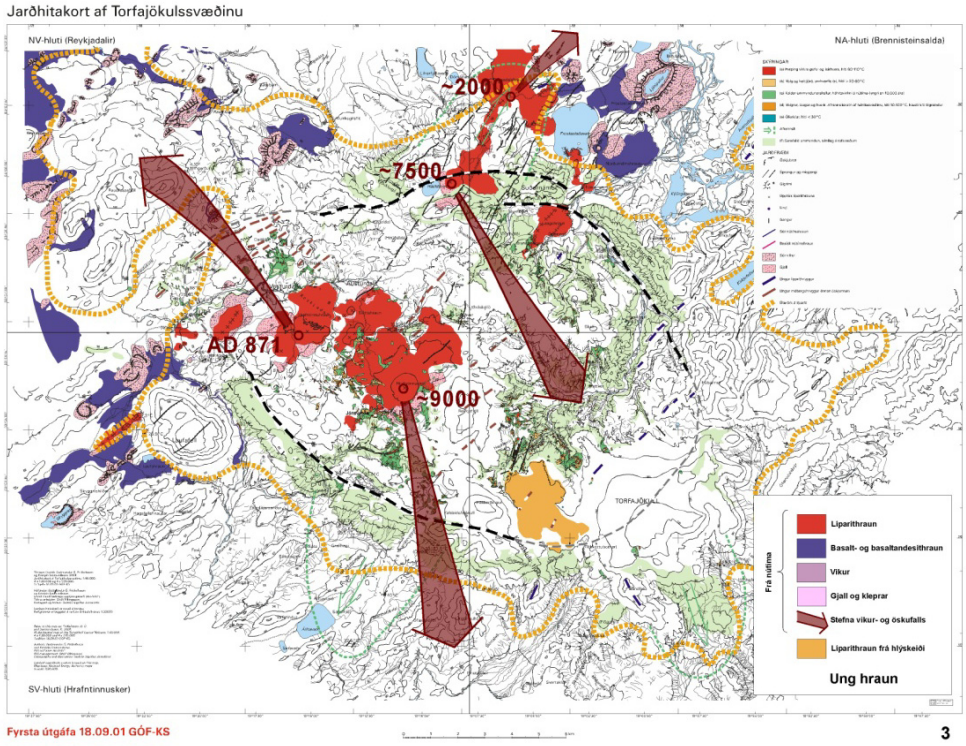

FIGURE 4: Holocene lavas of Torfajökull volcano and plinian phase fall-out of rhyolitic ash which was erupted in the initial stage of the eruptions. Rhyolite (mixed) lavas are red. Basaltic and andesitic lavas are blue. The yellow, stippled contour marks the rhyolite area

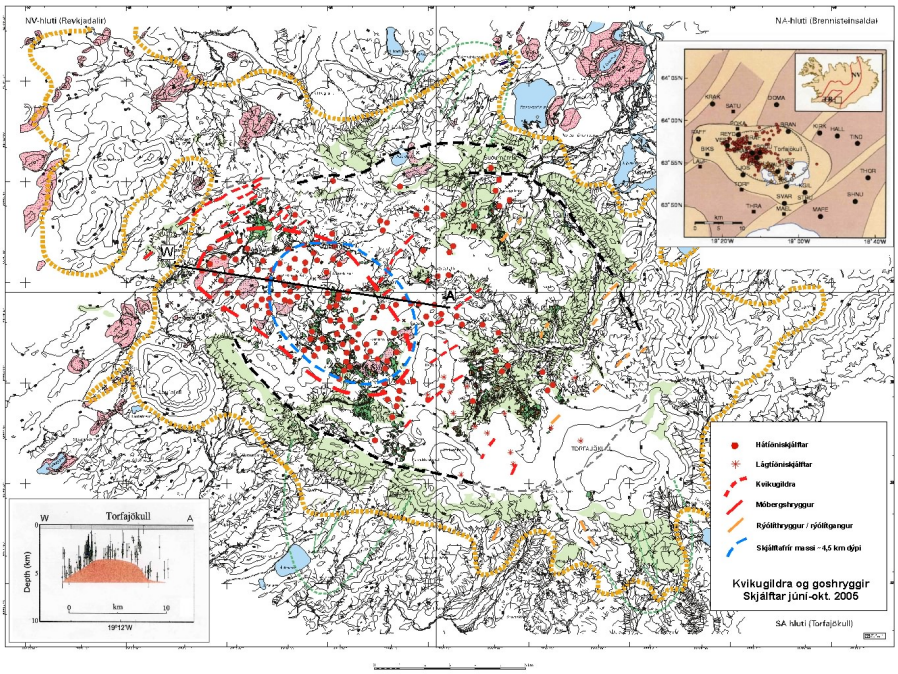

FIGURE 5: A volcanic shadow zone (red hatched contour) where basalt has not erupted is found in the SE of the caldera. It has narrowed with time. Until eruption of the voluminous ring fracture rhyolites about 80 ka it occupied almost the entire caldera. Microearthquakes are common in Torfajökull. Most of them are high frequency earthquakes (the common type which is caused by rock fracturing). They occur in the western part of the caldera. A large, dome-shaped area underneath the shadow zone is void of earthquakes. It is interpreted as ductile (nearly molten?) due to high temperature (blue stippled contour). Low frequency earthquakes (due to movement of fluid, perhaps of pneumatolitic origin) occur in the east of the caldera, extending down to about 15 km depth (stars)

3. GEOCHEMISTRY OF FUMAROLE GASES AND HOTSPRING WATERS

An extensive geochemical survey was made of Torfajökull (Figure 3). Fumarole gases indicate reservoir temperatures of 300-320°C in the entire caldera region. Deep reservoir water (high silica content) occurs in hot springs at the lowest level in the NE. The silica geothermometer indicates a temperature of about 265°C there. The peripheral hot springs are rich in CO_2 suggesting final phase fluxing from cooling intrusions. (Exhumed central volcanoes have a last phase aureole of $CaCO_3$ around them). A peculiarity is a relatively high concentration of methane in fumarole gases in the eastern central part of the caldera. Methane is a volcanic gas which reacts slowly in the rock. It's concentration in geothermal water may therefore be relatively high. The high concentration coincides with the focal area of low frequency earthquakes (Figure 5). It is probably expelled into a pneumatolytic phase from cooling intrusions.

4. GEOPHYSICS

Of geophysical methods resistivity soundings have been applied at Torfajökull specifically to investigate the subsurface thermal structure. Microseismicity has been registered for about 25 years adding significantly to understanding of it´s thermal activity and deep structure. Other methods carried out as part of larger projects include gravity and airborne magnetics. Recently ground levelling (GPS) was added to follow up indications from seismicity of a shallow magma chamber.

The resistivity survey (TEM) revealed a vast prospective area. Resistivity anomalies reveal themselves as high-resistivity bodies below a cap of low resistivity (Figure 6). Those bodies extend well beyond the limits of the caldera (stippled vertical lines in Fig. 7). However, resistivity does not separate between cold and hot rock in high alteration facies (chlorite-epidote zone). From geological evidence such as cold surface alteration outside the caldera and outflow character of thermal waters the areas outside the caldera are likely to have largely cooled down. The same resistivity structure inside the caldera, on the other hand is likely to define a still hot rock body of chlorite-epidote alteration (gives high resistivity) below 400–500 m depth (Figure 7). There is a correlation between geological structure, alteration zoning, thermal occurrences and resistivity in the eastern part of the caldera. This is expressed in a caldera parallel trend of those features. These conditions may apply also to the western part of the caldera where erosion has not exposed deep outcrops yet. There the fumarole activity is most intense in the area of the Holocene lavas.

Microseismic recordings of over 25 years revealed two types of seismic signals separated also by depth and area. High frequency earthquakes (due to fracturing) occur in the western part of the caldera down to 5 km depth. They concentrate around the shadow zone leaving an aseismic body below 3 km depth underneath it. They are interpreted as being due to a water front encroaching upon and cooling an intrusive body or a magma chamber. Low frequency earthquakes (kind of tremor due to fluid flow) occur in the eastern part of the caldera concentrating about an area of very intense fumarolic activity. Their origin is deeper, from surface to ~15 km depth. Seismologists have explained them as magma movements, a laccolithic intrusion or even as foreboding of an eruption. Ground levelling indicates minor subsidence in the east central caldera, however. Another explanation is more likely: i.e. they originate at the plastic to brittle transition at a critical temperature around a cooling intrusion. Such an intrusion gives off volatiles which may form metal rich solutions and precipitates in fractures, similar to epithermal mineral veins, well known from surroundings of shallow intrusive bodies around the world.

A gravity survey of South Central Iceland shows an extensive gravity low around the Torfajökull volcano and a marked gravity high within it (about 12-14 mgal) correlating with the caldera (Figure 8). The gravity high is interpreted as a heavy rock mass in the roots of the caldera, i.e. basic intrusions which were emplaced at the neutral buoyancy level underneath the lighter rhyolite. Most of the time the basaltic melt did not erupt in the caldera region but it did at lower levels close to and around the

volcano (Figure 10). The transitional basalt composition of the proximal low level volcanics as against the rhyolites of the central area gives evidence of a layered magma chamber.

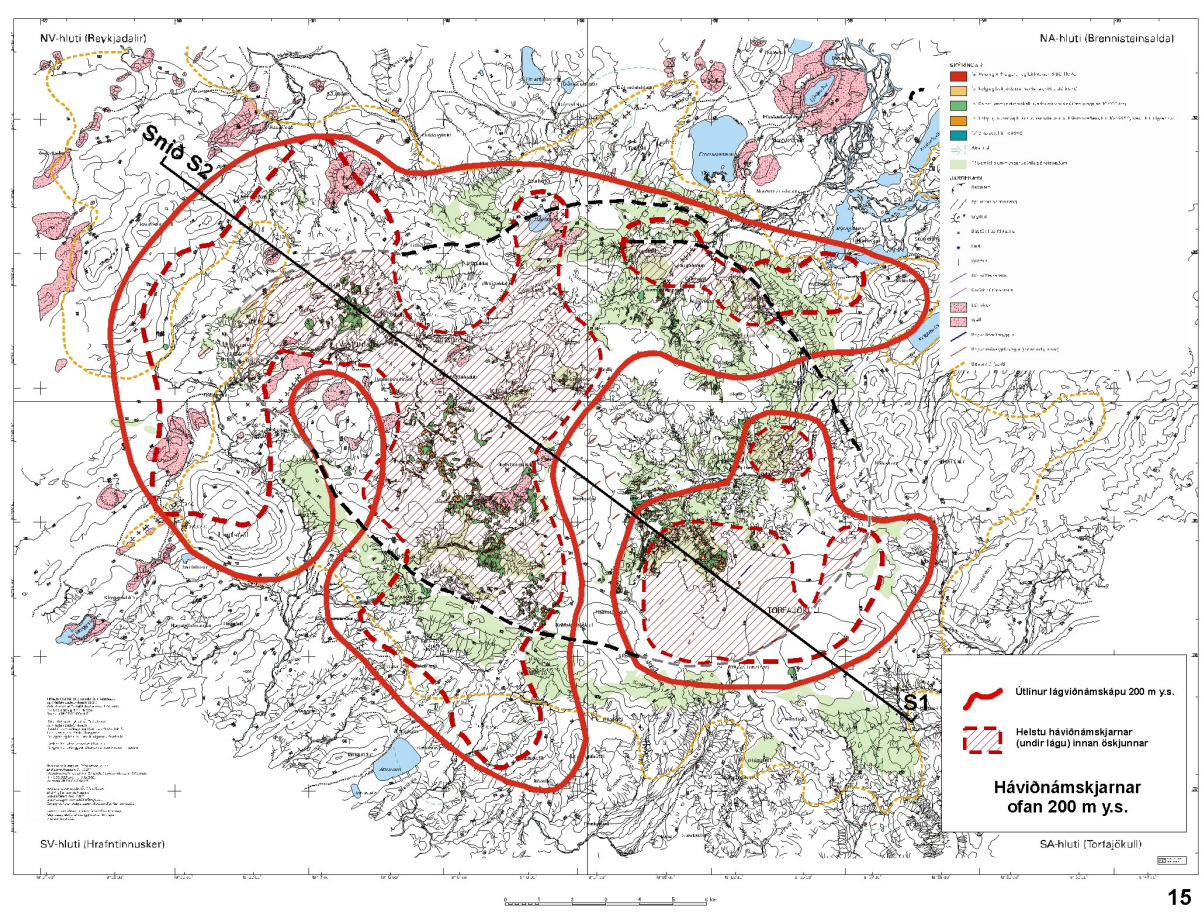

FIGURE 6: Prospective resistivity anomalies reveal themselves as high-resistivity bodies below a cap of low resistivity. They are unlikely to be sufficiently hot for steam production outside the caldera

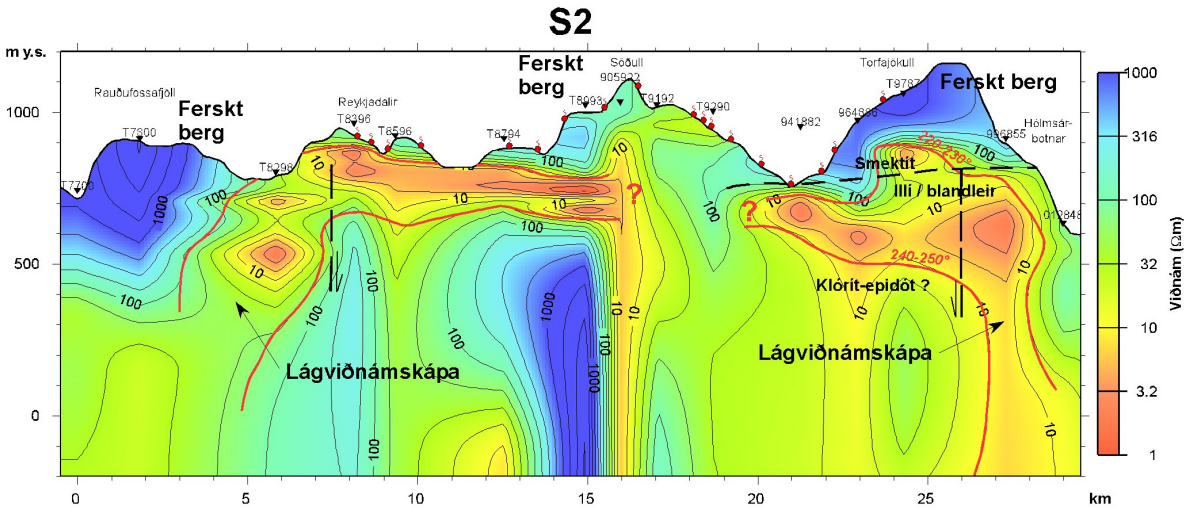

FIGURE 7. East-west section showing resistivity and its inferred correlation with alteration zoning. The alteration of the accessible uppermost few hundred metres gives a tie to conclude about the kind of alteration which causes the resistivity below.

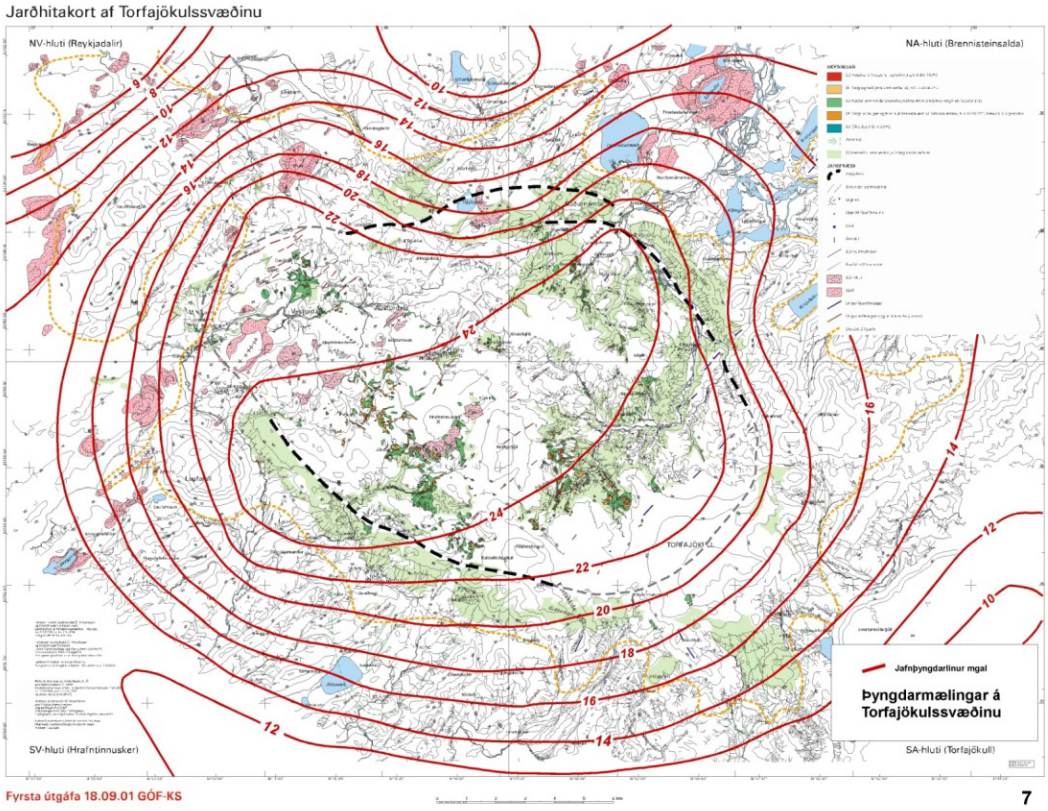

FIGURE 8: A gravity survey of South Central Iceland shows an extensive gravity low around the Torfajökull volcano and a marked gravity high within it (about 12-14 mgal) correlating with the caldera

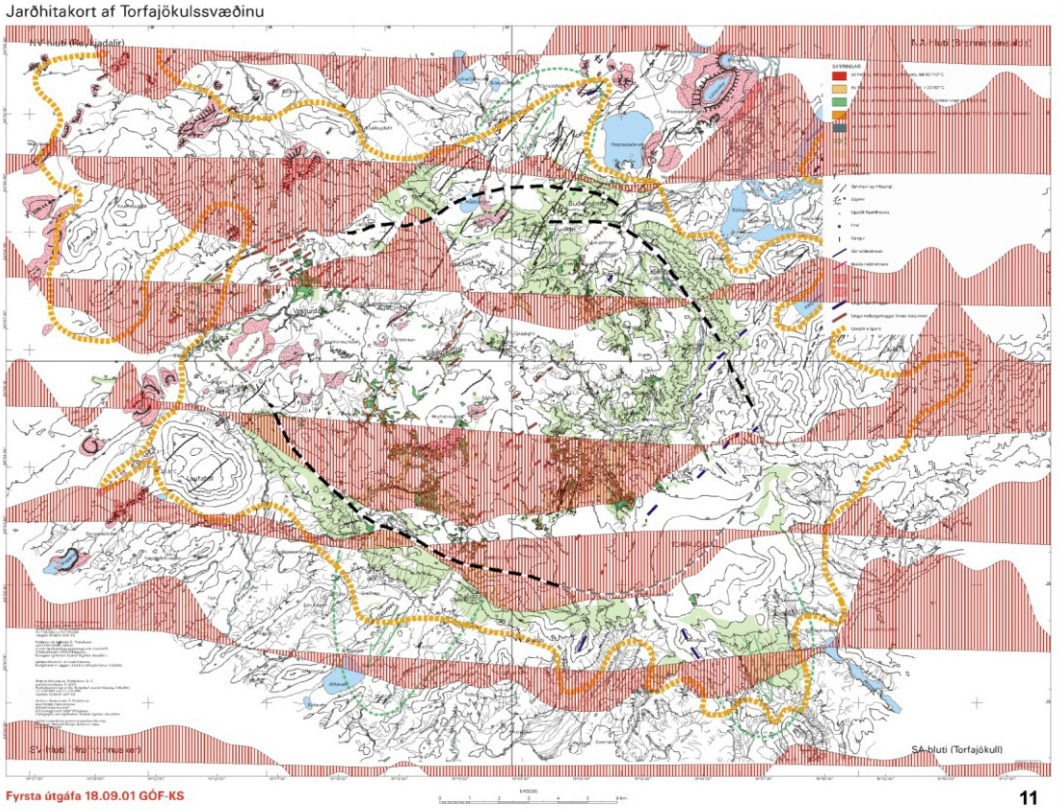

FIGURE 9: An aeromagnetic map shows low magnetization in areas where rhyolite predominates, especially where altered

An aeromagnetic map (Figure 9) shows low magnetization in areas where rhyolite predominates, especially where altered. Hyaloclastites and their accompanying basalt flows and pillow lavas which occur in the northern part of the young fissure swarm and largely cover most of the rhyolite, show up as strongly magnetized areas. For geothermal purpose the map is a significant addition. It reveals a magnetic low west of the Torfajökull caldera that may indicate subsurface alteration. It happens to correlate with the resistivity map.

5. GEOLOGICAL MODEL – DEEP THINKING

The geological structure of Torfajökull is shown schematically in Figure 11. The volcano began as a flank zone volcano on 5-10 million year old tholeiitic crust under a stress field with horizontal max compression (NE-SW). Heat from the mantle plume and a SW-propagating rift zone caused generation of transitional basic magma in the mantle. The magma rose to the LNB-level near the lower (intrusive) and upper (extrusive) crustal boundary forming a magma chamber. This went on during development of the volcano and a thick plug of gabbroic rock formed in the roots of the volcano. It may have developed into a stem-like rock body thus causing the gravity high. A profound revolution occurred in Late Pleistocene, beginning some 100 thousand years ago, when the spreading zone broke across the volcano. The first response was a voluminous eruption of at least 25 km³ of rhyolite on a ring fracture. Partial emptying of the magma chamber was followed by NE-SW fissure eruptions of first transitional basalt from deeper levels of the magma chamber and later mixed volcanics composed of high level lateral intrusions of tholeiite into residual rhyolite magma (small volume as compared to past situations) underneath the centre of the caldera.

This summary is an abridged version of a detailed report (in Icelandic) on the geology and geophysics of Torfajökull by the author compiled from various sources as regards topics other than geology which are largely his own. The figures presented here are from this report (Orkustofnun 2007, in press). They were put together by the author to illustrate a few of the main characteristics of the area, in particular those related to the geothermal phenomena.

Torfajökull was chosen here as an example of a rhyolite volcano. It hosts a powerful geothermal resource as does Olkaria, it´s closest analogue in the Kenya Rift Valley.

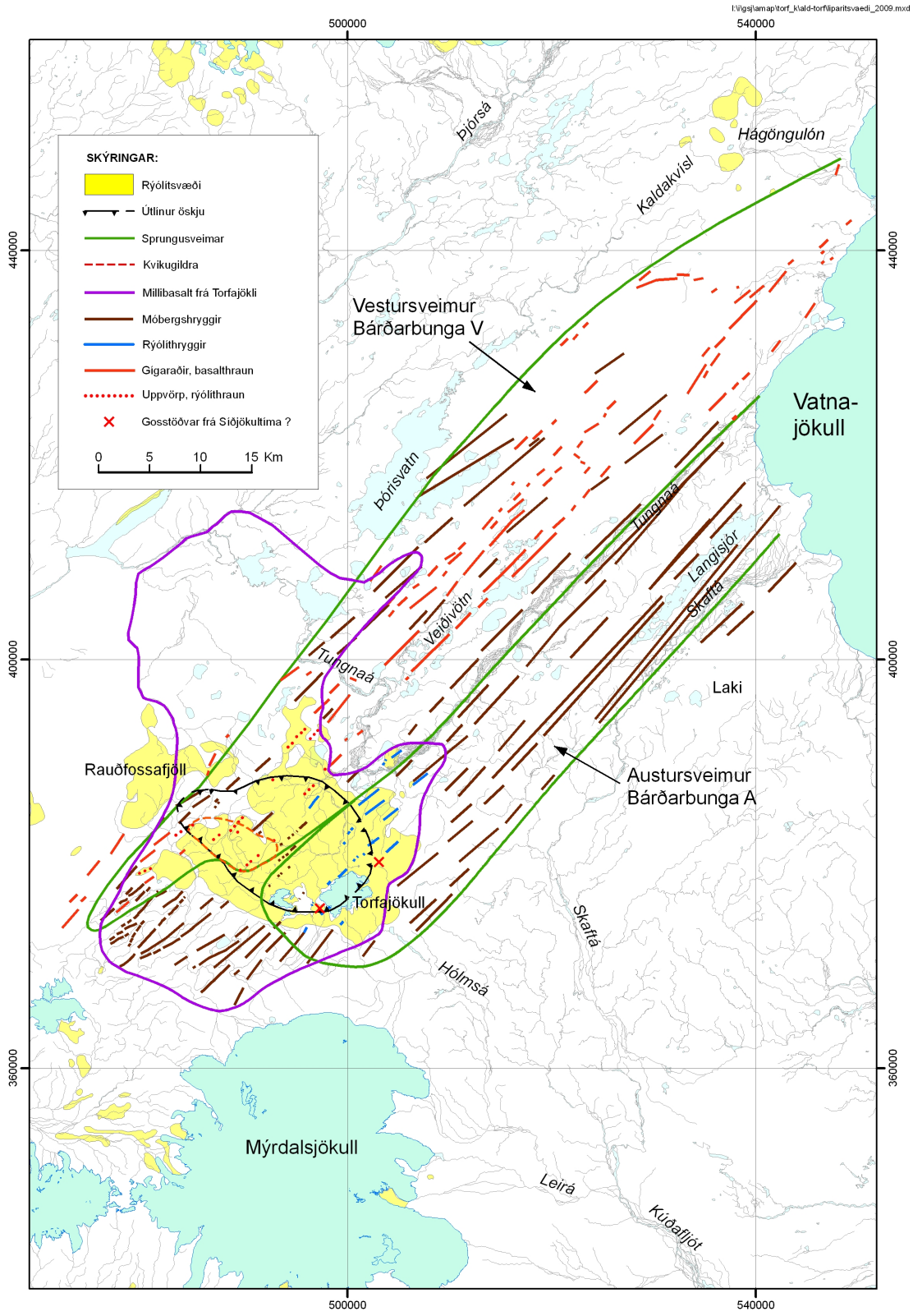

FIGURE 10: Main features of the wider surroundings of Torfajökull. An area of transitional basaltic rocks (violet line) dominates in the area around the rhyolite terrane. A fissure swarm cuts across the volcano. During the Holocene its western half has erupted tholeiite lavas to the northeast of Torfajökull and mixed lavas in the rhyolite area and to the southwest of it. The eastern half of the fissure swarm has not erupted in Holocene time. The Torfajökull caldera is shown and a volcanic shadow zone in the southwest of it

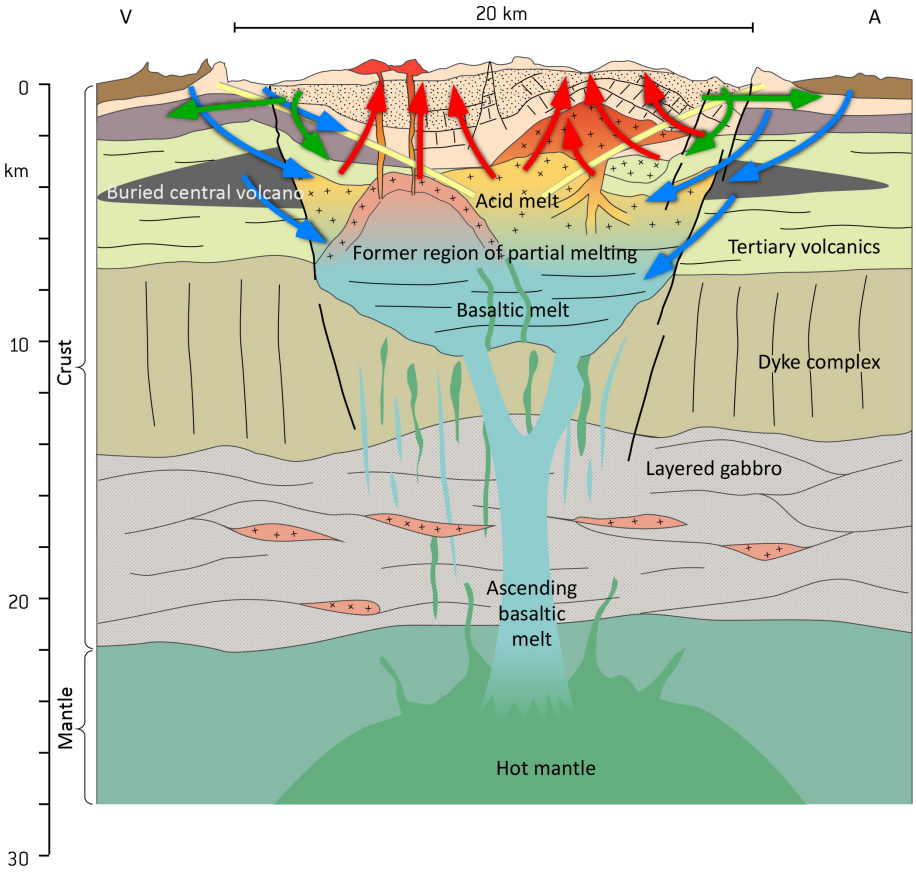

FIGURE 11: Conceptual model of the deeper structure of the Torfajökull volcano

Presented at *Short Course VIII on Exploration for Geothermal Resources*,
organized by UNU-GTP, GDC and KenGen, at Lake Bogoria and Lake Naivasha, Kenya, Oct. 31 – Nov. 22, 2013.

A STUDY OF THE KRAFLA VOLCANO USING GRAVITY, MICRO EARTHQUAKE AND MT DATA

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ABSTRACT

Some recent studies have been done in order to understand the deeper structure of the Krafla volcanic complex and its geothermal system. The studies comprise an extensive Magneto-Telluric survey and a passive seismic survey. The Magneto-Telluric survey was carried out by two groups, a group from Duke University, North Carolina in the summers of 2004 and 2005 and a group from Moscow State University and ÍSOR in the summer of 2006. The seismic survey was carried out in 2004 and 2005 by the Duke group and another group from University of North Carolina.

The Bouguer gravity map of the Krafla area has been reviewed and interpreted. It is suggested that the gravity map shows a buried inner caldera inside the caldera seen on surface. It is further suggested that both calderas are torn apart by a WNW-ESE trending oblique transform graben filled with hyaloclastite. 1D (layered earth) interpretation of the Magneto-Telluric soundings gives consistent results, showing a conductor in the uppermost few hundred meters, reflecting clay alteration of the rocks, and a deeper conductor. The depth to the deep conductor varies greatly. It is at the depth of about 8-12 km at the margins of the survey area but domes up with two “chimneys” reaching the depth of about 2.5 km, one under and to the north of Leirhnjúkur and another under Víti and Mount Krafla. A third narrow “chimney” is seen under Leirhnjúkshraun. The two main “chimneys” roughly coincide with the magma chambers defined by S-wave shadows during the Krafla fires.

The up-doming conductors seem to be confined within the inner caldera, inferred from the gravity data. The deeper resistivity structure seems also to be influenced by the transform graben. Seismic activity, both in the Krafla fires and recorded in 2004 and 2005, is mainly confined within the inner caldera, except where it is broken up by the transform graben in the west. The depth distribution of the earthquakes shows that the seismicity is shallow and clusters right over the up-doming conductors. The seismicity extends to greater depth away from the chimneys. This is consistent with the interpretation that the chimneys reflect very hot plastic or molten rocks. The earthquakes probably reflect where the overlaying geothermal system is mining heat from the rocks at the top of the heat sources. These studies indicate that the geological structure of the Krafla volcano and its geothermal system are more complex than believed till now.

1. INTRODUCTION

The resistivity structure of the shallow crust in the Krafla geothermal area has been studied extensively by DC-resistivity methods (Schlumberger and dipole-dipole soundings and head-on resistivity profiling, in the period of 1970 to 1983) and the central-loop Transient Electro-Magnetic (TEM) method (1991 to 1999) (Árnason and Karlsdóttir, 1996; Árnason and Magnússon, 2001). These resistivity surveys have given a detailed picture of the resistivity structure and geothermal activity in the uppermost 1 km of the crust. The resistivity structure suggests a strong influence of WNW-ESE trending structures and good correlation with the volcanic history of the Krafla volcanic system.

Landsvirkjun (LV) has plans for expanding the power generation in the Krafla geothermal field. LV has also offered the Krafla area as a site for the first deep well of the Iceland Deep Drilling Programme (IDDP), with the aim of taping deep geothermal resources, below conventional drilling depths (2000-2500 m). To facilitate successful location of further production wells and especially the IDDP well, a better understanding of the deep structures of the Krafla geothermal system is important. The most promising methods for studying such deep structures are Magneto-Telluric (MT) resistivity measurements to locate heat sources and monitoring of natural seismicity to locate permeability. The MT method can probe to the depth of 20 to 50 km, and the seismicity in the Krafla area extends down to about 5-7 km.

This report discusses the results of one-dimensional (1D, layered earth models) interpretation of MT soundings made in the years 2004 to 2006. A qualitative interpretation of gravity data (Bouguer map) collected in the years 1976 to 1984 (Johnsen, 1995) is made. The interpretation of the gravity data and the distribution of micro-seismicity, recorded during the Krafla fires and in the summers of 2004 and 2005, are compared to a 3D model compiled from the 1D models of the MT soundings. It is based on a report from ISOR – Iceland GeoSurvey (Árnason et al. 2007).

2. GEOLOGICAL SETTING AND GRAVITY DATA

A very comprehensive description of the geological structure and the volcanic history of the Krafla volcanic system have been given by Saemundsson (1991). The Krafla volcanic system consists of a central volcano and a NNA-SSW trending fissure swarm running through it. Generally speaking the central volcano is characterised by gently sloping topographic high with a caldera in the middle. The caldera has been associated with an eruption producing semi-acidic welded tuff about 110000 years ago.

An extensive gravity survey was carried out from 1967 to 1984, covering the Krafla area and its surroundings (Johnsen, 1995). Figure1 shows a Bouguer gravity map based on these data (red to blue background colour). The average density of 2.49 g/cm^3 was used for the Bouguer reduction and the map has been de-trended by subtracting long wavelength background. Figure 1 shows that there is an impressive gravity high associated with the Krafla central volcano. This is most naturally explained by massive intrusions in the roots of the volcano and its lava shield. There is a distinctive gravity low under and to the east of Gaesafjöll.

Figure 2 shows a de-trended Bouguer map of the Krafla volcano and its immediate surroundings (note that Bouguer values and colours are different from Figure 1 because different background field is subtracted). The figure shows that there is a relative gravity low within the caldera. Superimposed on the gravity low is a gravity high at Leirhnjúkur. This probably reflects intrusions and a magma chamber. The caldera is transacted by two more or less linear gravity lows. One is along the part of the fissure swarm that was active in the Krafla fires (bounded by green lines on Figure 2). The other is ESE-WNW trending from Mount Jörundur in the SE and to the valley Gaesadalur (south of Gaesafjöll) in the NW. Where these anomalies would cut through the caldera rim, it is not visible.

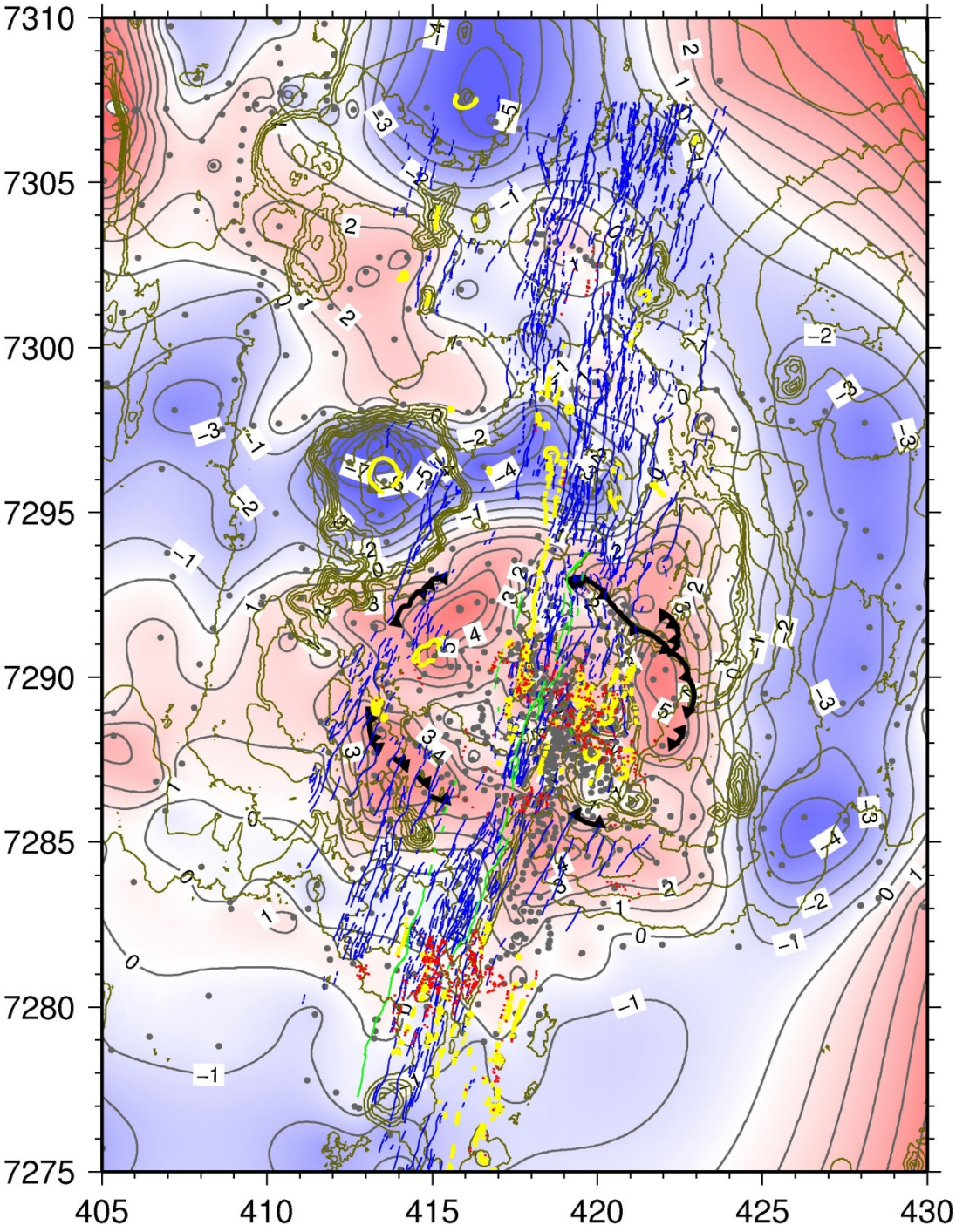

FIGURE 1: De-trended Bouguer gravity map (mgals) of Krafla and surrounding areas. Faults and fissure (blue), the caldera (hedged black lines) eruptive fissure and craters (yellow) and geothermal surface manifestations (alteration, hot springs and fumaroles, red). Boundaries of the part of the fissure swarm that was active in Krafla fires are shown as green lines. The topography (elevation contours) is shown with brown lines

Figure 2 shows other interesting features. There are gravity highs at and inside the caldera rim in the southwest, northwest and east. These high gravity anomalies are bounded by steep gradients towards a gravity low in the centre of the caldera, which is filled with less dense rocks. In the eastern part of the caldera the gradient co-insides with arc like eruptive fissures from Hólseldar, about 2000 years ago (Saemundsson, 1991). Some might like to argue that the high gravity at and inside the caldera rim is

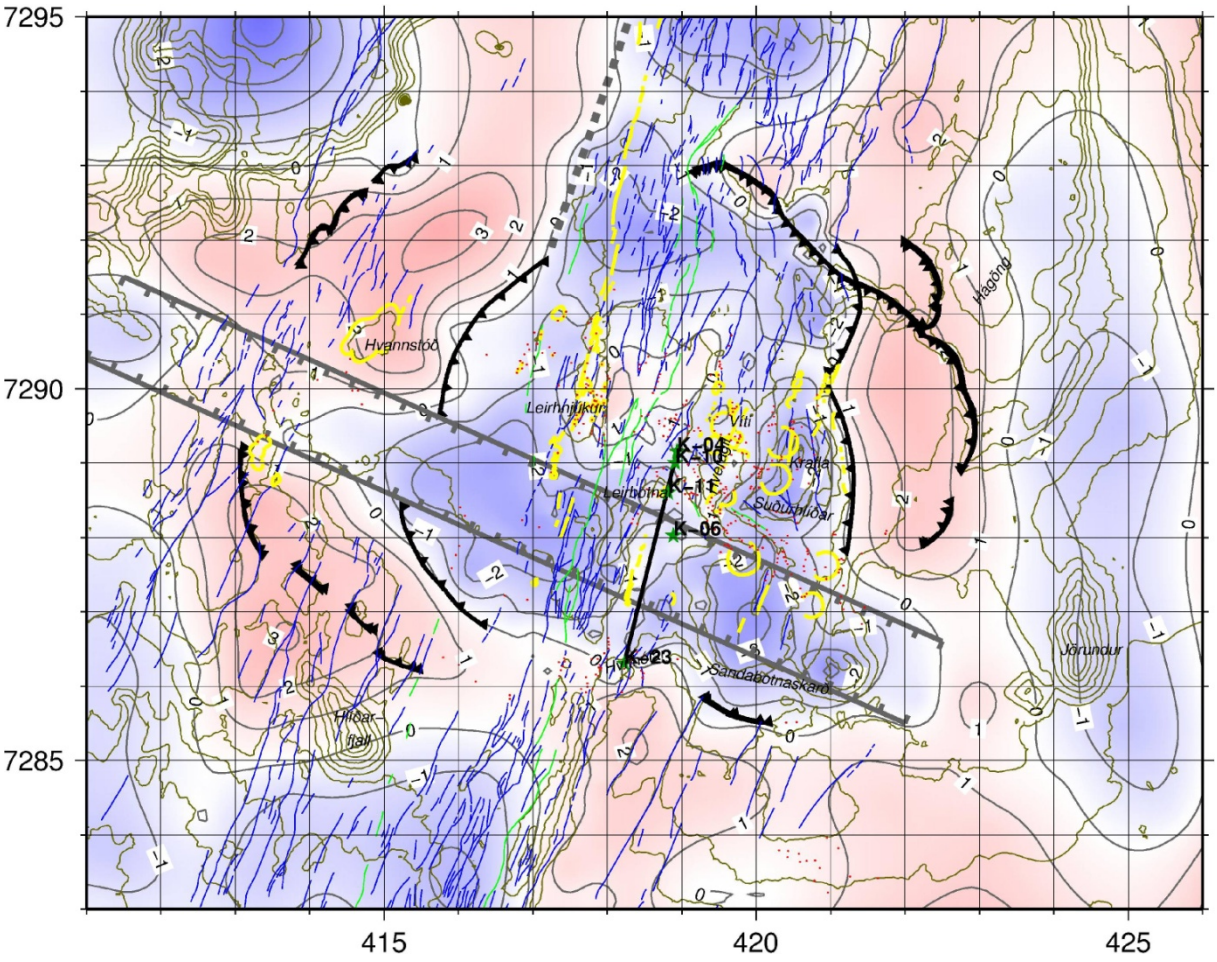

FIGURE 2: De-trended Bouguer gravity map (mgals) of Krafla volcano. Geological information is the same as on Figure 1. The rims of the outer caldera and the inferred buried inner caldera are shown (hedged black lines). An inferred ESE-WNW transform graben is shown (gray fault lines) A linear density contrast in the fissure swarm to the north is also shown (gray broken line). The location of a lithological section in Figure 3 is shown (black line) and the wells on which it is based (green stars)

due to dense intrusions, but the steep gradients clearly show that the density contrasts are at shallow depth. This strongly suggests that there is another caldera buried inside the caldera seen on surface.

The outer caldera has been dated as being 110000 years old. In the 30000 years between its formation and until glaciation, the outer caldera has been mostly filled with lava flows. The inner caldera was probably formed after the area was covered with ice. It was later filled and buried with hyaloclastite of considerable lower density than the subaerial lavas filling the outer caldera, producing the gravity low. The inner caldera must be older than Sandabotnafjall which was formed some 40000 years ago (Saemundsson, 1991) because it lies over the caldera rim. The inner caldera was therefore formed sometime between 80000 and 40000 years ago.

The gravity data indicate that the geological structure of the Krafla volcanic complex is more complicated than has been believed. There is no evidence of the inner caldera on the surface (except may be the volcanic fissures in the eastern slopes of Krafla). It is totally filled and buried by younger volcanic products. There is little or no evidence of inner caldera found in deep wells because they are all inside it or at its rims. There is, however, some evidence of the ESE-WNW oblique transform graben from drilling. Figure 3 shows a lithological section across the inferred transform graben (Ármannsson et.al., 1987). The wells on which the section is based and the location of the section is

shown in Figure 2. The section shows 600-700 m thicker pile of hyaloclastite with interbedded lava flows within the transform graben (well K-06) than north of the graben (wells K-08, K-10 and K-04). This lends support to the idea that the calderas are indeed transected by an ESE-WNW graben.

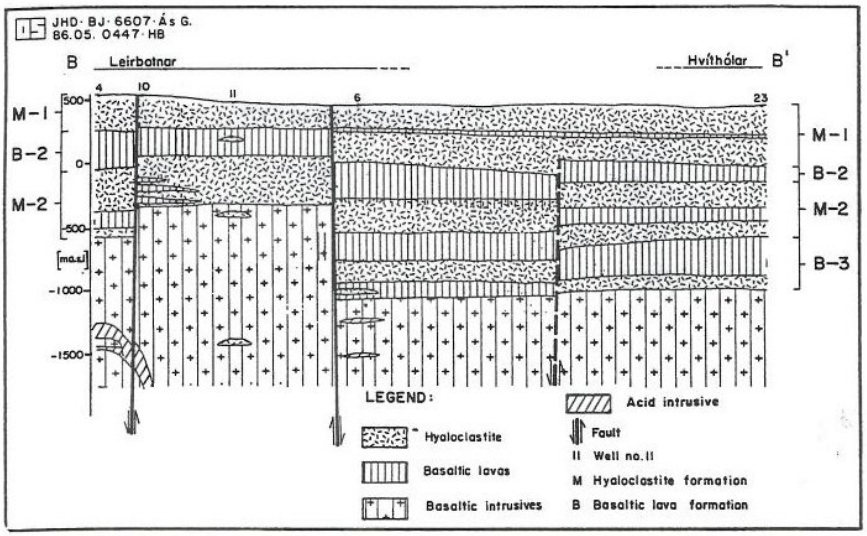

FIGURE 3: Lithological section based on wells, from north (left) to south (right) within the Krafla caldera. For location see Figure 2 (from Ármannsson et.al. 1987)

3. SEISMIC DATA

During the tectonic and volcanic activities in the ninety seventies and eighties the Krafla volcano and its fissure swarm was very seismically active. The earthquake activity was monitored and recorded by a seismic network operated by the Science Institute at the University of Iceland (Einarsson, 1991; Sandford and Einarsson, 1982). In the year 2004, two experiments were performed in the Krafla area. A group from the University of North Carolina, led by Prof. Jose Real deployed 20 portable seismic stations for about two months in the Krafla area to record micro-seismicity. A second group, from Duke University North Carolina, led by Stephen Onacha (a PhD student) and Prof. Peter Malin, deployed further 20 seismic stations and made 50 MT soundings to study the deep resistivity structure. In a second campaign, in 2005, the Duke group recorded micro-seismicity for one and a half month and installed two seismometers in boreholes and recorded for about six months.

Figure 4 shows the epicentres of all earthquakes considered in this study. Epicentres of earthquakes in the Krafla area recorded between 1974 and 1988 (1445 quakes) are located with horizontal uncertainty less than one km (Einarsson and Brandsdóttir, pers. comm.). The data from 2004 and 2005 were recorded by dense networks on top of the volcano (330 quakes). This means that the latter are located with much better accuracy. The figure shows that the earthquake activity was mainly confined within the inner caldera, except where the calderas are torn by the WNW-ESE transform graben in the west. The earthquakes seem to cluster in two WNW-ESE trending areas, one inside the boundaries of the resistive core in NE and another one where the transform graben runs through the calderas. Most of the earthquakes occur between 1 and 3 km depth. There is a tail of quakes at greater depths, mainly from the Krafla fires. Closer inspection shows that these are mainly events outside the inner caldera. Of the earthquakes recorded 2004 and 2005 there are only a five deeper than 3 km and they are all outside the inner caldera.

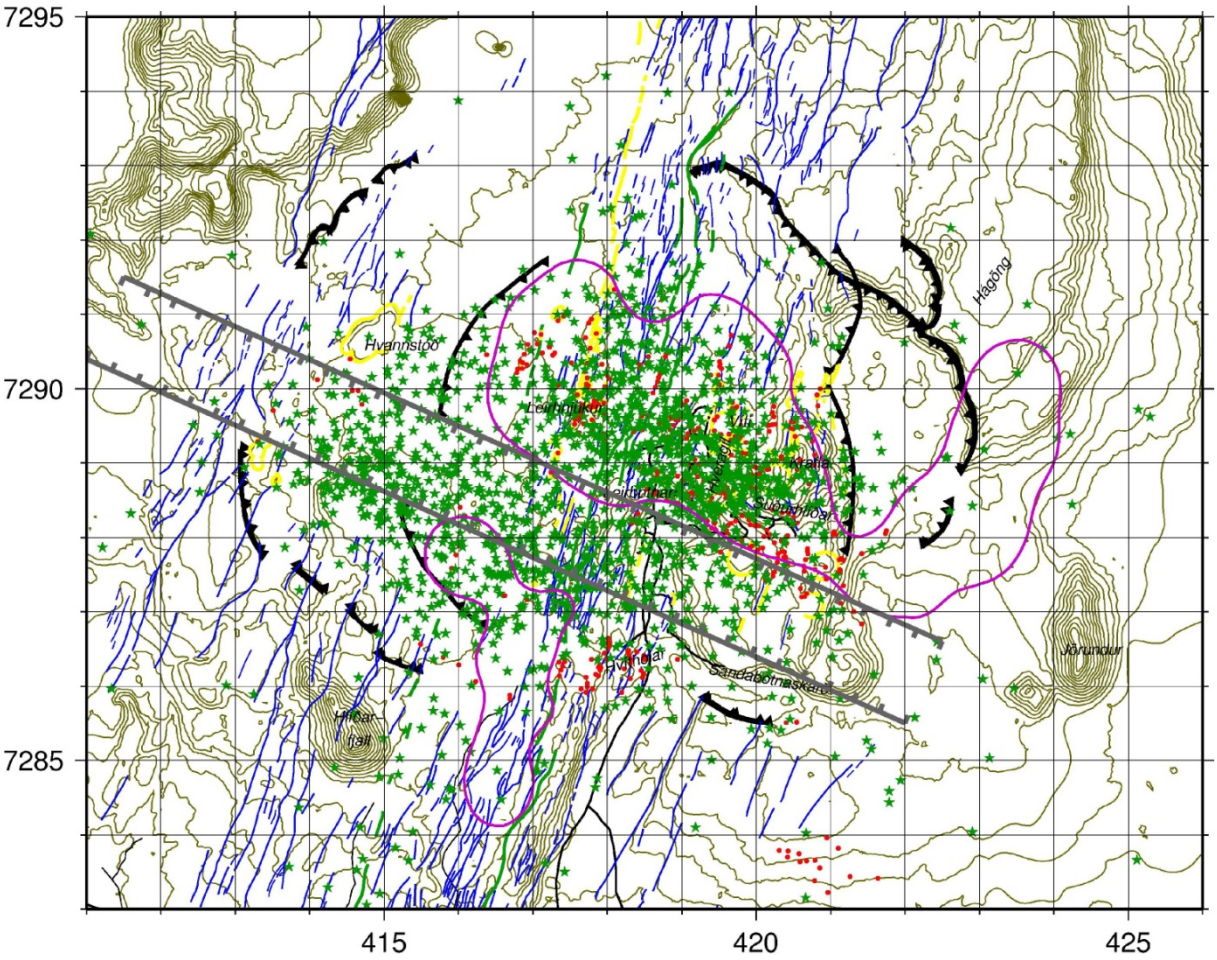

FIGURE 4: Epicentres of all earthquakes (green stars) in the Krafla area considered in this study. Faults and fissure are shown (blue), the two calderas (hedged black lines), the inferred transform graben (gray fault lines), eruptive fissure and craters (yellow) and geothermal surface manifestations (alteration, hot springs and fumaroles, red). The purple lines show the boundaries of the resistive core at 200 m above sea level as seen by TEM soundings

Earthquakes occur when rocks in the crust break under strain. At high temperatures, about 600-700°C, the basaltic rocks start to become ductile and creep under strain (they can though break if the strain rate is very high). This is called the brittle-ductile transition. At still higher temperatures, 1100-1200°C, the rocks are partially or totally molten and do not break under strain.

The depth distribution of earthquakes therefore gives information on prevailing temperature. The fact that there are almost no earthquakes observed in the inner caldera at depths greater than 3 km is most naturally interpreted in such a way that below that depth the rocks are not brittle. This indicates that at depths greater than 3 km the temperature is at least 600°C. Earthquake waves, radiating from the hypocentre, comprise two types of waves, pressure waves (P-waves) and shear waves (S-waves). The P-waves travel both through solids and liquids. The S-waves cannot travel through liquids and are highly attenuated in partially molten rocks. Analysis of the earthquake data from the Krafla fires revealed that S-waves could not penetrate through some volumes within the Krafla volcano. This was interpreted such that these volumes hosted magma chambers with molten rocks in the depth range of 3 to 7 km (Einarsson, 1991, 1978). Figure 5 shows the boundaries of the inferred magma chambers. This interpretation is consistent with the lack of earthquakes below 3 km depth. The presence of the S-wave shadows right below the lower boundary of the seismicity must mean that the temperature rises from about 600°C and to about 1100°C in a very narrow depth range.

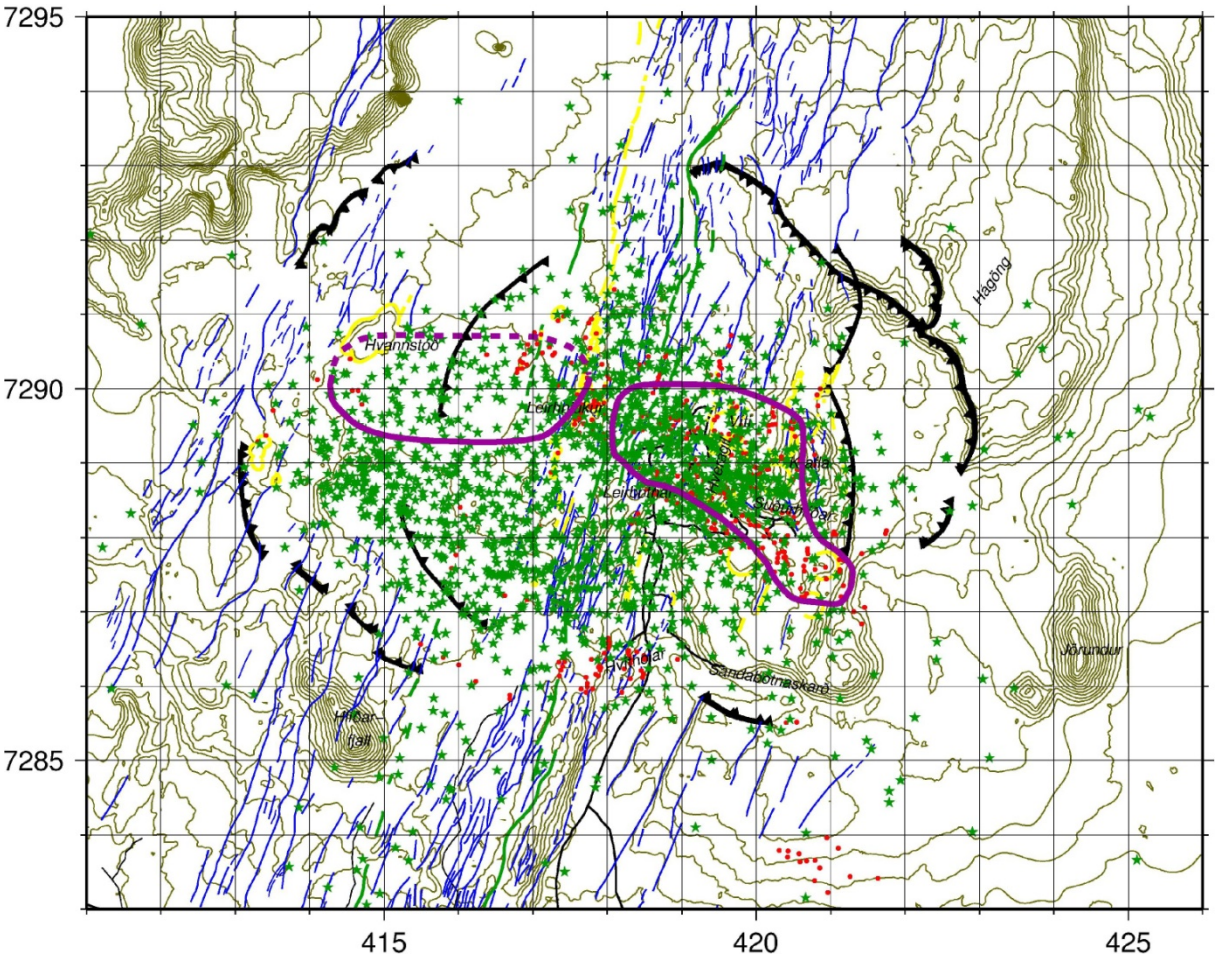

FIGURE 5: Earthquake epicentres (green stars) and boundaries of S-wave shadows (purple lines) observed during the Krafla fires (reproduced from Einarsson, 1991). Other geological features are the same as on previous maps

4. MT SURVEY

An MT survey has been carried out in the Krafla geothermal field. This was done in three campaigns. In the summer of 2004 a group from Duke University, led by Stephen Onacha made 50 soundings. The Duke group made a second visit in 2005 and made further 58 soundings. The distribution of the MT soundings from 2004 and 2005 is very uneven and it was therefore decided by LV to complete the coverage of the Krafla geothermal field by adding 55 MT soundings. This was done by a group of MT specialists from Moscow State University (MSU) and ISOR employees in the summer of 2006. The total number of MT soundings made in the area is therefore 163.

4.1 Processing and interpretation of the MT data

The MT data were collected with equipment from Phoenix, using the remote reference technique. The basic data processing of time series to produce impedances and tippers (as functions of periods) was done with software provided by Phoenix and the results written to files on the standard EDI format.
The MT method, like all resistivity methods where the electric field is measured in the surface, suffers a problem called the telluric shift problem. The reason for this is that local resistivity anomalies at the sounding site influence and distort the electric field, independent of frequency. The result of this is that the apparent resistivity values have an unknown multiplier (shift of logarithmic values). The TEM soundings do not suffer this problem because they measure magnetic induction in a receiver coil (or

loop). By interpreting together TEM and MT soundings made nearly at the same place, the TEM data can be used to determine the unknown multiplier of the MT apparent resistivity (see Figure 6).

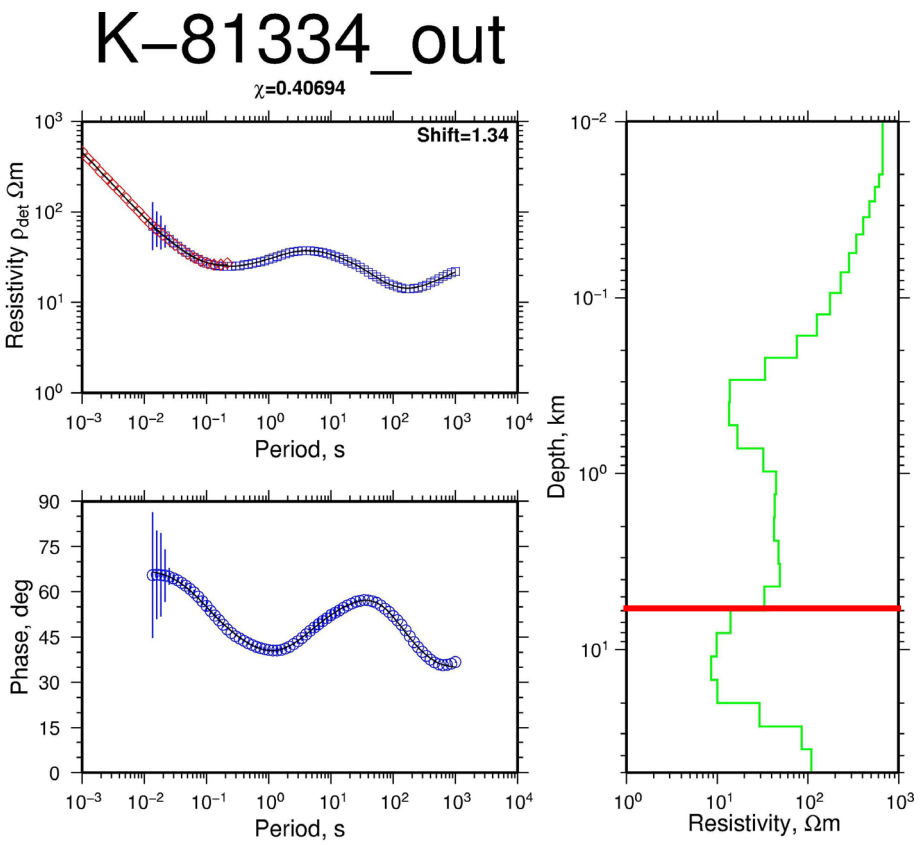

FIGURE 6: A typical result of a joint inversion of TEM and MT soundings. Red circles are the measured TEM apparent resistivity values and the blue circles are the apparent resistivity and phase values derived from the determinant of the impedance tensor. Black solid thin lines are calculated responses of the model to the right. In order to make the MT apparent resistivity tie in with that of the TEM, the MT apparent resistivity values have to be divided by a shift parameter of 1.34 (top right corner of the apparent resistivity panel)

The 1D inversion presented in this report is a so-called "minimum structure" or Occam's inversion. The soundings are fitted by the response of models with many layers (30-40) with constant thicknesses, increasing exponentially with depth. The variation in resistivity values is damped in order to get as smooth models as possible. The unknown parameters that are determined in the inversion are the resistivities of the layers and the shift multiplier.

A total of 72 out of the 108 soundings made by the Duke group have been interpreted and 53 of the 55 soundings made in 2006. The total number of soundings interpreted is 125 (locations in Figure 7). All the resistivity models resulting from the 1D inversion have similar structure to the one seen on Figure 6. An upper conductor (low resistivity) is seen with the upper boundary at variable depths, from near surface and to some hundred metres and the thickness of some hundreds of metres. It is underlain more resistive rocks. At greater depth a second deep conductor is seen with upper boundary at the depth of 2.5-12 kilometres (marked with red line on Figure 6) and thickness of some tens of kilometres. The deep conductor is again underlain by higher resistivity.

The shallow conductor is the low-resistivity cap (clay cap) and the higher resistivity below is what has been called the resistive core, as seen in previous TEM surveys (Árnason and Magnússon, 2001). The shallow resistivity structure is well understood (Árnason et al., 2000). The low resistivity cap reflects

clay (smectite) alteration formed in the temperature range of 100-240°C and the transition to the resistive core reflects transition from smectite to chlorite as temperature exceeds 240°C. The nature of the deep conductors is not as clear and possible explanations will be discussed later.

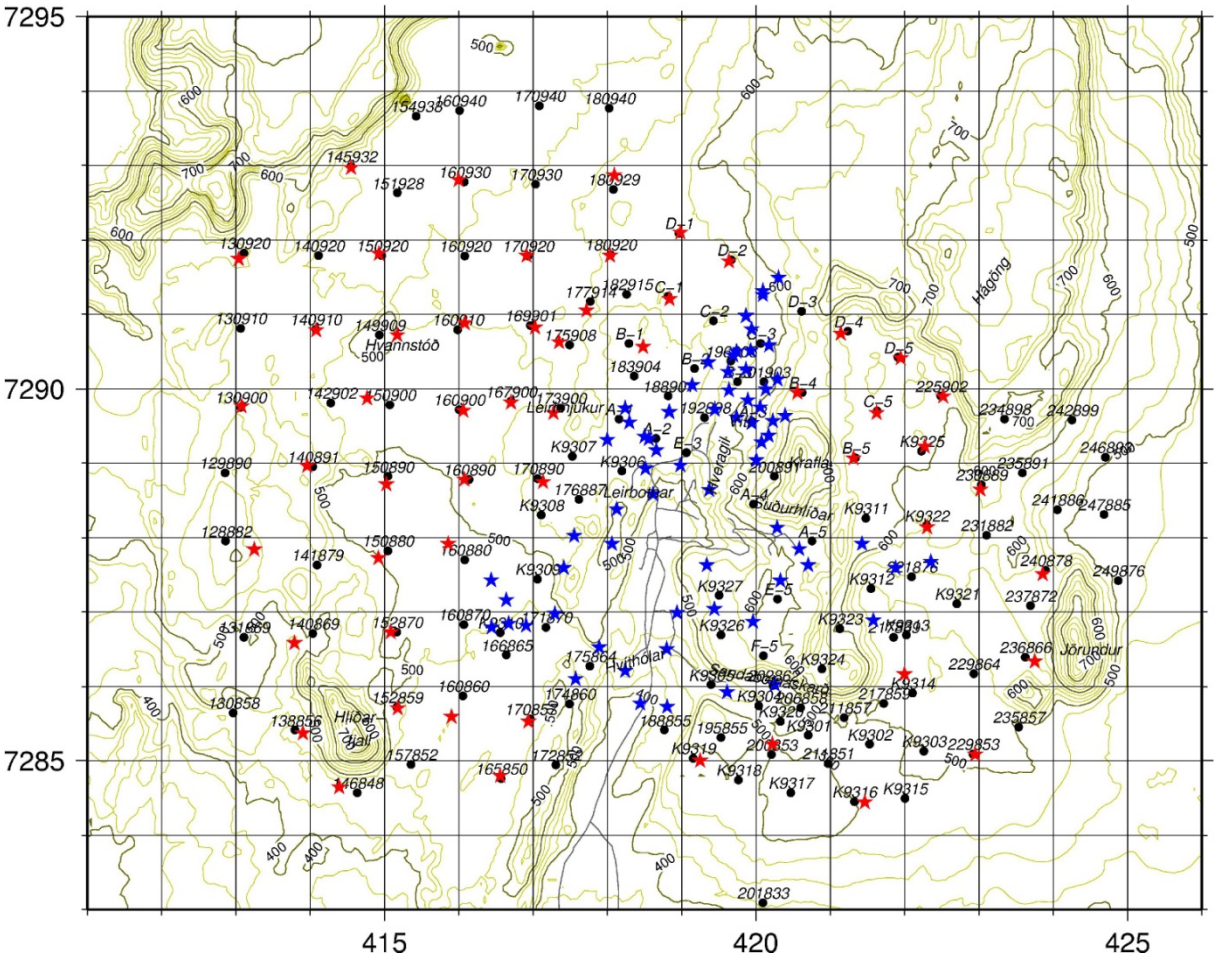

FIGURE 7: Location of interpreted MT soundings. Blue stars are soundings made in 2004 and 2005. Red stars are soundings made in 2006. TEM soundings are shown as black dots

4.2 Results of the 1D inversion; resistivity maps

The results of the joint 1D inversion of the TEM and MT data for various depths are not presented here but in Figure 8 is an example of an iso-resistivity map at 3000 m below sea level.

At the depth of about 2 km b.s.l. (2.5 km depth) the resistivity starts decreasing again within the inner caldera. These deep conductors reach closest to the surface NW of Mount Krafla, under and to the north of Leirhnjúkur and under Leirhnjúkshraun at the SW rim of the inner caldera. These deep conductors become more prominent with increasing depth but are almost entirely confined within the inner caldera to the depth of about 6 km b.s.l. Below 8 km b.s.l., low resistivity starts to spread out of the inner caldera and below 10 km b.s.l. low resistivity is seen in the whole study area.

Iso-lines of the upper boundary of the deep conductors are shown in Figure 9. The figure shows clearly how the main conductors are confined within the inner caldera inferred from the gravity data. They are found where the caldera rims can be seen in the gravity data but are absent where the caldera is torn apart in the west and south-east. The deep conductors in the NE part of the inner caldera show up as a big low resistivity anomaly at depth but with two chimneys reaching up to about 2 km b.s.l. or about 2.5 km depth.

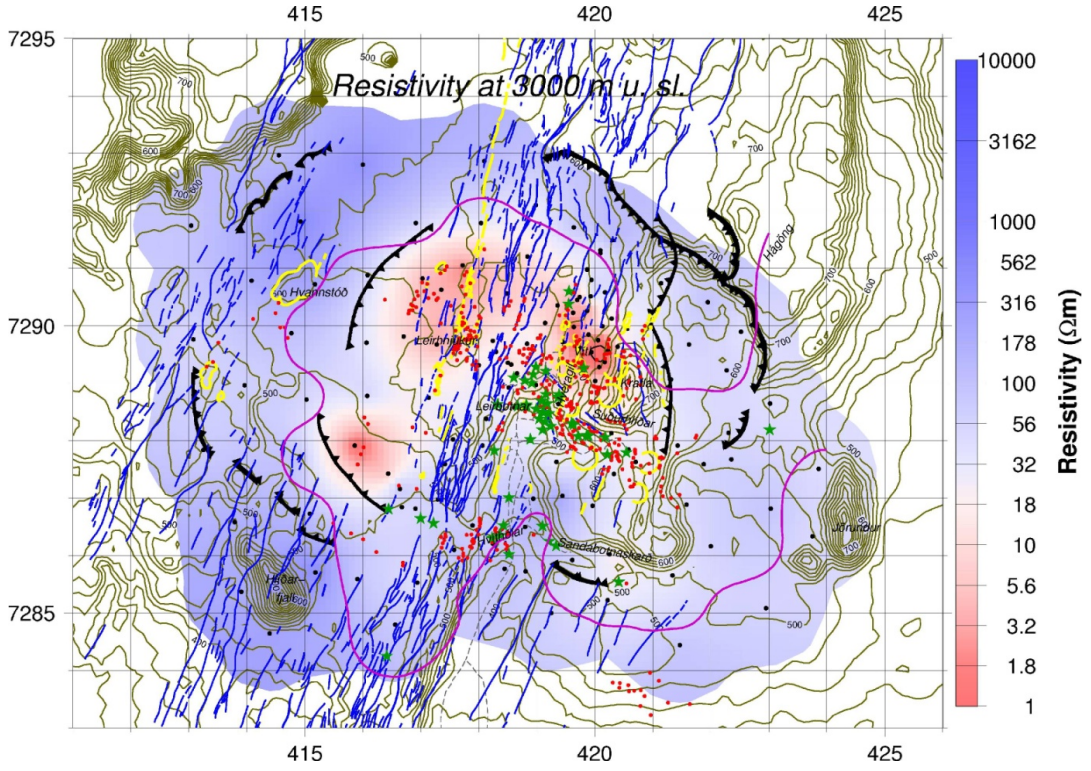

FIGURE 8: Resistivity at 3 km below sea level. The boundaries of the resistive core at 600 m b.s.l. are shown by a purple line

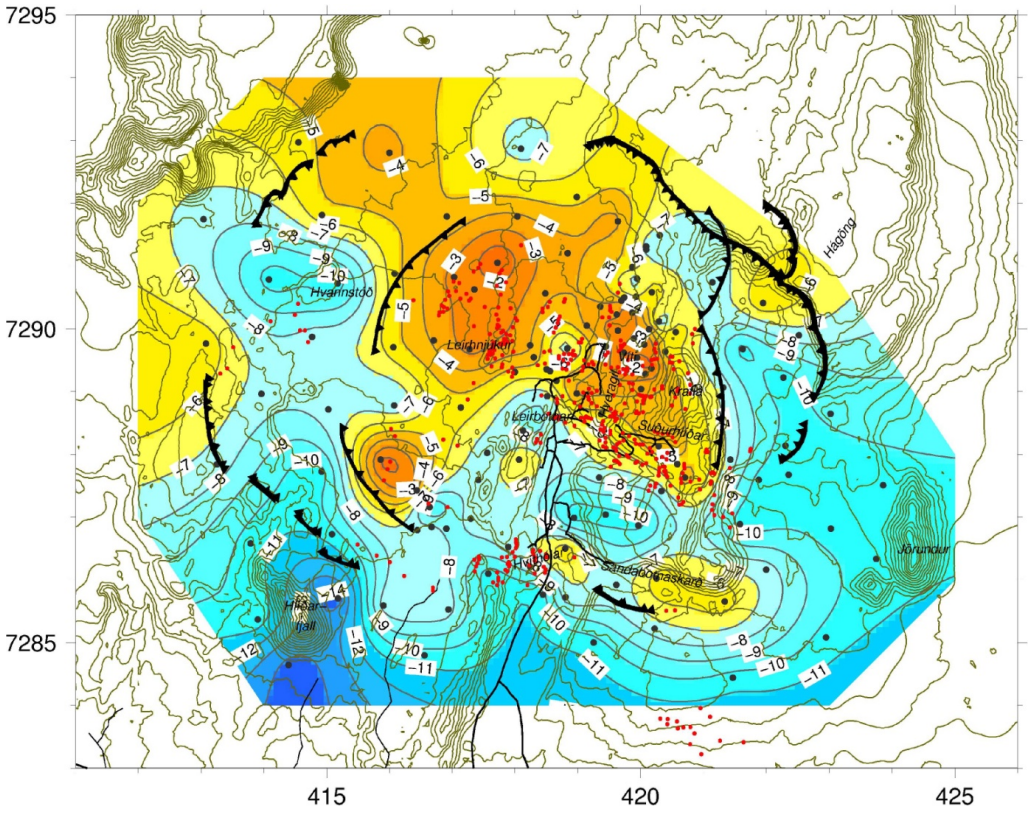

FIGURE 9: Elevation (km above sea level) of the upper boundary of deep conductors in the Krafla volcanic complex. Caldera rims are shown by black hatched lines and geothermal surface manifestation by red dots

4.3 Results of the 1D inversion; resistivity cross-sections

A total of 20 resistivity cross-sections were made, 9 W-E trending sections (AV7285-AV7293 numbered from south to north) and 11 N-S trending sections (NS413-NS423, numbered from west). Only one section is presented graphically in this paper, AV7290 (see Figure 10) as an example. All the sections showed a shallow low resistivity layer in the uppermost few hundred metres. This is the low resistivity (clay) cap and is underlain by higher resistivity (the resistive core).

The depth distribution of earthquakes (projected on the sections) showed some interesting features. Generally the quakes are concentrated above ore close to the up-doming deep conductors (as can be appreciated from Figure 10). There seems to be a correlation between resistivity at depth and the depth of earthquakes. The deeper to low resistivity the deeper are the earthquakes. The earthquakes are rare in the deep conductors

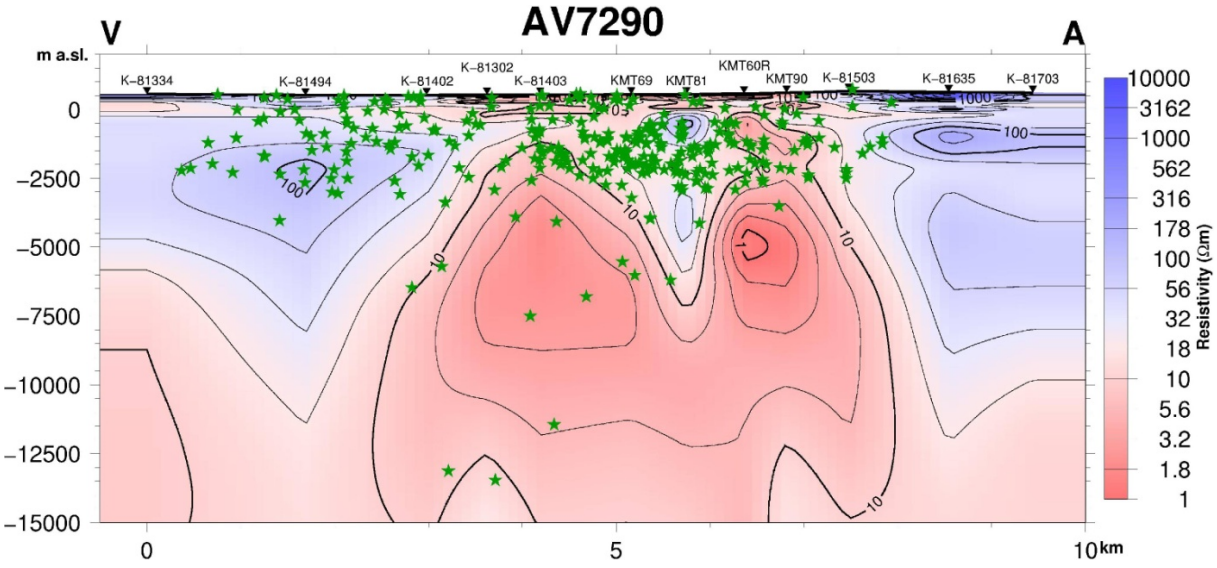

FIGURE 10: E-W cross-section AV7290. Located immediately south of line 7290 (see Figure 7). Earthquakes at distances less than 500 m are projected on the section (green stars)

4.4 What are the deeper conductors?

The shallow resistivity structure of the high-temperature geothermal systems in Iceland is fairly well understood, as discussed earlier (section 0). What makes the rocks more conductive again at greater depth and higher temperatures? What is the high conductivity reflecting? These are fundamental questions that have not been answered properly as yet.

The conductors at depth in the crust can in some cases be explained by melt but in other cases probably not. Another possible explanation could be trapped magmatic brine. Even though it is not in all cases clear what causes the low resistivity anomalies at depth in the crust, all realistic explanations assume high temperatures. If the low resistivity is caused by trapped magmatic brine, the temperature has to be above the brittle-plastic transition, i.e. above 600-700°C. If the low resistivity is due to melting, as is the case in at least parts of the Krafla volcano, the temperature must be about 1200°C. The conclusion is that even though the cause of localised good conductors in the crust is not always clear, they can, in relatively good confidence, be assumed to be heat sources for hydrothermal systems.

5. COMBINED RESULTS AND CONCLUSIONS.

In this study three independent data sets are considered, i.e. gravity data, seismic data and TEM/MT data. Each of the data sets indicates the presence of an anomalous ring structure within the caldera visible on the surface.

Figure 11 shows the combined results of the interpretation of the Bouguer gravity map, i.e. the inner caldera and the oblique transform graben. The figure shows how the crustal conductor dome up in the northern part of the caldera and are abruptly cut off at the northern margin of the WNW-ESE rift graben. The figure also shows that there is a shallow conductor found where the SW rim is seen south of the transform graben. It should be noted here that this anomaly is only sustained by two soundings and should be confirmed by making the TEM/MT coverage denser in this area.

Given that the relatively shallow conductive bodies reflected intruded magma bodies (which is known to be the case in the northern part of the caldera) then **FIGURE** Figure 11 indicates that intrusion have, mainly taken place within the inner caldera for the last tens of thousands of years. The absence of conductors in the transform graben indicates that intrusions are less favoured there. The reason for this is not clear.

The seismicity also indicates an anomalous structure within the outer caldera. Figure 4 shows that during the Krafla fires and more recently, the seismic activity is mostly within the inner caldera and west of it where it is transected by the transform graben. Figure 11 also shows the boundaries of the magma chambers (S-wave shadows) as mapped by Einarsson (1978 and 1991). It is seen that the up-doming of the conductor under Víti and Mount Krafla corresponds closely to the boundaries as defined by the S-wave shadow. The agreement is not as good for the western magma chamber. The S-wave shadow is shown to extend considerably to west of Leirhnjúkur and not as far to the north as the low resistivity anomaly under and to the north of Leirhnjúkur. This discrepancy might be due to lower spatial resolution of the S-wave shadow than in the MT data.

Figure 11 further shows the locations of some centres of uplift or subsidence (blue stars) estimated from ground deformation measurements during some inflation and deflation episodes in 1984 (Tryggvason, 1986). The deformation was consistent with a point pressure source at 2.6 km depth. Satellite Radar Interferometry, geodetic measurements and microgravity data show that the magma chamber(s) is deflating (Sigmundsson, 1997, Dalfsen et.al, 2005). The figure shows the estimated centre of subsidence (red star) that took place between 1992 and 1995 (Sigmundsson, 1997). Again the crustal deformation was consistent with a point sours at the depth of about 2.8 km.

The depth to the low resistivity bodies in the northern part of the inner caldera is about 2.5 km, in good agreement with the depth to the magma chamber(s) as estimated from ground deformation. The locations of the ground deformation centres seem to be in between and close to the southern edges of the S-wave shadows and the tops of the up-doming conductors. This might indicate that there is a structural weakness south of the magma chamber(s) and the uppermost two kilometres of the crust behave as a stiff plate on top of the magma camber(s).

The depth distribution of the earthquakes is consistent with the interpretation that the chimneys reflect very hot plastic or molten rocks. The earthquakes probably reflect where the overlaying geothermal system is mining heat from the rocks at the top of the heat sources.

As mentioned earlier, the three independent data sets considered here support each other remarkably well in consistently revealing anomalies within the Krafla volcano. These anomalies are most naturally explained by assuming some new geological features which are hardly or not visible on the surface. The data indicate that there is a buried inner caldera and a WNW-ESE oblique rift graben transecting both calderas. Both the inner caldera and the transform rift are filled with hyaloclastite and the covered with younger formations.

These studies therefore indicate that the geological structure of the Krafla volcano and its geothermal system is more complex than believed till now.

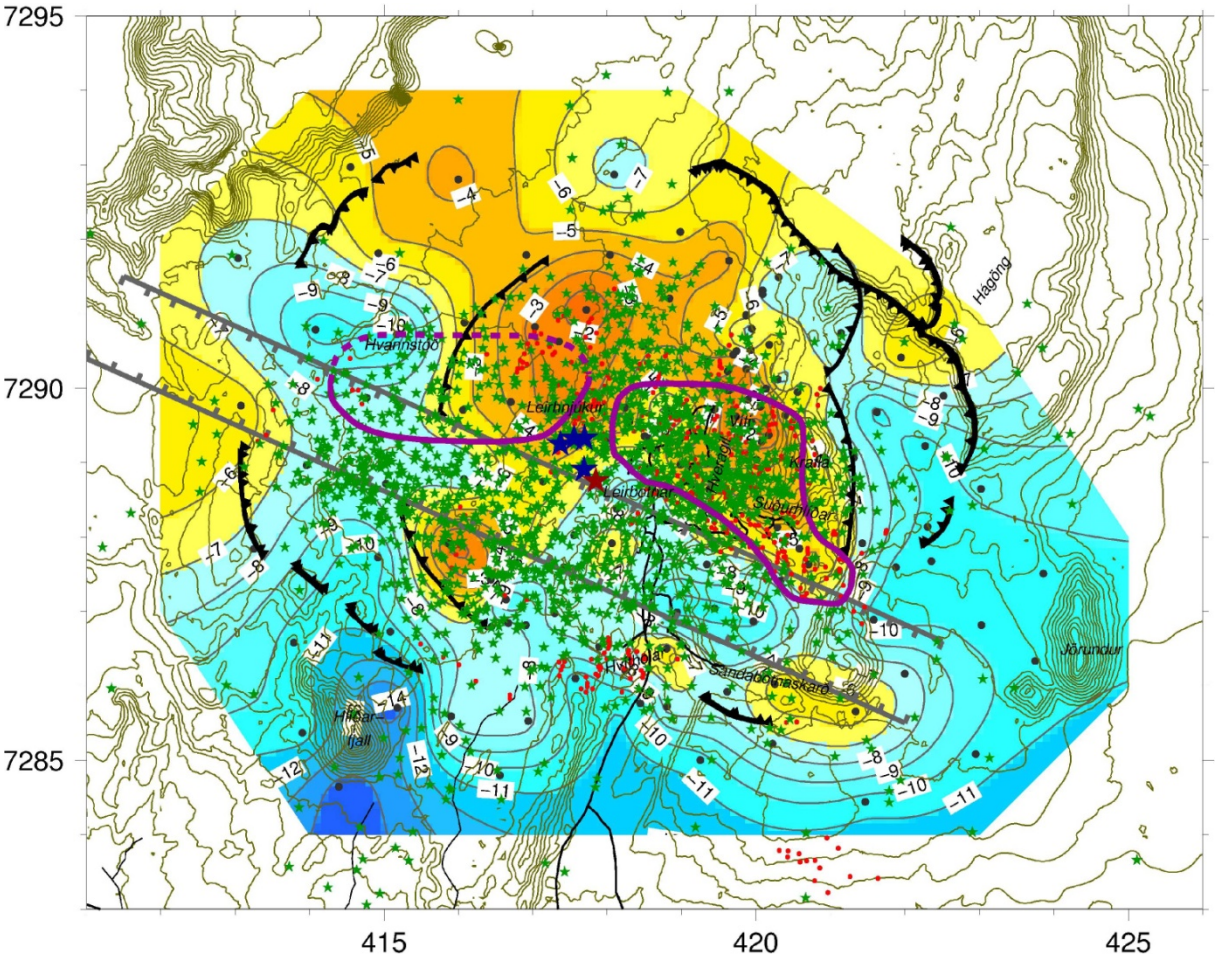

FIGURE 11: Elevation (km above sea level) of the top of conductors within the crust of Krafla, geological features inferred from gravity data (the inner caldera, black hedged lines and the oblique rift graben, gray fault lines), epicentres of earthquakes (green stars), boundaries of S-wave shadows (purple lines), centres of crustal deformation in 1984 (blue stars) and centre of subsidence from1992 to 1995 (red star)

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EAST-AFRICAN RIFT SYSTEM GEOLOGICAL SETTINGS OF GEOTHERMAL RESOURCES AND THEIR PROSPECTS

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1. INTRODUCTION

The geothermal areas of the East-African Rift System are not all of the same type. Even though related to the Rift the geological settings are different. Some are volcanic, and the volcanoes are different. Others are not volcanic. Parts of the rift zones are highly volcanic but large segments of them are sediment or lake filled grabens. Cases are also found where rift-related fractures produce permeability in basement rocks. In retrospect it may be useful to point out the differences and likely resource characteristics.

Below, the different types are described, and in which countries they occur as the dominant type. Most of those are genuine high temperature geothermal areas and they are accessible to a different degree. Others are high stratovolcanoes, difficult of access except in the off flow zone of the high temperature geothermal systems. Sedimentary basin type of low to medium temperature occur, and one of the low temperature type is related to fractured basement rock.

2. OFF MAIN RIFT VOLCANOES

Eritrea (Alid), Yemen (Al Lisi):

- Volcanic HT-systems probably over 260°C.
- Main resource at relatively high ground (Eritrea)
- Off flow to south? Perhaps suitable for binary.
- In case of off flow, temperature inversion likely.

Alid rather unique: uplifted ellipical block probably due to a silicic shallow intrusion. Later rhyolite flow(s) occur. The Alid dome is part of a larger volcanic centre.

Al Lisi: classical in structure; central volcano cut across by a fissure swarm; geothermal area within a collapse structure.

3. OCEANIC RIFT VOLCANOES (analog to black smokers)

Djibouti (Asal):

- Volcanic HT-system about 300°C.
- Recharge from sea water
- Probably a rather closed reservoir. Deposition of anhydrite from seawater clogs recharge pathways
- Steam zone likely
- Production from liquid-dominated reservoir may cause rapid drawdown and thickening of steam zone
- Utilization of steam zone and brine fluid.
- Close analogy: Reykjanes in Iceland.

4. OCEANIC TO CONTINENTAL RIFT VOLCANOES

Ethiopia (several), Kenya (several), Eritrea (Dubbi):

- Volcanic HT-systems. Many good prospects
- Some of the volcanoes in this category possess a volcanic shadow zone. This is a positive sign as regards a geothermal reservoir.
- Off flow possibly suitable for binary
- Sometimes at a fairly high relative altitude and hence great depth to water reservoir
- Question there about exploitation of steam on top of main reservoir?

5. RHYOLITE VOLCANOES

Olkaria is one of a few of its type among the volcanoes in Kenya. It is a rhyolite volcano with an extensive geothermal area. It has erupted rhyolite only, since far back in time. Basalts occur north of its volcanic shadow zone. Volcanic centres of this type host geothermal reservoirs of high potential. Other volcanic geothermal areas in the Kenya rift are not likely to equal Olkaria in power. Iceland has two examples among its active volcanic centres. One is Torfajökull which has been estimated by far the most powerful of the Icelandic geothermal areas (1000 MW for 50 years).

Other examples include Menengai with its voluminous ignimbrite sheets and post caldera acidic lavas. Ethiopia may have centres of this type, most likely in southern Afar near centre of domal uplift.

6. MAINLY SEDIMENT FILLED RIFTS

Kenya (Magadi, main part of Turkana), Uganda (central and north), Burundi.

- Possibility of medium-temperature geothermal systems, in faulted sedimentary rocks of variable permeability.
- Subordinate volcanism. Some dyking likely

7. DISTAL OFF FLOW FROM HIGH-TEMPERATURE SYSTEMS

Uganda (south), Burundi:

- Low- to medium-temperature (up to 160°C?) geothermal systems
- Bicarbonate waters likely.

- Dyking from distal volcanic centres probably not massive enough to constitute a heat source.

Research methods: Geology, hydrology, geochemistry, resistivity, shallow depth (800-1000 m) exploration wells

8. PROXIMAL OFF FLOW FROM HIGH-TEMPERATURE SYSTEMS

Tanzania (Rungwe), Congo, Rwanda (Virunga mtns):

- HT-resource present but difficult to access
- Only off flow with perhaps up to 150-200°C accessible
- Travertine sinters would indicate bicarbonate water
- Suitable for binary from temperature, but high carbonate content may in some cases pose a problem due to scaling
- Temperature inversion likely

9. FAULT CONTROLLED LOW-TEMPERATURE SYSTEMS

Zambia, Tanzania, Mozambique:

- Mostly low-temperature (<<150°C?) geothermal systems
- Suitable for binary if hot enough
- Other uses of low-temperature geothermal waters possible (Lindal diagram).

10. OCEANIC VOLCANOES, FRACTURE ZONE OR HOT SPOT RELATED

Comoros

- High stratovolcano may be inaccessible for drilling at a reasonably low level.
- Rock alkalibasalt? Are there silicic rocks too?
- Possibly warm or hot off flow towards north (La Grotta)
- Heat source at 1000-1700 m depth under La Grotta doubtful.
- Consider other interpretation: Perhaps low resistivity anomaly caused by reduction in permeability and alteration of glass (which would be abundant in submarine part of volcano) to smectite??

Don´t take all of the above for granted.
Make your own assessment with regard to possible flaws or ill founded statements.

11. FOR YOUR CONSIDERATION

11.1 A few general recommendations for geologists working in surface exploration of high-temperature geothermal prospects

Make a *hydrological study* of the field and its wider surroundings preferably a whole catchment. This should cover cold springs, streams, rainfall pattern, water levels in wells and any information about ground water movements. Define area of fumarolic activity where a boiling reservoir would exist underneath. Deep water hydrology will be reserved for reservoir people at later stages when deep wells are drilled.

Define the *volcanic system* (if there is one), its main volcanic centre and the fissure swarm which transects it. A high temperature geothermal reservoir if present is usually located in the area of highest volcanic production, the greatest rock variety and caldera if such has formed. Ring structures may extend far beyond caldera. Direct the exploration towards such volcanotectonic features. Locate secondary high volcanic production foci on the volcanic system. They may be of interest if the volcanics there are young and concentrated within a limited area.

In rift zone regime, take into account how the volcanic system which hosts the geothermal system developed with time. Try to find out the relative age pattern of the volcanics and follow this up by radiometric dating. There may be a focussed zone of intrusion (more or less stationary) which will cool off marginally in the direction of extension (minimum compression) with time.

11.2 Other issues

Western Rift is less endowed with geothermal than the *Eastern Rift.* This is evident from the less volcanic production of the Western Rift. Sediments form a larger part of the graben fill there and lakes occupy large segments of it. The rate of opening is probably also less. The Kenya rift is at the apex of a domal uplift (centred upon plume head) whereas the Western Rift follows its western margin.

The feeders of *explosion craters* may be good targets to drill into at depth. Recognize such as occur at low level of the ground (often with water in them). They are probably phreatic, i.e. conversion of cold ground water to steam upon contact with hot magma caused the explosivity. Hydrothermal explosion craters result from boiling of geothermal reservoir water if it finds access to a volcanic vent following an eruption. A distinction can be made by carefully searching the ejecta for hydrothermally altered rock fragments and thermal alteration in the surroundings would also be an indication that they are generated from geothermal steam.

An intensely fractured rift segment of a geothermal field may not be a good target because of high secondary permeability. This may provide a pathway for percolation of cooler ground water, i.e. a sort of drain leading away from the main reservoir. However, the temperaure of the water (if about 200°C) may be well suited for binary.

Hazard assessment was touched upon in lectures and discussions during the course. This may become an issue in future developments. As geology is concerned the hazards are volcanic (lava flows, ash flows, ash falls, mud flows), tectonic (fault movement) mass wasting (debris slides, mud flows), or flooding. In a highly volcanic area the geologist will be asked about the frequency and type of eruptions. For this it is necessary to study the most recent ashes and lavas, find suitable sections and material for dating. This is being done in Iceland and the Azores, probably also in SE-Asia. Don‘t forget, however, the time scale. It is very different for human live span on the one hand and geological processes of catastrophic nature on the other.

As regards choice of geothermal prospect the intensity, areal extent of thermal manifestations and chemistry of fumarole gases will always weigh heavily in exploration and decision. Hot spring areas may not be a good choice unless where silica sinter occurs and the water has high silica content. Therefore give due regard to *sinter deposits* if such occur. Avoid CO_2 rich hot spring areas depositing travertine unless you are looking for intermediate (possibly of use for binary?) or low temperature fields.