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Lectures on geothermal in Kenya and Africa

by

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LECTURES ON GEOTHERMAL IN KENYA AND AFRICA

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PREFACE

Kenya is the leading African country in geothermal exploration and development. Electricity generation from geothermal started in 1981 at the Olkaria I power station. In 2005 the installed generation capacity is 129 MWe, and the electricity production constitutes 11% of the total electricity production in the country. There is a plan to increase the generation capacity by 576 MWe by 2026. Behind all this is the Kenya Electricity Generating Company Ltd. (KenGen) and their very able staff.

The UNU Visiting Lecturer 2005 was Mr. Martin N. Mwangi, Chief Manager of KenGen´s Olkaria Geothermal Project, who is one of the leading geothermal experts of Africa. He received training in geophysical exploration as UNU Fellow at the UNU-GTP in 1982. With him came a geochemist (Mr. Zaccheus Muna) and a drilling engineer (Mr. Joseph Ng´ang´a). Including the trio from that vintage year in geothermal studies, a total of 37 Kenyans have completed the six months specialized training at the UNU-GTP. Of these, 33 have come from KenGen.

Martin gave an excellent summary of geothermal work in Kenya. In the first lecture (co-authored by Mrs. Martha Mburu, UNU Fellow 2003) he gave an update on geothermal development in Kenya and other African countries. In the second lecture (prepared by Mr. Mariita Bw´Obuya and Mr. Peter Omenda) he dealt with the history of development of the conceptual model of the Olkaria geothermal field by use of geophysics and other methods. In the third lecture (prepared by Mr. Cornel Ofwona, UNU Fellow 1996) he dealt with the response of the Olkaria reservoir to exploitation. In the fourth lecture (prepared by Mr. Godwin M. Mwawongo, UNU Fellow 2004) he dealt with the status of exploration and development of Kenya´s geothermal prospects outside Olkaria. In the fifth lecture (co-authored by Dr. Silas Simiyu, UNU Fellow 1990) he dealt with geothermal education in Africa, the past experience and future prospects. It was a great experience for the UNU Fellows to hear one of the leaders of geothermal exploration and development in Kenya describe the fruitful achievements which are so important for the Kenyan nation and the neighbouring countries. Martin is the fourth UNU Fellow who is invited to be the UNU Visting Lecturer.

Since the foundation of the UNU-GTP in 1979, it has been customary to invite annually one internationally renowned geothermal expert to come to Iceland as the UNU Visiting Lecturer. This has been in addition to various foreign lecturers who have given lectures at the Training Programme from year to year. It is the good fortune of the UNU Geothermal Training Programme that so many distinguished geothermal specialists have found time to visit us. Following is a list of the UNU Visiting Lecturers during 1979-2004:

1979 Donald E. White	United States	1993 Zosimo F. Sarmiento	Philippines
1980 Christopher Armstead	United Kingdom	1994 Ladislaus Rybach	Switzerland
1981 Derek H. Freeston	New Zealand	1995 Gudm. Bödvarsson	United States
1982 Stanley H. Ward	United States	1996 John Lund	United States
1983 Patrick Browne	New Zealand	1997 Toshihiro Uchida	Japan
1984 Enrico Barbier	Italy	1998 Agnes G. Reyes	Philippines/N.Z.
1985 Bernardo Tolentino	Philippines	1999 Philip M. Wright	United States
1986 C. Russel James	New Zealand	2000 Trevor M. Hunt	New Zealand
1987 Robert Harrison	UK	2001 Hilel Legmann	Israel
1988 Robert O. Fournier	United States	2002 Karsten Pruess	USA
1989 Peter Ottlik	Hungary	2003 Beata Kepinska	Poland
1990 Andre Menjoz	France	2004 Peter Seibt	Germany
1991 Wang Ji-yang	China	2005 Martin N. Mwangi	Kenya
1992 Patrick Muffler	United States		

With warmest wishes from Iceland
Ingvar B. Fridleifsson, director, UNU-GTP

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LECTURE 1

UPDATE OF GEOTHERMAL DEVELOPMENT IN KENYA AND OTHER AFRICAN COUNTRIES

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ABSTRACT

Prominent geothermal systems of Africa are associated with Great Rift Valley. It is one of the major tectonic structures on earth which extends for about 6,500 km from Lebanon to Mozambique. One of its most dramatic sections passes through East Africa, intersecting Kenya. The East African Rift starts from Djibouti crossing through 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. The North African countries including Egypt, Tunisia, Algeria, Libya and Morocco have low temperature resources not associated with the African Rift system. These resources have been used primarily for agriculture and bathing. Tunisia is the leader for greenhouse heating and irrigation.

Electricity generation from geothermal in Kenya started in 1981 with construction of Olkaria I station. The current output in Kenya is 129MW which is about 11% of the country's effective capacity. There is a plan to increase the generation by an additional 576MW by 2026. To achieve this, the government is in the process of establishing a special purpose company to concentrate on exploration and development of steam and heat for sale to generating companies and industrial processors. Efforts have also been increased in surface exploration and funds are being sought to drill exploration wells in more than five investigated fields. It is anticipated that the commencement of African Geothermal initiative (ARGeo) project together with other funding agents will assist in respect.

1. INTRODUCTION

Most of the East African countries rely on biomas 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. Djibouti and Eritrea depend on diesel generation entirely. With hydropower dominating the generation, these countries surfer 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. High fossil prices drain the merger foreign currencies which could otherwise be used to finance more required economic activities. This state of affairs subjects the countries to endless poverty.

Consequently, geothermal development can offer 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 and Ethiopia have so far produced power from their geothermal resources. In addition Kenya, Tunisia and Algeria have used geothermal for agricultural and recreational purposes. However, exploration for geothermal has been carried out to varied degrees in Djibouti, Eritrea, Uganda, Tanzania, Zambia and Malawi.

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. An example of such scenario was experienced in the year 2000. This affected the economy as industries suffered luck of electricity for long hours. 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. It is also anticipated that the commencement of African Geothermal initiative (ARGeo) project together with other funding agents will assist in development of the already proven geothermal resources i.e Olkaria IV, and Eburru, Suswa, Longonot and Menengai. This will result in huge savings normally incurred from use of fossil fuels as well as address the environmental issues. This paper gives the geothermal development update for Kenya and touches briefly on activities in several other African countries.

2. GEOLOGICAL BACKGROUND

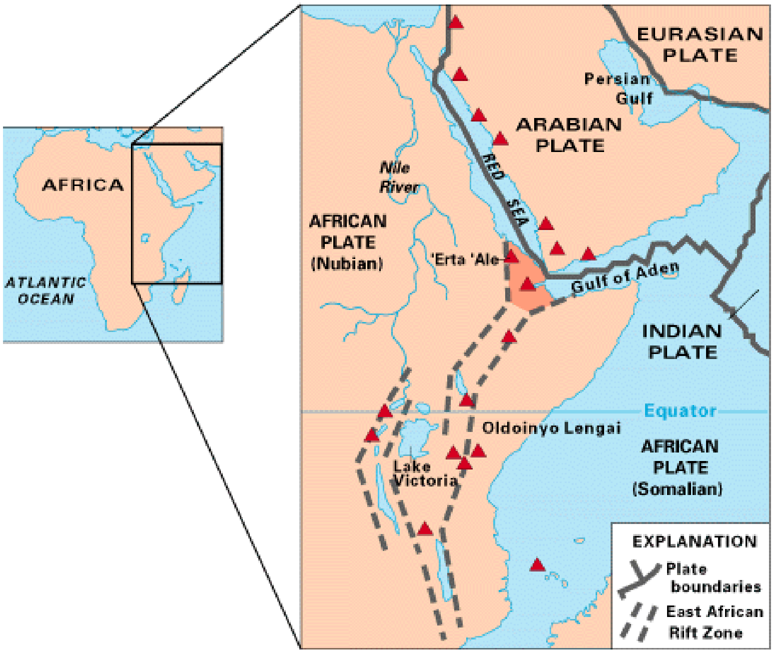

FIGURE 1: The East Africa rift system

Geothermal activities in Africa are concentrated in the East African Rift system (Figure 1). The East African rift system, is associated with the worldwide rift systems. It is a divergence zone which is still active. The rifting in the East African rift system has been associated with intense volcanism and faulting. A summarised structural sequence can be presented as follows:

- Domal uplift caused by convective currents accompanied by extensional crustal thinning;
- Down warping and major boundary faulting accompanied by powerful basaltic and trachy-

phonolitic volcanism;

- Closely spaced pararell faults across the whole width of the rift valley floor accompanied by volcanism of the trachytic ignimbrites.
- Faulting in a narrow central belt accompanied by intense central volcanic activity which gave rise to a number of calderas.

Volcanism associated with the central rift zone started in Miocene and continued upto the Late Pleistocene. The Late Pleistocene volcanism has a lot of significance for the geothermal activity in the central rift, in that it indicates the presence of at least partially molten chambers beneath the rift floor. The magma chambers are presumably the heat source for the geothermal systems in the rift valley (Nyambok, 1979).

3. GEOTHERMAL RESOURCES POTENTIAL IN KENYA

About fourteen (14) geothermal prospects have been identified in the Kenyan Rift valley (Figure 2). Their geothermal potential is estimated to be in excess of 2000 MWe. Wells have been drilled in only Olkaria and Eburru but exploitation so far has only been done at Olkaria geothermal field.

The Olkaria geothermal system

The Olkaria geothermal system is located on the floor of the rift valley about 120 km North West of Nairobi. The resource is associated with the Olkaria volcanic complex which consists of a series of lava domes and ashes, the youngest of which was dated at about 200 years ago (Clarke et al., 1990). The geothermal reservoir is considered to be bounded by arcuate faults forming a ring or a caldera structure. A magmatic heat source might be represented by intrusions at deep levels inside the ring structure. Faults and fractures are prominent in the area (Figure 3) with a general trend of N-S and E-W but there are also some inferred faults striking NW-SE. Other structures in the Olkaria area include the Ol'Njorowa gorge, N-S and NW-SE faults, the ENE-WSW Olkaria fault and WNW-ESE (Muchemi, 1999).

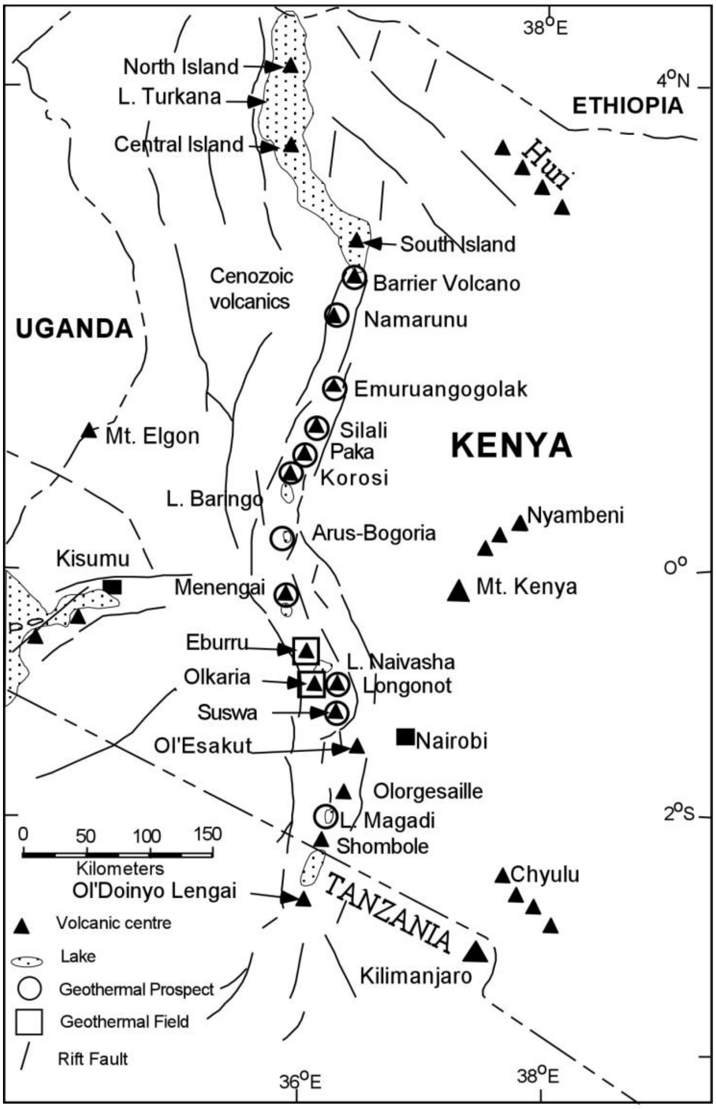

FIGURE 2: Geothermal prospects in the Kenyan Rift valley

Faults are more prominent in

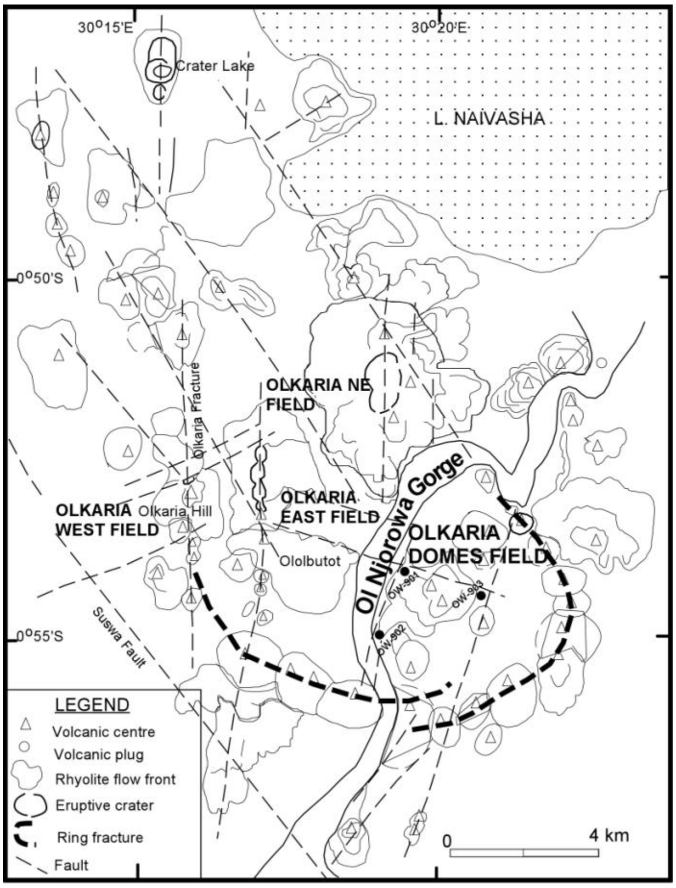

FIGURE 3: Volcano-tectonic map of Greater Olkaria geothermal complex

the Olkaria East, Northeast and West fields but are scarce in the Domes area, possibly due to a thick cover of pyroclastics. The NW-SE and WNW-ESE faults are thought to be the oldest and are associated with the development of the rift. The most prominent of these faults is the Gorge Farm fault, which bounds the geothermal fields in the NE part and extends to the Olkaria Domes area (Lagat, 1995).

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 (Figure 4). Currently, Olkaria East, and Olkaria Northeast Olkaria West and Olkaria Northwest fields are generating 129 MWe. In Olkaria Domes field, which is the forth field targeted for development, three exploration wells were drilled between 1998 and 1999 and plans for appraisal drilling are at an advanced stage. Exploration drilling has also been undertaken in the other sectors of Olkaria but has shown poor results.

Detailed surface exploration was concluded in Suswa and Longonot, Menengai, Lake Baringo and Lake Bogoria prospects and deep exploration wells sited. Surface exploration is about to commence at Korosi-Chepchuk area north of Lake Baringo. There is need to accurately assess power potential in all the remaining prospects within the Rift Valley in order to prioritise them for further development. More surface exploration work will therefore continue in the other prospects. A prioritization study of Suswa, Longonot and Menangai is being done in order to select the first field for exploration drilling.

4. GEOTHERMAL UTILISATION

4.1 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 (Figure 4) are generating a total of 129 MWe.

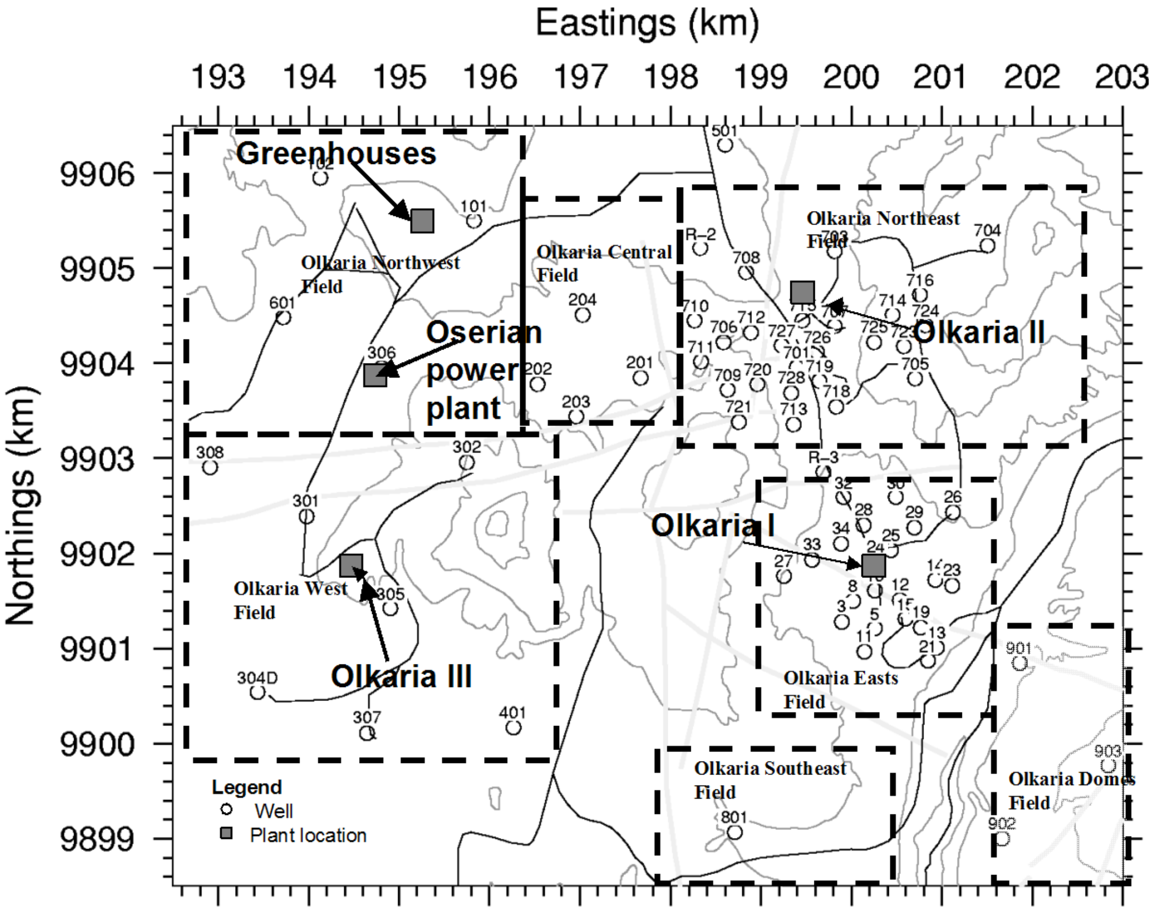

FIGURE 4: Olkaria geothermal area

4.1.1 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 twenty four (24) years. Olkaria East field, which supply steam to Olkaria I power plant has thirty three (33) wells drilled. Thirty one (31) of them were connected to the steam gathering system 9 of them drilled as makeup wells. Currently, twenty six (26) of them are in production while the rest have become non-commercial producers due to decline in output over time and some of these are earmarked to serve as reinjection wells. Currently, the steam available from this field is more than what is required to generate 45 MWe and studies are underway to determine the viability of increasing generation.

4.1.2 Olkaria II Power Plant

Construction of 2 x 35MW Olkaria II geothermal power station started in September 2000 was completed November 2003. The project which is publicly owned by KenGen also included construction of 116km of 220kV from Olkaria to Nairobi and 3.5km 132kV transmission line connecting Olkaria I and II stations.

The initial design had suggested 64 MWe but since the plant was built 10 years behind schedule, it took advantage of the latest technology. The plant is more efficient than the Olkaria I with a specific steam consumption of about 7.2 t/hr per MWe as opposed to the 9.2 t/hr for the Olkaria I plant. As a result of the efficient machines there is excess steam available in this field. Currently, KenGen is in the bidding process for the construction of a third 35MW unit to use excess steam from both Olkaria I and II fields.

4.1.3 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. The first phase of the project included drilling of appraisal wells and construction of a 12 MWe pilot plant. The first 8 MWe was put on commercial operation on September 2000 and the other 4 MWe in December 2000. The appraisal and production drilling commenced in February 2000 and was completed by March 2003, after drilling a total of 9 wells and adequate steam was proved for total development of 48 MWe over the PPA period of 20 years.

KenGen was contracted to do completion and heat-up tests in these wells. Both vertical and directional wells were drilled for appraisal as well as production with depth ranging between 1850 m – 2750m. To safe on the drilling cost, each group of three wells were drilled on one pad. Production success rate of 100 % was achieved from the new wells. The 36 MWe power plant is expected to be in operation 2007/8 (Reshef and Citrin, 2003).

4.1.4 Oserian plant

Oserian Flowers company has constructed a 2.0 MW binary plant Ormat OEC to utilise fluid from a leased well OW-306. The plant, which is supposed to provide electrical power for the farm's operations is was commissioned in July, 2004.

4.2 Direct uses

4.2.1 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 green house heating system in May 2003 using a 15MWt 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.

4.2.2 Swimming pool heating

Hot springs have been used to heat spas in tourist hotels for example in Bogoria hotel which is located near the Bogoria prospect

4.2.3 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.

5. FUTURE DEVELOPMENTS

5.1 Electricity generation in Olkaria fields

5.1.1 Olkaria I

The initial design of Olkaria I power plant and steamfield had proposed a life of 25 years. The units been in operation for the last 24 years. In one year's time, Unit 1 will have exhausted its initial design life. The current study shows that the plant and the reservoir are in good condition, and the reservoir is having more steam than is required to generate 45 MWe (Figure 5). KenGen is currently conducting an optimisation study of the field and plants to be completed in 2006 with a view to extending the life of the plant and steamfield and a possibility of increasing generation from this field.

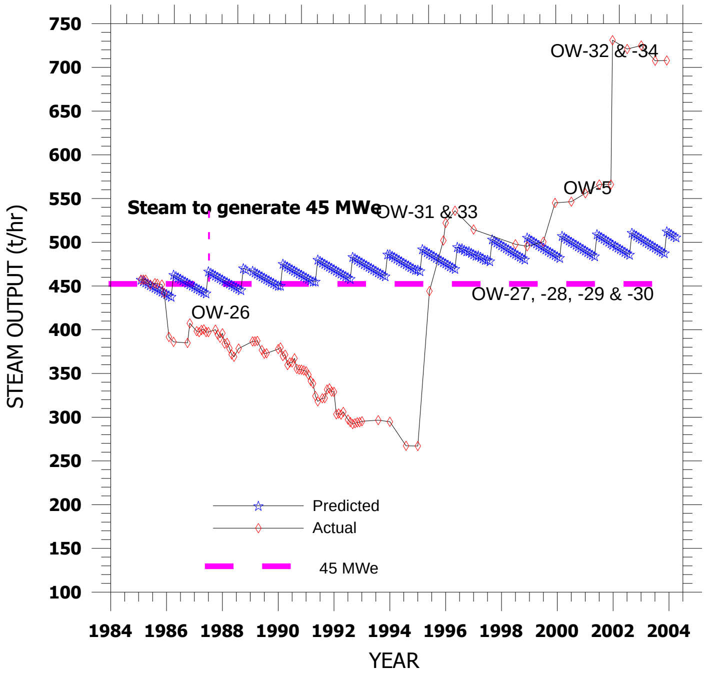

FIGURE 5: Steam output at Olkaria East field for 23 years

5.1.2 Olkaria II

Since the two turbines installed at Olkaria II plant are more efficient, there is excess steam at Olkaria NE field. A proposal to install a third unit of 35 MWe in Olkaria II to utilise the excess steam from Olkaria East and Olkaria Northeast fields is being evaluated. The funds are already available and the plant is expected to be commissioned in the year 2008.

5.1.3 Olkaria III

Appraisal and production drilling was completed in 2003 after which enough steam to generate 48 MWe over the next 20 years was proven. A 36 MWe plant in Olkaria III is was planned to be commissioned in 2006 (Reshef and Citrin, 2003). This target may however not be realised since todate, construction has not commenced.

5.1.4 Olkaria IV

KenGen drilled three deep exploration wells in Domes field between September 1998 and May 1999. This field is designated for development with expectation of generating 60 to70 MWe for 25 years and will be the site of Olkaria IV power plant. Plans are at an advanced stage to drill six (6) directional appraisal wells in this field.

5.2 Direct uses

Oserian Development Company, which is a flower growing company has realised to advantages of heating the greenhouses using geothermal brine in heat exchanges. Also, the carbon dioxide gas from the wells enhance 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.

5.3 Other geothermal prospects

A prefeasibility study for multiple use of geothermal for electricity generation and water production for agriculture and domestic use was carried out at Eburru geothermal field (WestJec 2003). The first phase of this project which is the construction of a 2.5MW binary plant is in the bidding stage and is planned to be commissioned at the end of 2006.

Detailed surface exploration work at Suswa, Longonot, , Lake Baringo and Lake Bogoria have been completed. The prioritisation of the Suswa, Longonot and Menengai is being carried out with the assistance of BGR of Germany.

6. STATUS IN OTHER AFRICAN COUNTRIES

6.1 Ethiopia

Ethiopia has actively been exploring for its geothermal resources since 1969 in the Ethiopian Rift valley. Over 16 high temperature geothermal potential areas have been identified with an estimated potential of about 700MWe (Tadesse and Kebede, 2002). A larger number of areas are potential for low temperature use in agriculture.

Exploration work in Aluto-Langano field culminated in the drilling of 8 deep wells (max 2500m) between 1981 and 1985. Four of these wells were productive. In 1998 an Ormat binary pilot plant with net output of 7.2 MWe was commissioned. However, due to wells and plant and management problems, the plant is not operational. Currently, Ethiopia Electricity Company (EEPCO) has contracted Geothermal Development Associates (GDA) to rehabilitate the plant.

During the early 1990s, three deep wells and 3 shallow exploration wells were drilled in Tendaho and encountered high temperature resource. Currently the wells are being tested with the aim of carrying out a feasibility study for development of a 5MW pilot plant. The plant will be developed under the ARGeo initiative (Teklemariam and Beyene, 2005).

There are other geothermal prospects which have either been studied to detail or reconnaissance including drilling of temperature gradient wells. These include Tulu- Moye and Corbetti, Abaya and also Dofan Fantale, Teo, Danab, Kone and others.

Ethiopia has also consistently trained it manpower and accumulated equipment for undertaking exploration work.

6.2 Djibouti

Djibouti is located at volcanically active triple junction of the Red Sea, Gulf of Aden and East African rift. It is characterized by high heat flow.

The geothermal potential of Djibouti has been estimated to be between 230 and 860 MW from Lake Abbe, Hanle, Gaggade, Arta, Tadjourah, Obock and Dorra (Mohamed , 2002). Geothermal investigations carried out from 1970 to 1983 identified Assal area as the most promising. Six exploration wells were drilled in the field which proved the existence of high temperature high salinity resource. The high salinity is associated with proximity of the resource to the Gulf of Aden. The salinity and potential scaling problems pose some development difficulties but which can be overcome. In addition, a long transmission line is required to the capital city of Djibouti which is the main demand centre.

In 2000, Geothermal Development Associates undertook a feasibility study with an intention of signing a PPA for a 30 MW plant. However, the deal fell through. Given that Djibouti depends on imported fuel for all its generation, there is every good reason to proceeding with this project. ARGeo is considering funding the services of a transaction adviser for this project.

6.3 Eritrea

Initial exploration work by UNDP in 1973 with a followup detailed survey by USGS in 1996 identified Alid as the most promising prospect in Eriteria for geothermal exploitation (Woldegiorgis et. al. 2002).

Alid is located about 120 kilometers south of Massawa, Eritrea's dominant port city and main thermal electricity generating center. Detailed geological studies indicate that a relatively young, large, shallow, and still hot magmatic heat source is probably present beneath the volcanic center in the northern Danakil Depression of Eritrea. Fumaroles and hot springs are widely spread. Geothermometer predict subsurface temperature in excess of 250°C. The resource has yet to be drilled.

6.4 Uganda

Uganda is endowed with high hydropower potential along the river Nile with the current installed capacity of 317MW. Unfortunately, hydropower development has met a lot of resistance from civil society due to its effects on environment. As a result of this and the growing demand of power estimated at 7.4% per annum (Bahati and Tugume, 2005), Uganda is seriously considering the development of other alternative sources of energy.

Although reconnaissance survey has been carried out on geothermal areas of Uganda since 1935 and later during UNDP programme, no power generation has been achieved todate. UNDP project has estimated the countries potential to be about 450MW. More recent studies have concentrated on three geothermal systems of Buranga, Katwe and Kibiro. These prospects are located in the active volcanic belt in the western Rift valley along the border of Uganda and Democratic Republic of Congo. The African Development Bank with the Uganda Alternate Energy Resource Agency (UAERA) conducted research at Katwe, Buranga and Kibiro. Also, the government of Iceland conducted a geophysical study at Kibiro Geothermal prospect area and is planning to cover the Katwe and Buranga as well. Kibiro has been advertised for international bidding for drilling temperature gradient wells to assist in locating deep exploratory wells.

6.5 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 the financial support of the Swedish International Development Authority (SIDA). Reconnaissance studies of surface exploration were carried out in the north (near Arusha, Lake Natron, Lake Manyara and Maji Moto) and in the south (Mbeya region). At least fifteen (15) thermal areas with hot (T>40°C) spring activity have been identified. However, the geothermal work in all locations 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 (a local firm) by analyzing wells drilled for petroleum exploration. 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 occurrence of significant potential (> 200 °C) for the existence of a geothermal resource.

6.6 Zambia

Zambia has over 80 occurrences of hot springs of which Kapisya and Chinyunyu have been identified for development of power generation.

In 1986, Zambian Geological survey in conjuction with DAL, SpA (Italy) determined that the hot springs in Kapisya were favourable for commercial power generation and a pilot plant was installed at Nsumbu on the shores of L. Tanganyika funded by the Italian government. The plant uses a total of 15 shallow exploratory wells, four of which have submersible pumps. The plant also has two Organic Rankine Cycle (ORC) turbogenerators with a nominal capacity of 200 kW. The project was based on insufficient information and never became operational because the resource temperatures were found to be too low (maximum 85°C). Zambia Electricity Supply Company (Zesco) has approached KenGen for assistance with the rehabilitation of the Kipsya plant after 15 years of being idle.

There are also plans to develop a power plant to provide electricity to the local community at Chinyunyu hot springs located 50 km east of Lusaka. The Japanese International Cooperation Agency (JICA) in conjuction with the Zambian Geological survey undertook this project and has not progressed due to lack of funds (Musonda and Sikazwe, 2005).

6.7 Tunisia

Tunisia has mainly low enthalpy geothermal resources located in the southern part of the country at Kebili, Gabes and Tozeur. This is a large acquifer with relatively hot water 30-75 oC that extends to Algeria and Libya. In Kebili area about 16,000 hectares are irrigated by water cold in towers and cascades ponds. In 1986 Tunisia started utilising the hot water from boreholes for heating greenhouses at night when the temperatures are low and currently 110 hectares are being heated for growing cucumber, watermelon, pepper and tomatoes (Mohamed, 2005). After heating the greenhouses the hot water is further cooled down for irrigation purposes.

The use of “hamams” for bathing to cure diseases and recreation has been going on in Tunisia for thousands of years. It is also used for tourism, washing clothes and for animal husbandry. The resources are estimated at 4850 l/s for heating about 300 hectares.

6.8 Morocco

Geothermal exploration work in Morocco started way back in 1970. The work mainly involved determination of chemical composition and temperatures of thermal spring and borehole. Hydrogeological characteristics of aquifers has also been carried out. The presence of thermal springs and elevated temperature gradient is an evidence of geothermal activity in this region.

6.9 Algeria

The geothermal exploration program in Algeria started in 1967 and was undertaken by the national oil company (SONATRACH). In 1982, the electricity company, SONELGAZ, in association with an Italian company, ENEL undertook geothermal studies in the northeastern part of the country. From 1983 to present, geothermal work is being done by Renewable Energies center, CDER and the programme has been extended to all the northern part of the country.

The geothermal exploration in Algeria has proven a low enthalpy geothermal potential. Geothermal utilization mainly include therapeutic purposes and few experimental greenhouses located in Touggourt and Ouargla in the southern Algeria which utilise geothermal water at 50°C.

7. DISCUSSION

Due to unreliability of hydropower during prolonged dry seasons, many countries in Africa which rely heavily on hydropower have been forced to use expensive and environmentally unfriendly fossil fuels. Exploitation of the large geothermal potential can make geothermal energy the leading source of electrical power and hence avoid such negative effects in future as well as safe on fuel imports. At Olkaria for example, over 84,800 GWH have been generated from geothermal resulting to a saving of over US$ 4.9 billion in foreign exchange. More attention should therefore be focused in the development of this resource.

The acceleration of geothermal power development has been hampered by lack of funds. The Olkaria II power plant, for example, was supposed to be commissioned in early nineties but it did not until 2003, about ten years later. Building of the plant started in 2000 and was commissioned in 2003. The initial plans were to have the plant in two years but it ended up taking more than 3 years because of the funding problems. More power plants were expected to be commissioned by this time but this has not been possible. There is however more commitment from the government since the beginning of 2003 to accelerate geothermal development by providing funds from the exchequer to conduct surface exploration and appraisal drilling.

The future of geothermal energy in Kenya and other African countries is bright. In Kenya for example, there is fresh commitment from the government to exploit this resource. In the next several years, it is believed that massive exploration drilling will be undertaken in Suswa, Longonot and Menengai prospects where detailed information is already available. A new company, Geothermal Development Company (GDC) is in the formation to be dedicated for geothermal exploration drilling and sale of steam and heat. In addition, a new funding initiative known as African Geothermal Initiative (ARGeo) has been established to assist the Eastern African countries with geothermal potential to accelerate the development of this resource. The initiative plans to pool together upto US$250million dollars to be used for the establishment of a regional resource centre, manpower development, surface exploration and risk guarantee fund for exploration and appraisal drilling and promotion of private participation. The initiative has been initiated by the United Nations Environmental Programme (UNEP). The Global Environment Fund (GEF) and Kreditanstalt fur Wiederaufbau (KfW) together with other international agents are funding the projects. The recipient countries will be expected to contribute either financially or in kind. Projects will be implemented in collaboration with national institutions in the region. Kenya will be among the countries to benefit from this initiative with Djibouti, Eritrea, Ethiopia, Tanzania and Uganda.

Use of Geothermal energy in Kenya is almost entirely for electricity generation. There is very little application of direct uses of geothermal energy in Kenya. Applications of this resource for example in swimming pools and Spas, balneology, drying of farm produce and greenhouse heating will be encouraged through GDC. Other African countries with low enthalpy geothermal potential can leap huge benefits by using it for direct uses as is the case in Tunisia.

The performance of some of the earliest geothermal fields in the world show that with good reservoir management practices, a geothermal reservoir is sustainable. Also with good maintenance practices, some power plants have been is relatively good condition after being in operation for over 50 years. For example, Wairakei in New Zealand has been in operation since 1958.

8. CONCLUSIONS

Given the frequent drought that affect the hydropower, variation of fossil fuel prices in the world market and the rapid increase in demand for more power, geothermal offers an indigenous environmentaly friendly alternative to some Eastern African countries. The slow development of geothermal resource has been due to lack of knowledge, availability of cheap hydropower and lack of funds and manpower. The success achieved in Kenya and the large geothermal potential of upto

7000MW in the Eastern Africa rift system, should motivate other countries in the region to pursue this development. Initiatives like ARGeo and other donor funding agencies augmented with local funding under the global framework of renewable resources and climate change will see accelerated development of geothermal resource development. Manpower development will also play an important role in getting the job done.

Creation of a special purpose geothermal development company by the government will be a useful milestone in geothermal energy exploitation and is expected to accelerate geothermal development in Kenya to achieve the least cost development plan.

Commercial direct uses of geothermal energy should be encouraged in countries with low enthalpy resources. For example Oserian Development Company, Kenya, a flower growing company has benefited from the use of geothermal heat leased from KenGen for heating their green houses. As a result several flower growing companies in Kenya have requested KenGen to look into possibility of providing hot water for this use. Tunisia also uses geothermal water to heat the greenhouses for growing cucumber, watermelon, pepper and tomatoes.

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LECTURE 2

HISTORY OF DEVELOPMENT OF THE CONCEPTUAL MODEL OF OLKARIA GEOTHERMAL FIELD BY USE OF GEOPHYSICS AND OTHER METHODS

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ABSTRACT

Olkaria Geothermal field is a high temperature geothermal resource in the Kenya Rift Valley, which has been used for electricity generation since 1981. The geothermal resource is associated with an area of Quaternary volcanism in which rhyolites dominate. Geophysical exploration for the resource during the early stages of development included dipole, Schlumberger, electromagnetic, head-on, gravity, seismic and magnetics and various levels of success were achieved. It was noted that whereas resistivity was the most important in identifying the reservoirs, depth of penetration was low for dipole and Schlumberger while interpretation of head-on data was ambiguous. Latest investigations at Olkaria have involved the use of transient electromagnetics (TEM) and magnetotellurics (MT) due to their ease of deployment and better depth of penetration than the other resistivity methods. The results of the studies indicate that the Olkaria geothermal system is controlled by rift structures where upflow zones are at fault intersections while N-S and NW trending faults are mainly recharge paths. Gravity, seismic and MT data indicate that the heat sources for the system are discrete shallow magma intrusions located under the main upflow zones.

1. INTRODUCTION

Olkaria Geothermal field is located within the central Kenya segment of the East African Rift System. The geothermal area is characterized by Quaternary volcanism of silicic composition of which the youngest is of Holocene age. The rock outcrops are dominated by comendite rhyolites and pyroclastics while in the subsurface are trachytes, basalts, rhyolites and tuffs. Geothermal manifestations include fumaroles, hotsprings and hot grounds. Exploration for geothermal resources in Kenya started in 1950's with mainly geological investigations in the region between Olkaria and Lake Bogoria in the north rift. The exploration resulted in the drilling of two wells X-1 and X-2, which encountered high temperatures at depth. The exploration then gained momentum with support of the United Nations Development Programme (UNDP), which saw more extensive geophysical investigations undertaken and additional wells drilled between 1973 and 1980.

The geophysical studies included gravity, various resistivity techniques (dipole, Schlumberger, electromagnetic, head-on), magnetics and seismics. The activities resulted in the construction and commissioning of Africa's first geothermal power plant at Olkaria with 45 MW capacity between 1981-1985. Changes in technology saw 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 better geothermal models developed.

The Olkaria geothermal system currently has three operating power stations (45 MW Olkaria I, 70 MW Olkaria II, 13 MW Olkaria III and 2.0 MW Oserian plant) and a greenhouse-heating project is utilizing one of the wells at Olkaria.

2. GEOLOGICAL SETTING

Olkaria geothermal system is located just to the south of Lake Naivasha in the Kenya Rift valley. The formation of the Kenya rift started about early Miocene in the north and about middle to late Miocene in the central segment. 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. On the floor of the rift axis were erupted major central volcanoes and volcanic complexes of which Olkaria is one (Figure 1).

The Olkaria volcanic complex lies on the axis of the rift but with a bias towards the Mau escarpment. The rock outcrops is dominated by rhyolite flows and pyroclastics of which the youngest is the Ololbutot rhyolite obsidian flow that erupted at 180 ± 50 yr BP (Clarke et al., 1990). The landscape is also dotted with volcanic centres (Figure 1). Fault systems at Olkaria are dominantly in three directions: NW-SE, N-S and NE-SW. The latter two are younger and have affected even the Holocene flows while the NW trending faults are older and often associated with the rift graben formation. They are more common in the west where the field merges into the Pliocene Mau escarpment.

In the sub surface, the volcanic complex has been divided into east and west with the divide being the fault zone that runs through Olkaria Hill (Omenda, 1994, 1998). The lithology in the western sector is dominated by Mau Tuffs but minor trachytes, rhyolite and basalt occur within the formation (Figure 2).

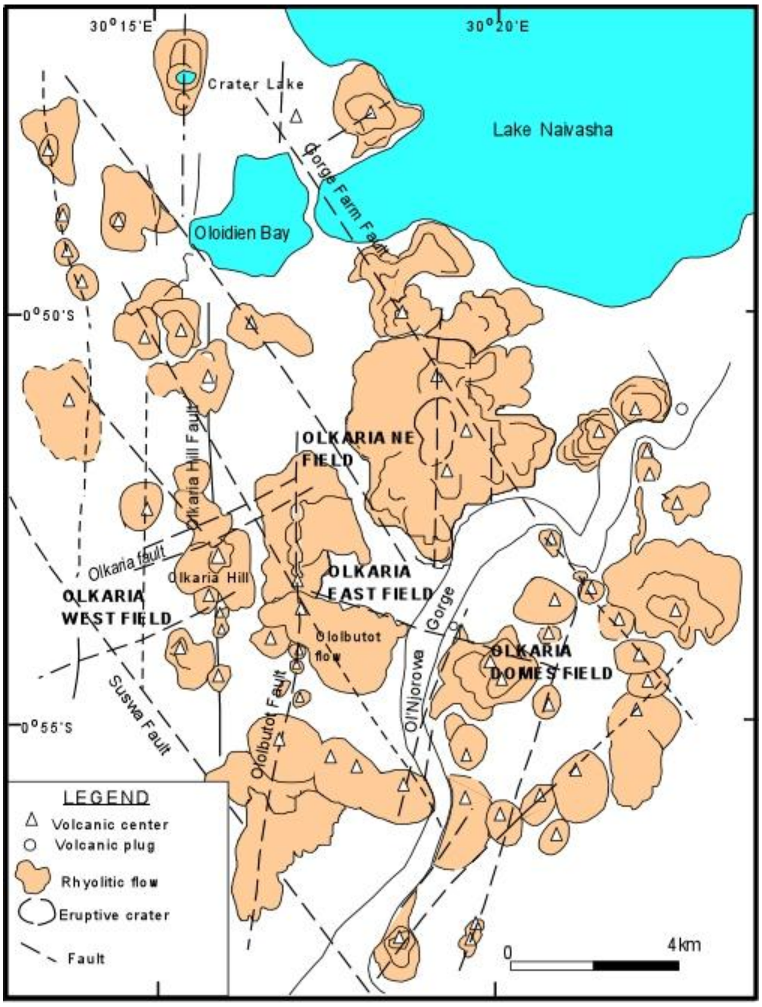

FIGURE 1: Geological map of the Olkaria volcanic complex

It has been projected that the formation is more than 5km thick. In the eastern sector, flood trachytes overlie the Mau Formation and were erupted onto a graben floor and have a thickness of more than 1,500 m (Omenda, 1998). Above the trachytes occurs basalt-pyroclastics formation, which is also thought to be cap-rock for the East and NE fields. Quaternary rhyolitic lavas and pyroclastics dominate the upper formation in the entire area from the West field to the eastern fields. Then thin layer of surficial pyroclastics are eruptives from mainly Longonot volcano located in the east.

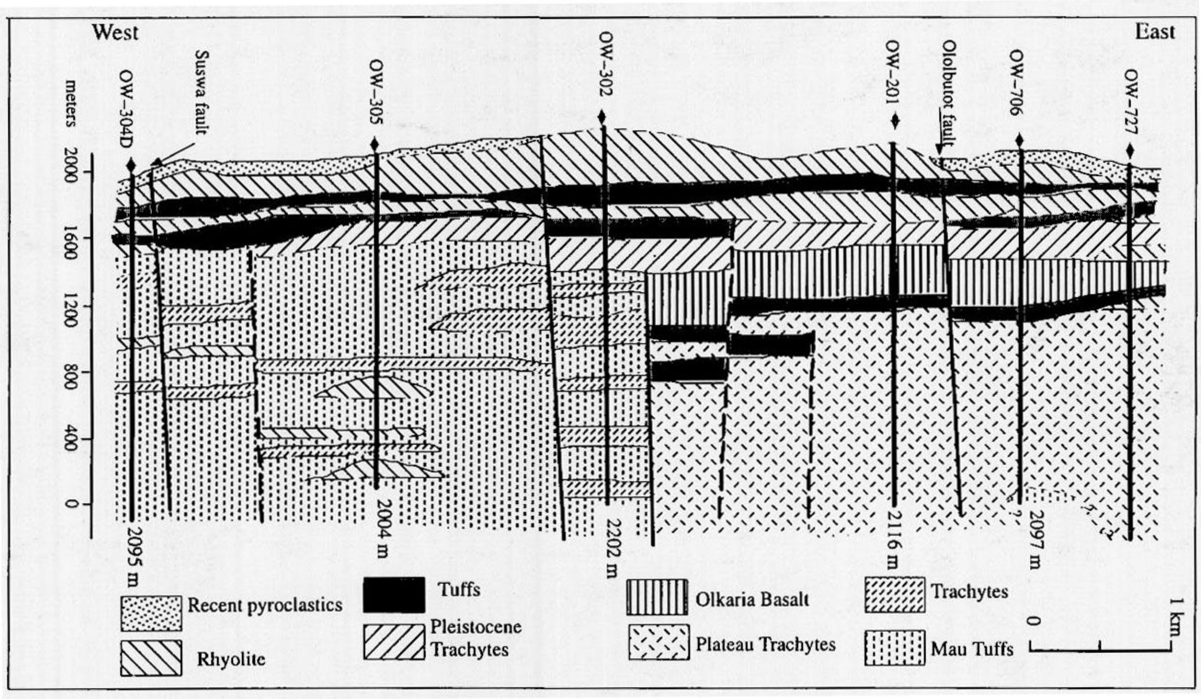

FIGURE 2: Geological cross-section through Olkaria geothermal field (from Omenda, 1998)

3. GEOCHEMISTRY

About 96 deep wells have been drilled in the entire Olkaria geothermal field and most of which the reservoir fluid and gas have been sampled and characterized. Results indicate that the Olkaria geothermal reservoir varies between the sectors in an E-W pattern in line with the main geological division of the field along the Olkaria Hill fault. Wells in the West Field (OWF) discharge H_2CO_3 fluids with carbonate content of over 10,000 ppm, which increases westward. The field has low chloride, typically 50-200 ppm but the Cl contents increase towards the Olkaria Hill (Figure 3). In the NE field (ONEF), the fluids are neutral NaCl with Cl contents of 400-600 ppm and H_2CO_3 contents of <1000 ppm. Initial fluid discharge from the Olkaria East Field (OEF) was of neutral NaCl with Cl and H_2CO_3 contents of 200-350 ppm and <200 ppm, respectively. The Olkaria Central field (OCF), which lies between ONEF and OWF discharges mixed NaCl and H_2CO_3 fluid with Cl contents generally within 200-300 ppm while H_2CO_3 is over 5,000 ppm but increasing westward (Figure 4).

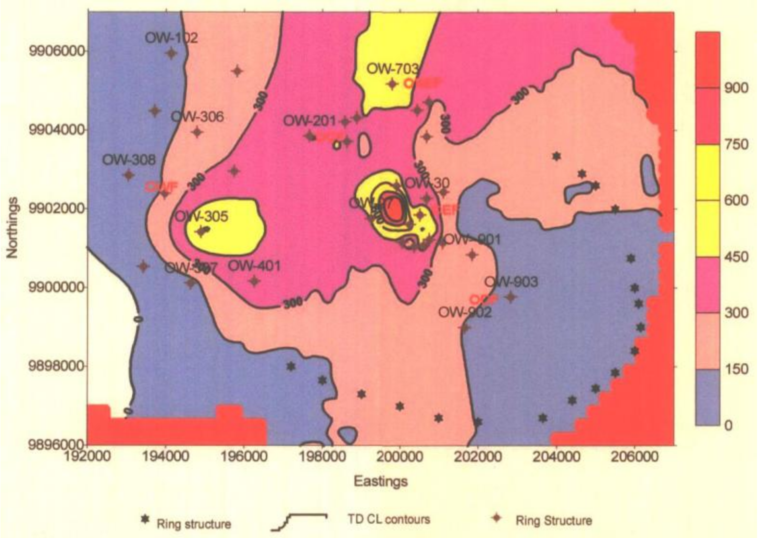

FIGURE 3: TD chloride plot for Olkaria field

Three wells drilled in the Olkaria Domes field (ODF) tapped chloride – bicarbonate – sulphate fluids with Cl and bicarbonate contents of 180-270 ppm and >2,000 ppm, respectively. However, Karingithi (1999) postulates that these might not be the deep reservoir fluid as shallow fluids have modified the fluid discharged by well OW-903. The CO_2/H_2S ratio, which is often used to determine proximity to upflow regions, indicates low values for most parts of ONEF and OEF fields but very high values in the OWF. H_2 gas in steam generally follows the same pattern with low values in the OWF and ODF.

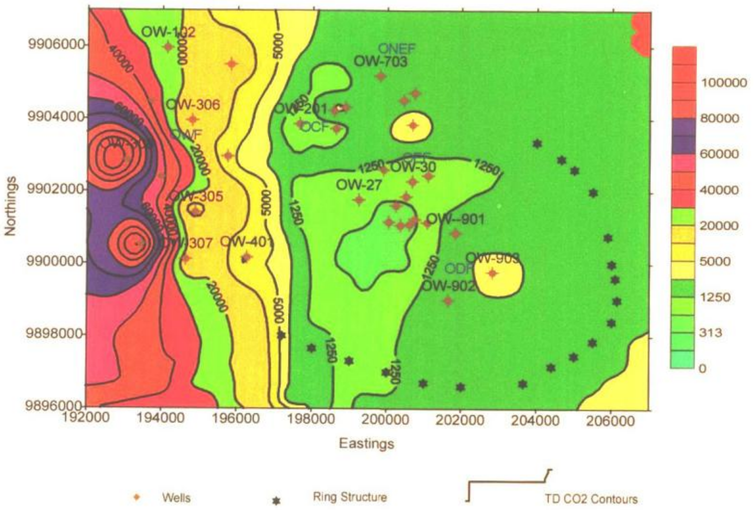

FIGURE 4: TD CO_2 in Olkaria field

4. RESERVOIR CONDITIONS

Analysis of stable well temperatures reveals high temperatures in OEF, ONEF, ODF and OWF fields with the highest measured temperature of 343°C occurring in ODF. Most wells in these fields show increases in temperature with depth except at the margins of the fields where lower temperatures have been recorded (Figure 5). Low temperatures and temperature inversions with depth occur within the Olkaria Central field. Pressure distribution in Olkaria shows high-pressure zones in OWF, ODF and ONEF and decreases towards Olkaria Central field (Figure 6). In OCF, ODF and ONEF, pressures decrease southward. Results of numerical simulation indicated that the permeability thickness product for Olkaria wells varies between 1.4 and 10 Darcy metres but with an average of 3.0 (Bodvarsson, 1993).

The upper part of the Olkaria reservoir is two-phase vapour dominated while the lower reservoir is water dominated. The temperature and pressure distribution in Olkaria follows structural patterns such that the Olkaria fault is major upflow zone while most of the NNE and NW trending faults are channels for cold-water inflow into the reservoir (Figure 5 and 6). Whereas chemistry suggests that the OCF could be a zone of mixing of fluids from OWF and ONEF, the Ololbutot and Olkaria Hill faults are major hydrological barriers limiting E-W fluid flow but promoting southward flow in the OCF region.

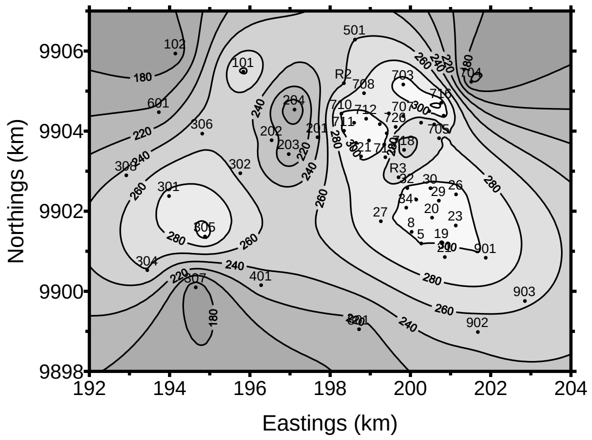

FIGURE 5: Temperature distribution at 500 m a.s.l.

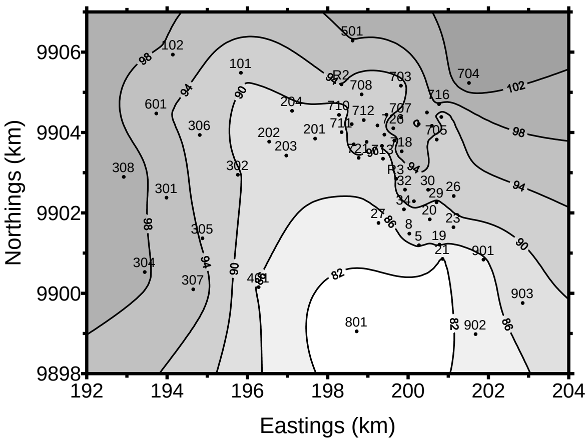

FIGURE 6: Pressure distribution at 500 m a.s.l.

5. GEOPHYSICS

A wide range of geophysical surveying methods has been employed at Olkaria over the years including seismology, resistivity, gravity, magnetics and electromagnetic (Mwangi, 1984). Various levels of success have been achieved with each of the techniques as described hereunder.

5.1 Seismology

The earliest seismic investigation in Olkaria involved passive and active source seismic studies and was undertaken by the United States Geological Survey using an eight-station network (Hamilton *et al.*, 1973). A 2-year seismic monitoring program was then carried out in Olkaria between 1996 and 1998 (Simiyu, 1999; Mariita, 1995; Mariita *et al.*, 1996; Simiyu et al., 1998a, 1998b). 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. During this period more than 4,800 local earthquakes originating within the study area (t_s-t_p<3 sec) were recorded (Figure 7).

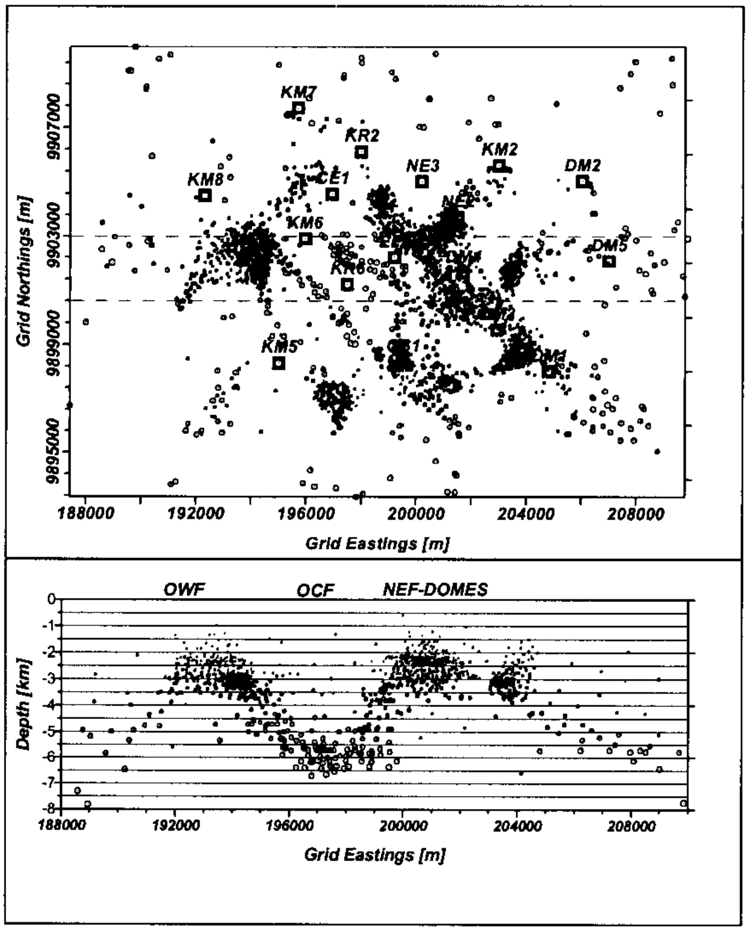

FIGURE 7: Micro-earthquake event locations around Olkaria; thick square boxes represent the locations of seismic receivers

The results also show that seismicity is more intense in the centre of the field where smaller and shallower events were recorded. On the periphery and outside of the field, events are larger and deeper. However, outside of the geothermal field, earthquakes deepen to the west, north and east away from the centre of the geothermal system (Figure 7).

Seismic gaps were mapped within the Olkaria field and found to mark zones of hot magmatic intrusions under Olkaria Hill, Domes field, and NE field near Gorge Farm centre at depths of 6-18km. Simiyu et al. (1998) used seismology to determine fluid flow patterns in the field. Low Poisson's ratio in the Olkaria West, NEF, OEF and ODF indicated zones of hot fluid upflow while high Poisson's ratio determined for OCF and western OWF indicated that the regions are fluid dominated and are possible recharge zones.

5.2 Resistivity

At Olkaria, direct current resistivity methods have been used for reconnaissance mapping, location of faults for drilling targets and to define the boundaries of geothermal reservoirs. The methods previously applied include dipole, head-on, Schlumberger, electromagnetic, Transient Electromagnetic (TEM), and Magnetotelluric (MT). In recent years, however, we have favoured sounding methods.

5.2.1 Dipole

Group Seven (1972) undertook the earliest comprehensive resistivity investigations in Olkaria. The methods they employed included dipole, Schlumberger, and EM methods. In the dipole technique they used 3 roving dipoles and constructed apparent resistivity and conductance maps for the Olkaria area. Whereas the method had a shallow depth penetration of less than 500m, low resistivity was detected in West Olkaria (5-20 Ωm) but relatively higher resistivity in the Northeast and East fields.

More extensive dipole-dipole survey was undertaken by the Kenya Power Company in 1973/74 with dipole lengths of 250 m. Dipole-Dipole apparent resistivity maps produced for various n sizes revealed a large area of low apparent resistivity with sharp boundaries (Noble and Ojiambo, 1975; Ross *et al*., 1979; Hochstein *et al*., 1981 and Mwangi, 1983). Their results also indicated that the technique is not appropriate for the deep Olkaria reservoir since it is severely influenced by near surface resistivity structure.

5.2.2 Schlumberger array

Since the early seventies a large number of Schlumberger vertical soundings have been carried out at Olkaria. Group Seven (1972) collected and modelled 21 Schlumberger sounding data in Olkaria with a view to exploring the resource potential in the area. The array was set with maximum spacing of 1 km and concentrated in the centre of the field in the vicinity of wells X-1 and X-2. Re-interpretation of these data in the early eighties (Hochstein *et al*., 1981; Mwangi, 1984b) indicated that the soundings had shallower penetration and so relatively higher resistivities were measured leaving undetected the main conductive part of the resource deeper down.

Later, in the early 1990's, improved Schlumberger equipment and longer cables were acquired. These increased the probing depth considerably. It was now possible to investigate depths down to 2 km. Interpretation of the new data indicated that the Olkaria area is divided into two regions with markedly different resistivity structure by a north-south discontinuity, which relates to deep fault structures (Onacha, 1993). However, towards the end of the 1990's, the method was discontinued in favour of Transient Electromagnetic method due to the elaborate logistics required.

5.2.3 Electromagnetics

Group 7 (1972) carried out 43 electromagnetic soundings in Olkaria using off set distances of 4-7 km providing penetration of 2-3 km. Their results indicated that the method had better depth penetration than Schlumberger and dipole arrays. With electromagnetics a low resistivity anomaly was detected to depths of between 1500-2100 m. The survey indicated that a low resistivity layer of 8 to 20 Ωm and 1 to 2 km thickness exists beneath the Olkaria area and that this layer increases in thickness and depth to the west of Olkaria Hill.

5.2.4 Head-on resistivity

In 1982 it was proposed that the head-on resistivity method be tried in Olkaria to see if it could be of any value in providing detailed information about the location and angle of dip of the fault zones to assist in siting of wells. Similar work in China had been successful in locating and determining the dip of conducting zones. Mwangi (1982) carried out numerical modelling of head-on resistivity data using Schlumberger data as constraints for near surface resistivity structures. Results from this work showed that there can be considerable ambiguity in modelling head-on data, especially in the quantitative determination of the angle of dip and extent of narrow conductive features. The size of the electrode arrays used limited reliability of the information gathered to depths of between 200 and 400 m.

Though it was possible to model vertical conductive features, possibly relating fault zones, it was difficult to isolate the cause of particular head-on resistivity anomalies to provide the resolution required to locate the fault zones for the siting of wells.

5.2.5 Transient electromagnetic methods - TEM

Use of TEM method started at Olkaria in the 1990's and our experience is that it gives better resolution with depth than the Schlumberger method. However, for the Olkaria situation the depth of penetration of TEM is limited to about 700 m depths depending on the resistivity structure of the location. 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 using an ungrounded loop of wire measuring 300 m x 300 m square. The data collected, processed and plotted in apparent resistivity maps in form of contours at various elevations (Figure 4). 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 areas with resistivity value of less than 15 Ωm at an elevation of 1400 m a.s.l. (Figure 8).

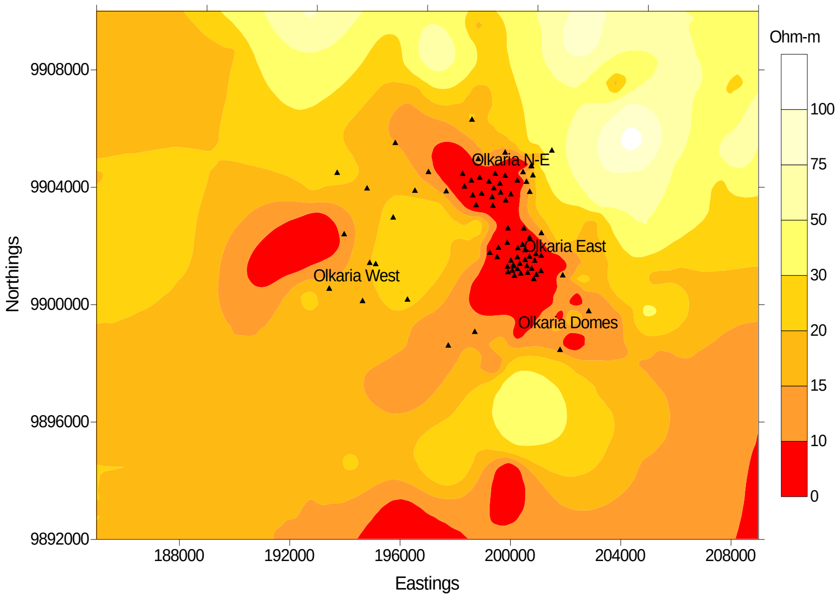

FIGURE 8: Resistivity distribution at 1400 m a.s.l. from TEM measurements

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 between the areas 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).

5.2.6 Magnetotellurics - MT

The Magnetolluric resistivity technique is the latest method that has been acquired for geothermal exploration in Kenya. The method has gained favour than other resistivity techniques since it probes deeper. The method is usually employed together with TEM, which provides shallow depth component and serves to assist with MT static shift correction. Analysis of MT data from Olkaria indicates the presence of significantly enhanced conductivities below ODF, OWF and OEF (Figure 9). The deep anomalies have been associated with possible heat sources for the geothermal systems.

5.3 Gravity

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 downthown the Mau Formation to more than 3-km in the eastern area (Omenda, 1994, 1998).

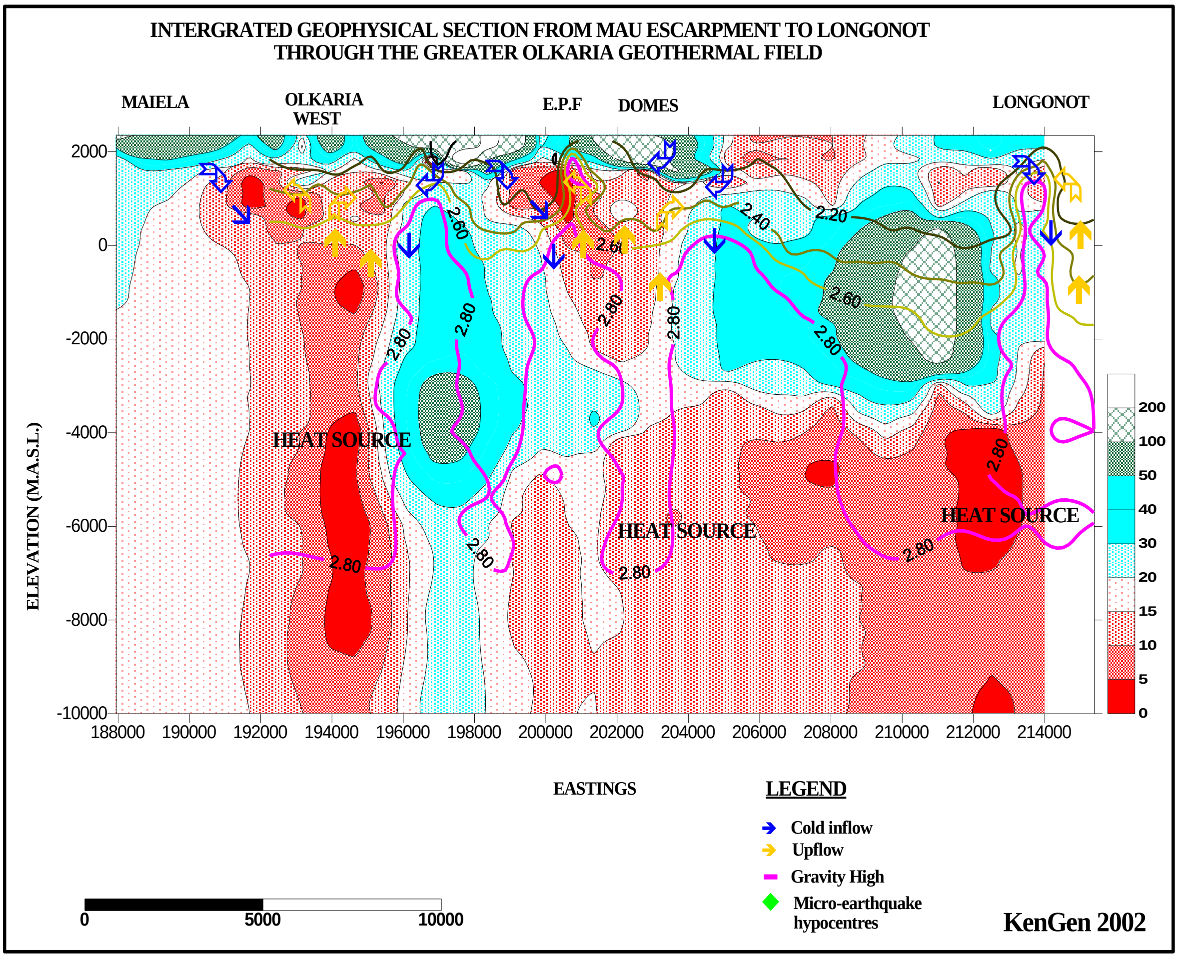

FIGURE 9: Combined MT and TEM resistivity distribution across Olkaria geothermal field (Onacha, 1993)

The developed eastern graben was later infilled with late Pleistocene - Holocene volcanism that was dominated by trachyte, basalts and rhyolite lavas and relatively minor pyroclastics, thus resulting in higher gravity. The geology of the area is consistent with gravity data, which shows a high Bouguer anomaly trending NW and with N-S boundary though Olkaria Hill (Figure 10). Precision gravity surveys at Olkaria Geothermal Field began in 1983 to monitor gravity changes as a result of geothermal fluid withdrawal (Mwangi, 1983). A review of the observed gravity data over each benchmark indicates minor decrease over the years during monitoring period (Mariita, 2000).

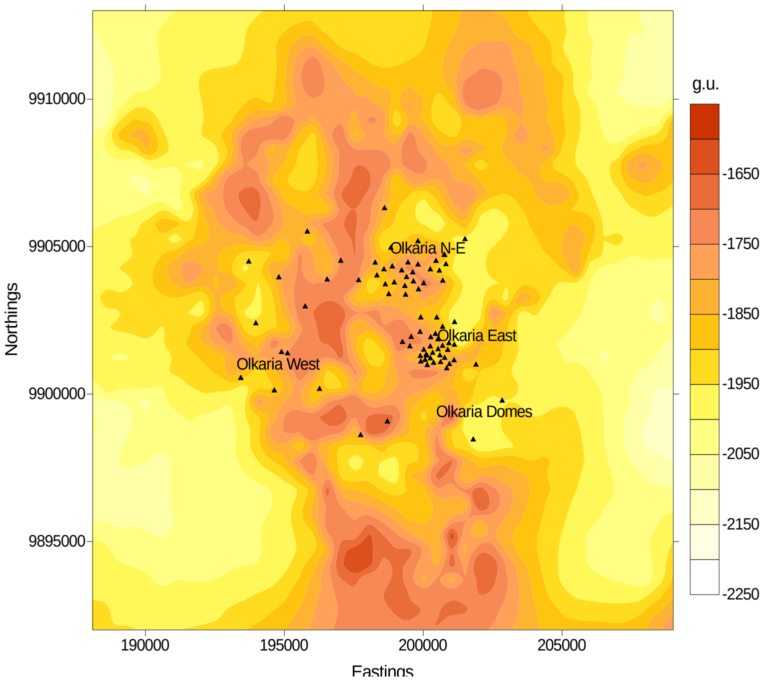

FIGURE 10: A Bouguer map using a density of 2.5 g/cm^3 for the Olkaria area

5.4 Magnetics

In Olkaria, both ground and aeromagnetic data have been used to investigate the presence of a geothermal resource in combination with gravity. From the aeromagnetic maps several of the anomalies can be clearly correlated with surface expressions of volcanism such as craters, domes or cones, localised basaltic lavas or plugs. 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.

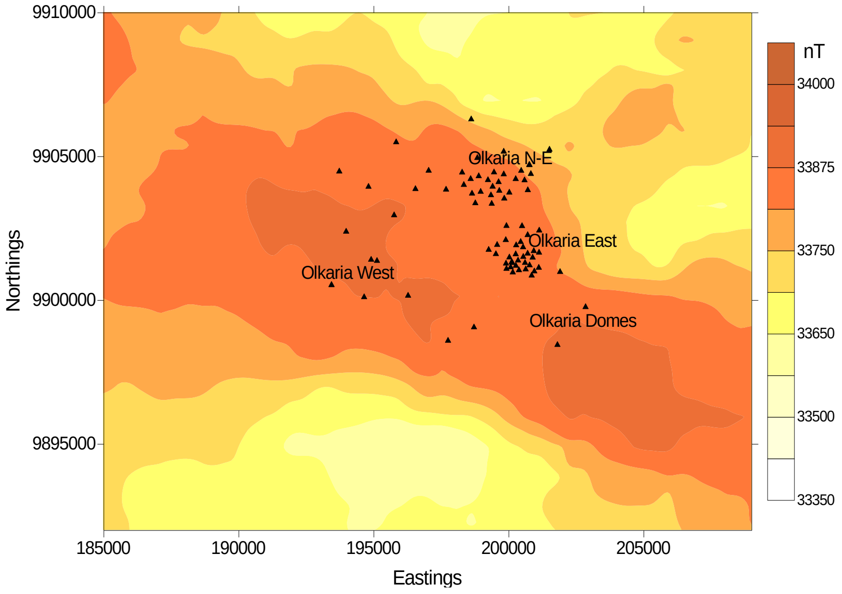

FIGURE 11: Total magnetic intensity map

Bhogal and Skinner (1971) analysed residual draped aeromagnetic data flown at 300m above ground surface within the Olkaria area. Their results showed that the central geothermal area had a positive magnetic anomaly trending NW-SE (Figure 11). The anomaly is superimposed on a broad regional negative anomaly that covers the entire southern Lake Naivasha region.

Whereas, Mwangi and Bromley (1986) interpreted the positive anomaly to represent de-magnetized rocks due to alteration by chemical and thermal processes at reservoir depth, it is currently thought that the anomaly is related to the NW-SE geological and structural development of the segment of the rift than demagnetisation by hydrothermal processes. The NW-SE trend is that of the main rift structural trend at Olkaria. A minor trend in the magnetic anomaly is in a NE-SW direction corresponding to the Olkaria fault zone.

6. DISCUSSION

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 epoch. The occurrence of late phase rhyolites (comendite) lavas and pyroclastics indicates the presence of shallow magma bodies since it has been established that they are products of protracted fractional crystallization and crustal anatexis (Omenda, 2000; Macdonald et al.; 1987; Black et al., 1997). Such processes have the potential to transfer large quantities of heat to the upper crust via the shallow crustal bodies. Results from seismics and magnetics indicate the presence of attenuating bodies at 6-18 km depth in Olkaria West, NE and Domes fields (Simiyu *et al.*, 1998a). The bodies also occur within regions of positive magnetic anomaly (Mwangi and Bromley, 1986). 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 (Black et al., 1997; Macdonald et al., 1987).

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 and inline with the recent fault trends (Figure 10). These local gravity highs are interpreted as dike intrusions which are considered heat sources in some areas while in others e.g. along the Ololbutot fault zone they act as hydrological barriers and heat sink between fields (Figure 12). Whereas some earlier geological studies suggested the presence of a caldera at Olkaria and marked by the eastern ring of domes (e.g. Naylor, 1972; Mungania, 1992; Clarke *et al*., 1990), gravity and seismic data do not show any indications of the presence of a caldera structure at Olkaria (Simiyu et al., 1998a; 1998b; Ndombi, 1981). Martin Trauth (pers. comm.) of Potsdam University while studying the diatomites in the Olkaria area did not see any evidence of possible caldera structure at Olkaria and instead also postulated that the rhyolite domes observable in the eastern Olkaria field could have occurred at fault intersections.

Micro-earthquake monitoring for epicentre and hypocenter 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 upflow 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 upflow zones and signify tectonic movements along the main faults.

Results of resistivity soundings at Olkaria indicate a main conductive body oriented NW-SE with deep lows in Olkaria West, NE and Domes fields. These lows correspond to geothermal upflow zones where extensive hydrothermal alteration and high temperatures occur in the subsurface. The lowest resistivity (<5 Ωm) in Olkaria occurs in the western sector due to low pH fluids, extensive alteration due to tuffs and higher primary permeability (Muchemi, 1999). In contrast, the resistivity is relatively higher (>10 Ωm) in the eastern fields where the reservoir is hosted within the flood trachytes. These trachytes are less susceptible to hydrothermal alteration except along secondary structures.

The reservoir in Olkaria is similarly divided into two main regions defined by structures along the Olkaria Hill and Ololbutot faults (Figure 12). The reservoir in the western field is hosted largely within the Mau Tuffs while in the eastern fields the reservoir is hosted within the faulted flood trachytes. This therefore, implies that the permeability in the western reservoirs is expected to be low because of the high potential of self sealing in tuffs. Permeability in the eastern field, however, is largely controlled by faults and fractures and as such larger producing wells are encountered where wells have intersected the faults at depth. The capping formation for the eastern reservoirs is the Basalt formation that occurs from about 400m depth. The formation consists of basalt lavas and tuffs above which occurs the sequence of trachyte – rhyolite – tuff of the Upper Formation (Figure 12). In the West field, no clear capping formation is discernable from the well logs and that could explain the smooth and gradational temperatures recorded in the wells.

Chemistry of discharged fluids in Olkaria also follows the same pattern with the OWF, OCF, ONEF and ODF having different fluid characteristics. The fluid discharged in OWF is highly bicarbonate-rich due to proximity to the rift master faults, which are known to transmit deep CO_2 that are not related to geothermal processes to shallow levels (Clarke et al., 1990; Omenda, 1998). The ONEF and OEF have similar fluid chemistries (NaCl-type) while OCF has mixed composition ($NaCl-HCO_3$). The mixed composition in the central field is most likely due to a combination of factors: 1) outflow from the West and NE fields which mixes with the NaCl-fluid in the central field to produce the mixed compositions; 2) the Central field being close to the deep seated west major rift faults could be having some input from mantle CO_2 as is the case for the West field.

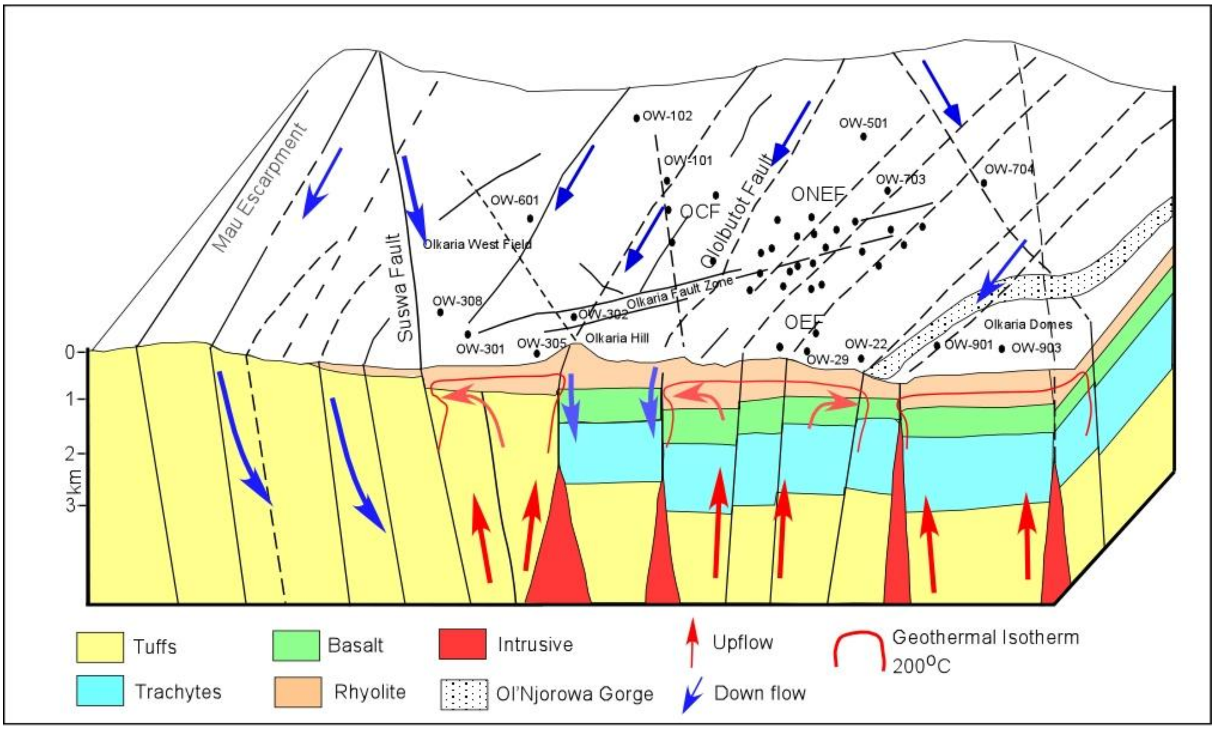

FIGURE 12: Geothermal model of the Olkaria system showing structures and fluid flow patterns

7. CONCLUSIONS

1. The results of the review indicated that the geothermal system at Olkaria has been well described and modelled by use of an integrated approach that included various geophysical techniques, geochemistry, geology and reservoir studies. The heat sources have been mapped more effectively by use of seismics and MT while the hydrological patterns are best understood from fluid chemistry, resistivity and geological observations.

2. The Olkaria geothermal system is characterized by discrete magma bodies which are oriented NW and are the main heat sources. The fluid upflow zones are mainly at intersection of faults while cold recharges are along NW-SE and NNE trending faults. A major hydrological barrier exists between Olkaria Hill fault and Ololbutot fault.

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LECTURE 3

OLKARIA RESERVOIR RESPONSE TO EXPLOITATION AND FUTURE DEVELOPMENT

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ABSTRACT

Exploitation of Olkaria field started in 1981 when Olkaria East reservoir began producing steam for the 45 MWe Olkaria I power plant. Exploitation of Olkaria West reservoir started in 2000 with installation of 13 MWe Ormat binary plant, Olkaria Northeast in 2003 with 70 MWe conventional plant and Northwest in 2004 with 2.1 MWe Ormat binary plant. Well OW-101 has been in commercial exploitation for supply of heat and carbondioxide for flower growing since 2003. Performance of Olkaria East reservoir for the last 23 years has been quite good with minimal drawdown of about 22 bar in the deep reservoir. Only eight make-up wells have been drilled and were first connected in 1995. Enthalpies have remained high (>2000 kJ/kg) and total steam available has been in excess since connection of the make-up wells. Well OW-5 was deepened from 901 m to 2200 m to tap deeper parts of the reservoir. Production drilling in Olkaria Domes and the re-assessment of the capacity of the field are planned after completion of a current optimization study.

1. INTRODUCTION

Exploration of Olkaria geothermal field started in 1956. This early exploration work involved drilling of two wells, X1 and X2, both of which were sited on the basis of surface manifestations. Well X1 which was drilled to 502 m, encountered dry steam at a relatively shallow depth but the flow could not be sustained. The bottom hole temperature was 120°C. Well X2 was drilled to 942 m and encountered high temperatures (245°C) at the bottom but proved difficult to discharge. It produced a low enthalpy fluid at low wellhead pressure and work was stopped in 1959. Interest in geothermal development then subsided until after mid 1960's when reconnaissance geophysical survey was carried out in the Rift Valley between Lake Bogoria and Olkaria in 1967. The survey identified Olkaria, Eburru and Lake Bogoria as suitable areas for further prospecting (KPC 1981; KPC 1985).

In 1970, the Olkaria Geothermal Project that was jointly financed by UNDP and the Kenya Government was started. Extensive exploration work consisting of well data analysis, geological mapping, geophysical and geochemical surveys were carried out. In 1972, well X2 was discharged and continuously produced for a year before being shut-in. Glover (1972) also gave an estimation of the natural heat loss from the geothermal system to be close to 400 MWt with 90 % of this coming from steam discharge. On the basis of the success in producing steam from well X2, the good surface exploration results and good access to Olkaria, a technical review meeting was held in 1972 which recommended drilling of four more exploration wells.

Drilling started in 1973 with well OW-1 located to the southeast of the Olkaria hill that was to a depth of 1003 m with a temperature of 126°C but never discharged. An attempt was made to stimulate the well to discharge by air-lift, but failed. Following this unsuccessful result, OW-2 was drilled 3.5 km to the northeast of this well. The major considerations in locating well OW-2 were:

1. To make one more attempt to locate a discharging well in the area.
2. To move up along the ground water gradient (without going into Hell's Gate), but also to keep the wellhead elevation as low as possible in order to minimize depth to static water level.
3. Favorable resistivity and gas chemistry. The chemical data obtained from fumaroles gave indications of high underground temperatures and the resistivity surveys showed a pronounced low at 1000 – 1200 m (Sweco and Virkir, 1976).

Drilling of well OW-2 gave positive results. It was drilled to 1350 m and encountered a 246°C steam zone at 650 m. Maximum temperature recorded was 280°C at the bottom. Discharge at atmospheric pressure gave 70–75 % steam and total flow rate was 9 kg/s (32.4 t/hr) at a pressure of 6 bar-abs. It is due to the success in this well that further appraisal and production drilling were done in its vicinity and 1976, a feasibility study for utilization of geothermal steam for generation of electricity at Olkaria (Sweco and Virkir, 1976) was done. The study indicated that the development of the geothermal resource was attractive and it was decided to construct a 30 MWe power plant of two 15 MWe units with possible extension by addition of a third 15 MWe unit (Svanbjörnsson, et. al., 1983). The first unit was brought on line in July 1981, the second in December 1982 and the third in April 1985. This plant is owned by Kenya Electricity Generating Company Ltd. (KenGen). Since then, Olkaria East field (Olkaria I) has been producing steam for generation of 45 MWe and in most occasions stretched to 48 MWe.

Further exploration and development work has shown that the Olkaria field is very extensive (more than 80 km^2) and is now divided into several sectors namely: Olkaria East field (Olkaria I), Northeast field (Olkaria II), Central field, West field (Olkaria III), Northwest field, Southeast field and Olkaria Domes field (Olkaria IV). A 13 MWe binary plant was commissioned in Olkaria III in August 2000 by ORPOWER4 Inc (a subsidiary Company of Ormat International). KenGen commissioned a 70 MWe conventional steam power plant in Olkaria II in October 2003. Oserian Development Company Ltd has been utilizing well OW-101 to supply heat and CO_2 for flower growing in greenhouses since May 2003. They also commissioned a 2.1 MWe binary power plant in June 2004. The total number of wells drilled to date is 98 and appraisal drilling will now be focused in Olkaria Domes field. Total electric power now generated at Olkaria is 130 MWe.

2. RESERVOIR CHARACTERISTICS

2.1 Geology

Olkaria geothermal field is a remnant of an old caldera complex which has subsequently been intersected by N-S normal rifting faults that have provided loci for later eruptions of rhyolitic and pumice domes. Eruptions associated with Olkaria volcano and Ololbutot fault zone (Figure 1) produced rhyolitic and obsidian flows while eruptions from Longonot and Suswa volcanoes ejected pyroclastic ash that has blanketed much of the area. NW, NNW, N-S, NNE and NE trending faults are observed in the geothermal complex (Muchemi, 1999; Odongo, 1993). The most prominent structures are the NE trending Olkaria fault, N-S trending Ololbutot fault, Olkaria Hill fault, Suswa fault and Gorge Farm fault.

Subsurface stratigraphy of Olkaria wells show that from the surface (which is at an average elevation of 2000 m.a.s.l) to about 1400 m.a.s.l, the rocks consist of Quaternary comendites with an extensive cover of pyroclastics. Below these, the dominant rocks are trachytes with basaltic lava flows and tuffs

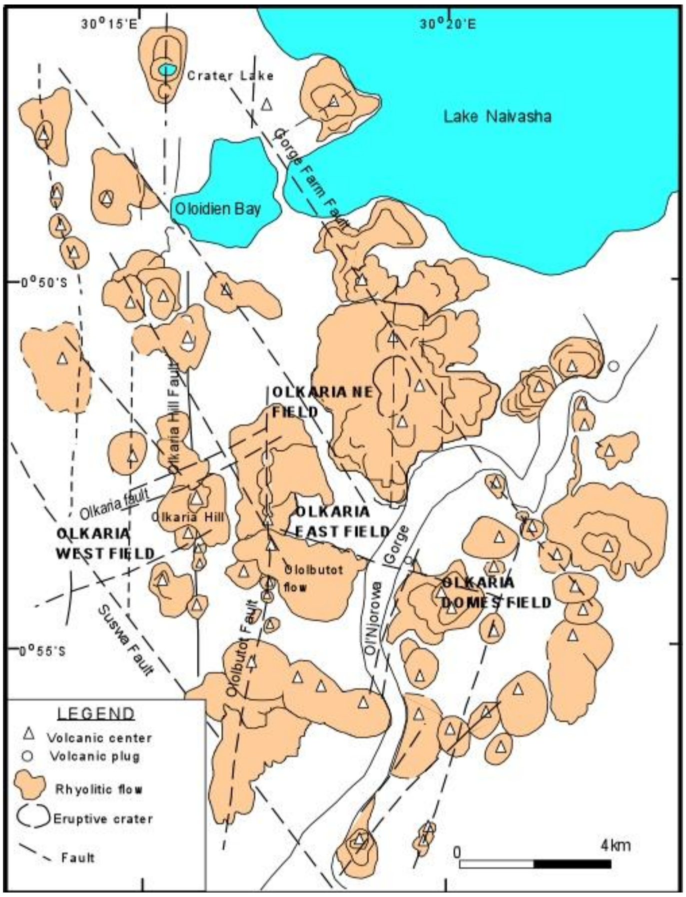

FIGURE 1: Geological structures

that mainly occur as thin intercalations (Figure 2). The general rock stratigraphy across the greater geothermal system is essentially horizontal (Muchemi, 1999; Brown, 1984). Rocks down to 1400 m a.s.l. are nearly impermeable and act as caprock to the system. Below this depth permeability is encountered at the fractures, lava contacts and porous pyroclastic beds and tuffs. A look at well productivity indicates that wells located close to known or inferred faults produce highest mass flows indicating the importance of vertical permeability.

2.2 Geophysics

Low-resistivity anomalies within the Olkaria field are controlled by linear structures in the NE-SW and NW-SE directions (Muchemi, 1999). The geothermal resource is defined by less than 15 Ωm resistivity anomaly at 1000 m.a.s.l and occur at the intersection of these structures. High-resistivity regions within these low-resistivity anomalies coincide with NE and NW trending faults and are interpreted to be conduits channeling cold water recharge. Deep low-resistivity data below 5 km depth from MT data reflects the heat source.

Seismic monitoring of micro-earthquakes within the Olkaria geothermal system (Simiyu and Malin, 2000) has shown that shallow, high frequency events associated with movement of hot geothermal fluids, occur at the intersection of NE-SW and NW-SE trending faults. Deep, low frequency events, which have been associated with movement of cold water far from areas of strong heat source, occur

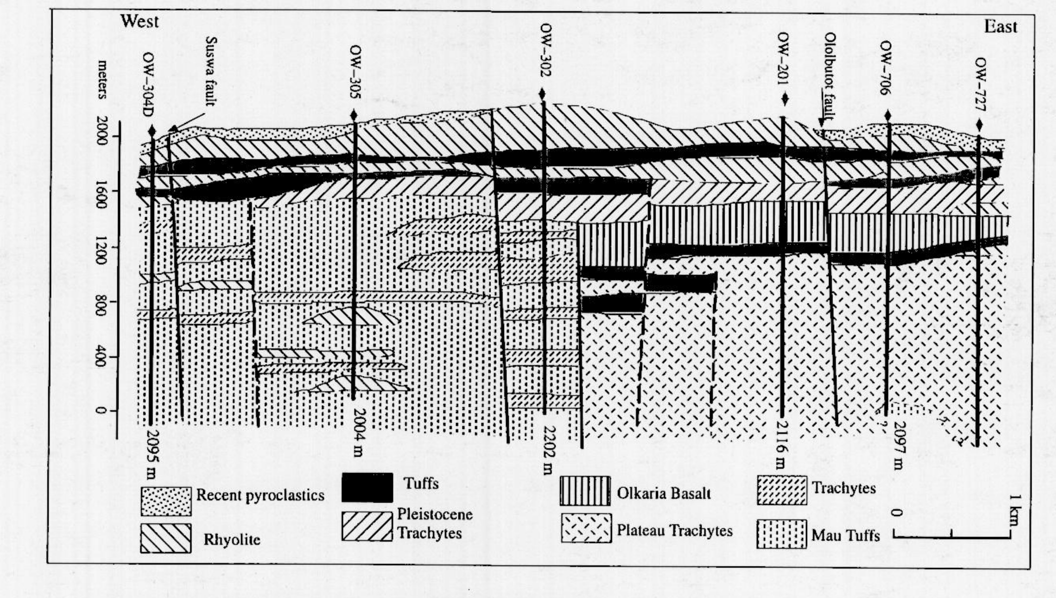

FIGURE 2: General E-W geological cross-section across Olkaria reservoir

away from these zones (Figure 3).

Studies of shear wave attenuation beneath Olkaria geothermal field (Simiyu, 1998) indicate deep attenuating bodies below Olkaria hill, Gorge Farm volcanic centre and Domes area at about 7 to 18 km depth. These bodies coincide with zones of deep low resistivity and positive magnetic anomaly and have been interpreted to be zones of molten magmatic bodies that provide heat source for the Olkaria geothermal system. From magnetic studies, these bodies are approximated to be at temperatures above 575°C.

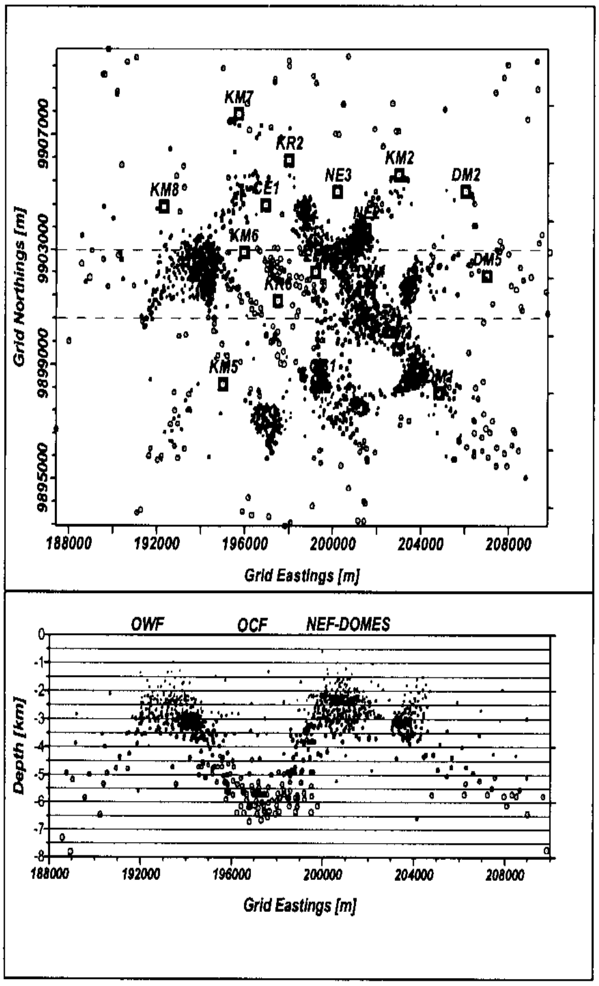

FIGURE 3: Location of micro-eartquakes in the Olkaria geothermal system (Simiyu and Malin, 2000); OWF - Olkaria West field, OCF - Olkaria Central field, and NEF - Northeast field

2.3 Chemistry of discharged fluids

The reservoir waters discharged by wells in the Olkaria geothermal system (before exploitation) vary depending on which field the well is located. Wells in Olkaria Northeast field discharge neutral sodium chloride waters with chloride concentrations in the range of 400–600 ppm and bicarbonate concentrations < 1000 ppm. Wells in Olkaria West field discharge mainly sodium bicarbonate waters with bicarbonate concentrations about 10,000 ppm and chloride concentrations ranging from 50–200 ppm while wells in Olkaria Central field discharge a mixture of sodium chloride and sodium bicarbonate waters. Olkaria Domes wells discharge mixed sodium bicarbonate-chloride-sulphate waters with mean chloride concentrations of 180–270 ppm and Olkaria East wells discharge sodium chloride waters with chloride concentrations in the range of 200–700 ppm. NCG content from Olkaria East and Northeast discharge ranges from 0 to 0.75 (Wambugu, 1996).

2.4 Temperature and pressure in the Olkaria field

Temperature and pressures obtained from wells in Olkaria East field follow the boiling point with depth curve (Figure 4 and Figure 5). Similarly, temperature and pressures from wells located in the upflow zones of Olkaria Northeast and West also follow the boiling point with depth curve. Wells outside these upflow zones show either isothermal temperatures at depth, indicating inter zonal flow or reversed temperatures suggesting counter flow of hot outflow and cold inflow from shallow and deep aquifers, respectively (Ofwona, 2002). Areal temperature distributions (Figure 6) show hottest zones in Northeast field, West field and in the north around well OW-101. Coldest zones are in NE around well OW-704, in the NW around well OW-102, in the south and SW around wells OW-307 and well OW-801 and in the Olkaria Central field. Pressure distribution (Figure 7) shows that low pressure zones occur in the Olkaria Central along Ololbutot fault zone. High pressure zones coincide with areas of low temperatures associated with cold inflows into the geothermal system.

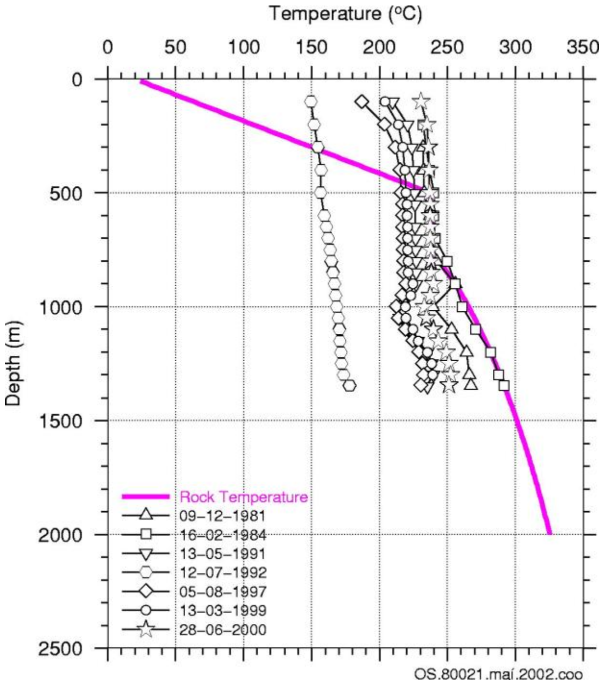

FIGURE 4: Temperatures in well OW-21, a typical Olkaria I well

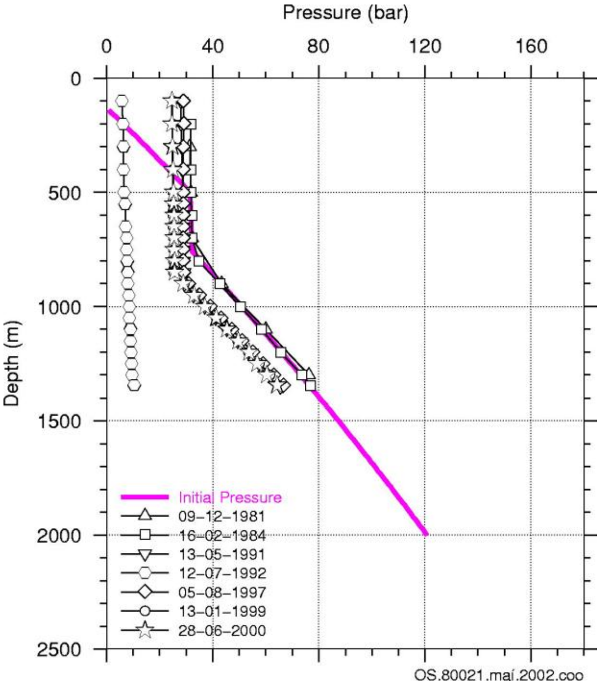

FIGURE 5: Pressures in well OW-21

2.5 Conceptual model

Figure 8 is an E-W schematic cross-section across Olkaria geothermal system. It postulates existence of deep high temperature reservoirs in Olkaria West and Olkaria Northeast from where hot upflowing fluids originate. Part of the upflow in Olkaria Northeast move to the east and part to Olkaria Central from where a substantial cooling by steam loss along Olobutot fault occur resulting in colder temperatures at depth in wells drilled in this zone. Similarly, part of the upflow from Olkaria west move to Olkaria Central and this agrees with the mixed fluid chemistry obtained from wells drilled in Olkaria Central. Possible upflow zones exist in Olkaria East field and Olkaria Domes (Ofwona, 2002 and 2003).

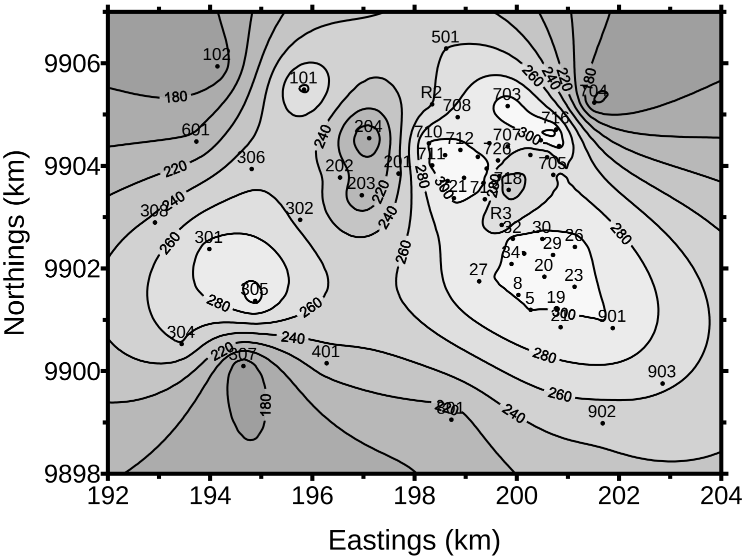

FIGURE 6: Temperature distribution (°C) at 500 m a.s.l.

Figure 9 is an early schematic section across Olkaria East reservoir (SWECO and VIRKIR, 1976). It depicts the field as a boiling two-phase liquid dominated that is overlain by a 100 – 200 m thick steam zone and capped by a 700 m thick cap rock. Initial temperature and pressure profiles obtained in wells drilled into this reservoir follow boiling point with depth curve from the point where the steam zone intercepts the water reservoir (Figure 6 and 7). 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 is 330°C.

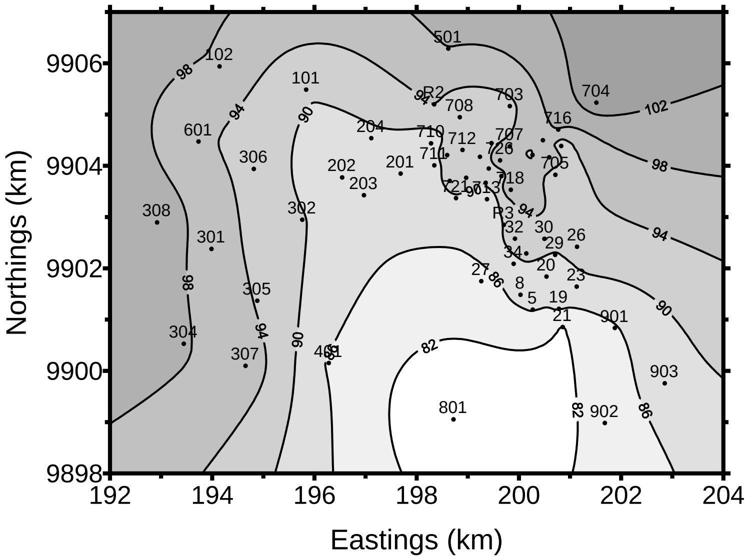

FIGURE 7: Pressure distribution (bars) at 500 m a.s.l.

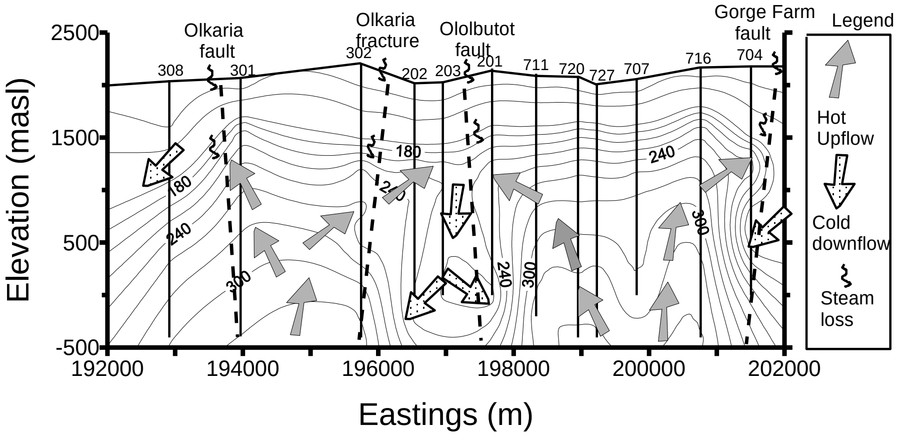

FIGURE 8: A schematic cross-section across Olkaria field (contours show temperature in °C)

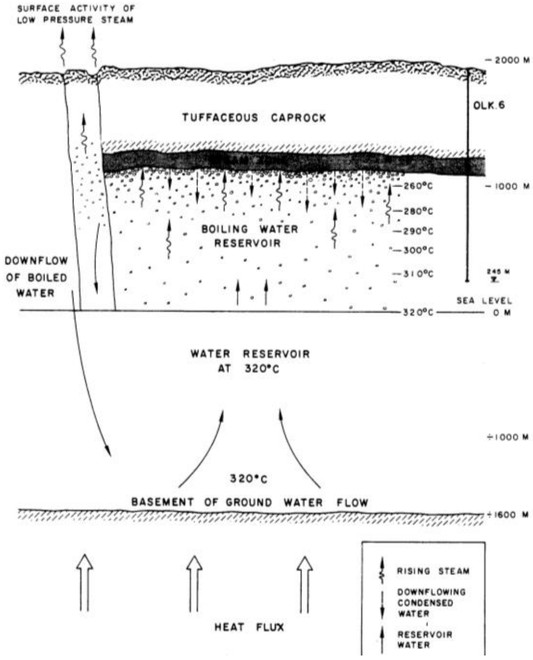

FIGURE 9: A schematic model of Olkaria East geothermal reservoir (from Sweco and Virkir, 1976)

3. RESERVOIR RESPONSE TO EXPLOITATION

3.1 Production history of Olkaria East field

Olkaria East field reservoir has been in production since July 1981. At the time of commissioning unit 3 in 1985, 23 wells (all drilled to depths ranging from 900 m to 1685 m, except OW-19 drilled to 2484 m) were connected to supply steam to the power plant but as time progressed, some of the wells (mainly drilled to depths between 900 m to 1200 m) declined in output and had to be isolated. New make-up wells were then drilled to restore the generating capacity, which had declined to 31 MWe by 1994 (Mwangi, 2000). Four make-up wells were connected in 1995 (OW-27, 28, 29 and 30), two more in 1996 (OW-31 and 33) and another two (OW-32 and 34) in 2001. After connection of the make-up wells, and deepening well OW-5 (in 1998) from 900 m to 2200 m, total steam available from the existing exploitable wells increased and since then has remained high exceeding what is required for generation of 48 MWe. Total steam available at the wellhead is now approximately 720 t/hr and to generate 48 MWe, 442 t/hr is required hence excess steam is over 280 t/hr. Since production started, only two wells (OW-12 and OW-14) have been retired

Figure 10 shows the overall Olkaria East field production history, the values of mass production rates are yearly averages and the enthalpies are weighted averages. It is generally observed that the water output had been on the increase and the enthalpy on the decline even before the make-up wells were connected. This has been interpreted as recharge of fluids into the reservoir.

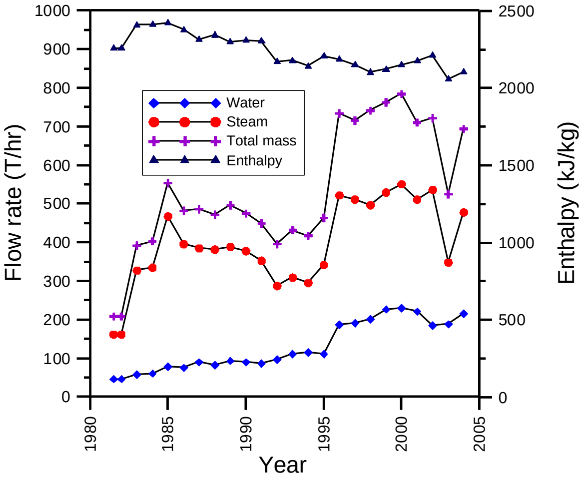

FIGURE 10: Production history of Olkaria East reservoir

3.2 Production history of Olkaria Northeast field

The Olkaria Northeast Production Field has been under production since October 2003 with an installed capacity of 70 MWe consisting of two machines of 35 MWe each. At the time of commissioning, the steam consumption was 250 t/hr and 260 t/hr for Unit I and II respectively.

Auxiliary steam for the two Units metered at a common point, was 15 t/hr. Upto fifteen wells supply steam to the power plant at any one time even though the field has a total of twenty wells connected and to date, no well has been retired. Figure 11 shows the overall Olkaria Northeast field production history up to December 2004. The values of mass production rates are monthly averages and the enthalpies are weighted averages.

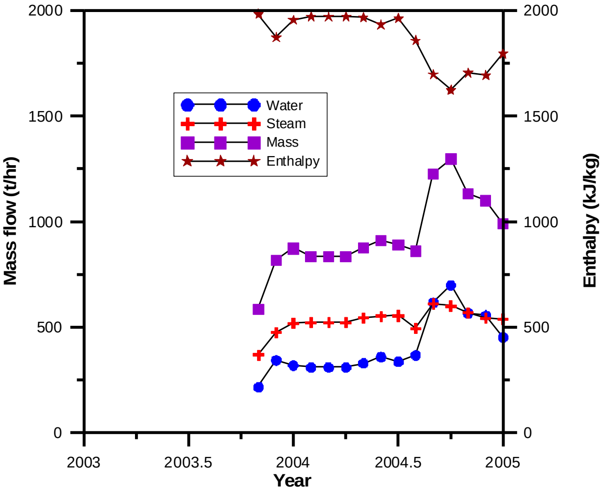

FIGURE 11: Production history of Olkaria Northeast reservoir

3.3 Injection / re-injection in Olkaria I

Well OW-3. A tracer and injection test experiment was done in well OW-3 from April to September 1993 (Ambusso, 1994). Cold fresh water at 18°C from Lake Naivasha was injected in this well continuously for 172 days at an average rate of 100 t/hr (27.78 kg/s). 125 kg of Sodium fluorescein dye was introduced as a slug after 45 days of injection. Production and chemical changes were observed in wells OW-2, 4, 7, 8, 10 and 11. Chloride decline occurred in wells OW-2 and 4 during the injection period and tracer returns were observed in wells OW-4, 2 and 7 with OW-4 registering the highest recovered mass of about 38 %, well OW-2, 0.1 % and well OW-7, 0.07 % (Ofwona, 1996). Hot re-injection of separated brine from wells OW-27, 31 and 33 has been going on in this well (OW-3) since May 1995 at approximately 13 t/hr (3.6 kg/s).

Well OW-12. Tracer/injection test experiment was done in this well from 12.7.96 to 1.9.97. Cold fresh water from Lake Naivasha was injected continuously at an average rate of 100 t/hr (27.78 kg/s) for 416 days. 500 kg of Sodium fluorescein tracer was introduced as a slug after 20 days of injection. Wells around OW-12 were monitored for chemical and output changes. High tracer returns were obtained from wells OW-15, OW-16 and OW-19. The same wells also experienced drastic decline in chloride concentration and enthalpies with big increase in water flow.

Well OW-R3. Tracer/injection test experiment was done in this well from May 1995 to July 1.9.96. Cold fresh water from Lake Naivasha was injected continuously at an average rate of 100 t/hr (27.78 kg/s) over the duration of the experiment. 500 kg of Sodium fluorescein tracer was introduced as a slug after 27 days of injection. Wells close to OW-R3 were monitored for chemical and output changes. Very little tracer returns were obtained from wells OW-25, OW-29 and OW-30 and none from the closest wells OW-32 and 34. There was also very little or no change at all in the fluid chemistry as well as production output from the neighbouring wells.

3.4 Hot re-injection in Olkaria Northeast

Hot re-injection in Olkaria Northeast field is infield and is done in wells OW-R2, OW-R3, OW-703 and OW-708. By the end of 2004, a total of 4,895,726.5 tones of hot brine had been re-injected into the field with 1,186,266 tons flowing into OW-R2, 1,057,768 tons flowing into OW-R3, 1,105,296 tons into OW-703 and 1,546,397 tons flowing into OW-708 (Mwawongo, G. M., 2004). Tracer tests have been conducted in well OW-708 and returns were observed in wells OW-712. Monitoring of these wells for the effect of re-injection is ongoing but preliminary results show that there is positive respone.

Cold condenser blowdown from Olkaria II plant is injected in wells OW-201 and OW-204 in Olkaria Central field. By end of 2004, a total of 708,261.5 tons had been re-injected into the two wells.

3.5 Pressure response due to production

Due to high demand for steam, no wells within Olkaria I production field were available for monitoring pressure response due to production. Only well OW-3 and well OW-9 were considered unsuitable for production and could have been used for this purpose but well OW-3 was used for field injection experiments and well OW-9 had internal flow and was also later on plugged due to its close proximity to the project offices. However, well OW-8 offered some good pressure decline history. This well was first drilled to 1080 m in November 1978 and intercepted permeable zones at 600 - 700 m and 900 - 1080 m depth. It was then deepened to 1600 m in 1983 intercepting more permeable zones at 1300 – 1400 m. It remained shut-in from 1979 to 1983 and again to September 1985 when it was connected to the steam supply system. Production from this well continued until October 2000 when it was shut-in. It has remained shut-in to date and is now used as pressure monitoring well.

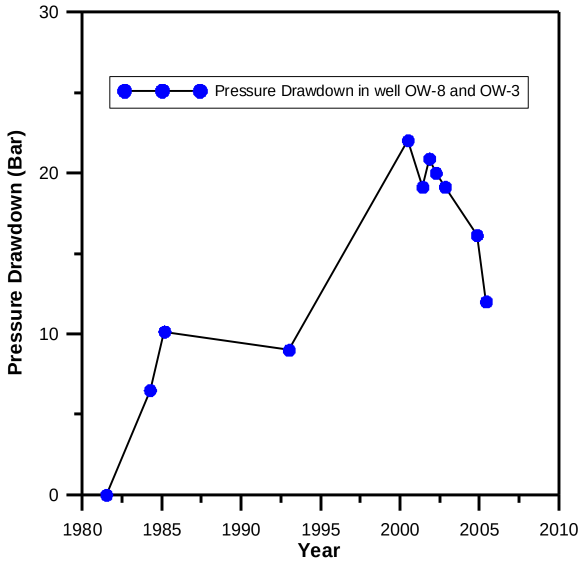

FIGURE 12: Pressure drawdown at 640 m a.s.l. in wells OW-3 and OW-8

Well OW-3 was never connected to the production system and has been used for re-injection experiments. It was shut in for a long period of time before 1992 and can offer some good pressure drawdown data up to 1992. Other producing wells have been logged at different times when opportunity arises during wellhead equipment servicing and unit shut downs during maintenance. Figure 12 shows the pressure drawdown as measured in wells OW-3 and OW-8 at 640 masl (1300 m depth). Maximum drawdown was 22 bars in June 2000. The decrease in pressure drawdown in the year 2003 and 2004 is due to shut-in of most wells as a result of overhaul of Unit 1.

From the pressure logs (Figures 13 to 16), it is observed that the steam zone is expanding down into the liquid reservoir as exploitation time increases resulting in lowering of the steam/boiling water interface. Pressure logs from well OW-5 suggest that below 1600 m depth, the reservoir is still unexploited. Downhole measurements in well OW-21 shows that it had pressure decline only up to 1997 and thereafter has been stable suggesting a good pressure support boundary. However, the measurements are done only when the well is temporarily isolated from the system and has not been shut long enough to attain stable pressure.

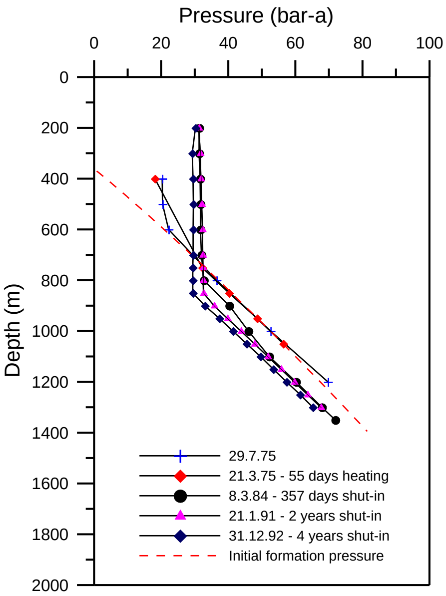

FIGURE 13: Pressures in well OW-3

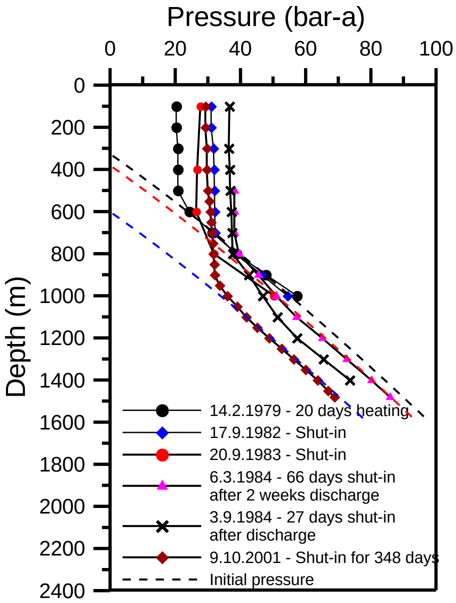

FIGURE 14: Pressures in well OW-8

3.6 Changes due to exploitation

Figure 17 and 18 shows production histories of wells OW-2 and OW-19, which represent the behavior of most production wells in Olkaria I. Generally, there was an initial high decline rate of about 3% – 4% up to early 90's and from then, the wells show either constant production or increase in output. The decline rate is now practically zero. This has been interpreted to imply that the reservoir has

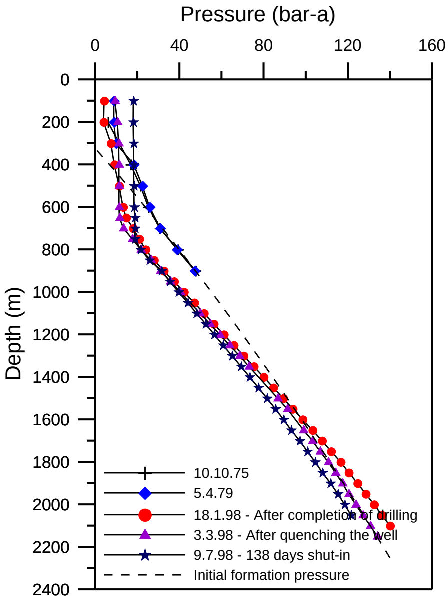

FIGURE 15: Pressures in well OW-5

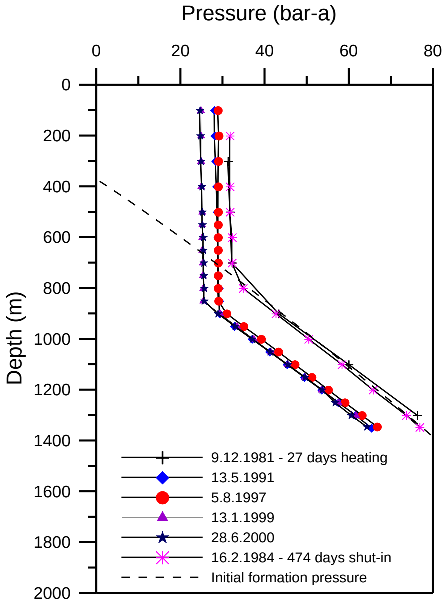

FIGURE 16: Pressures in well OW-21

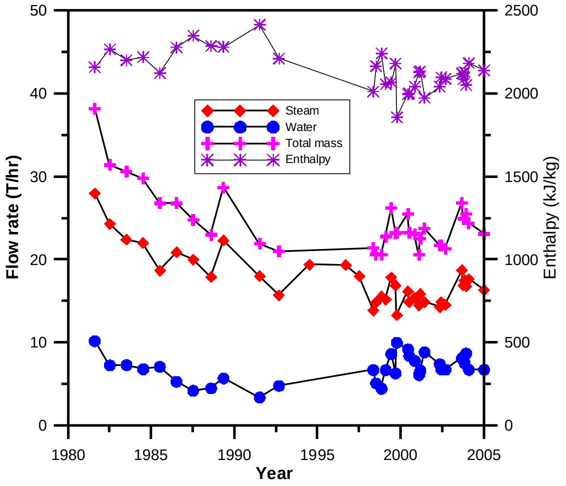

FIGURE 17: Production history of OW-2

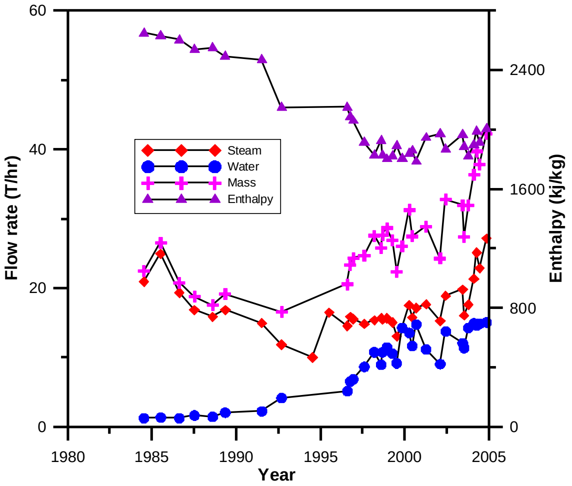

FIGURE 18: Production history of OW-19

either reached steady state and/or triggered in recharge. Figure19 and 20 show changes in reservoir chloride and NaK geo-thermometers from 1983 to 2004. Figure 19 shows that well OW-10, which is located in the centre of the field has increased chloride concentration, possibly due to boiling. Wells OW-2 and OW-25 had decline in concentration in the 90's due to cold injection and drilling activities in their vicinities. Figure 20 shows that temperatures have remained constant. The field response can therefore be summarized as increased boiling in the centrally located wells giving rise to dry steam and high chloride concentration and possibly induced recharge in the wells located at the periphery resulting in modest decline in chloride concentration. The recharging of these wells is also supported by the slow pressure depletion rates depicted in their downhole data.

Cold and hot re-injection has also had positive effects as wells in Olkaria East and Northeast have responded well with increased or stabilized outputs. Cold injection though has been done intermittently due to breakthroughs leading to drop in enthalpies but after few months of stoppage, the wells do recover and increase their outputs.

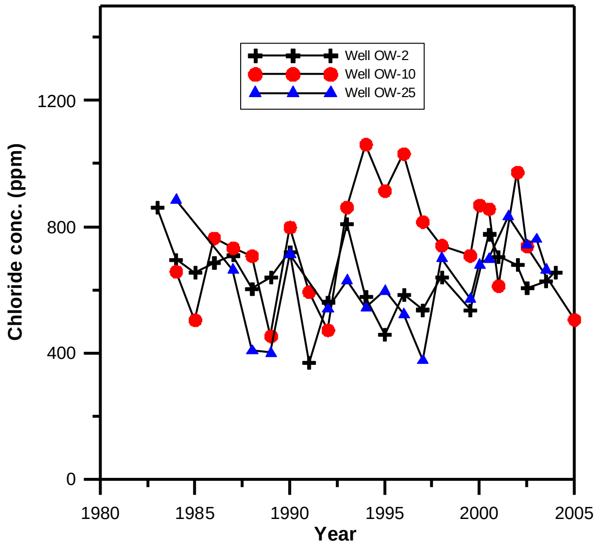

FIGURE 19: Chloride variations

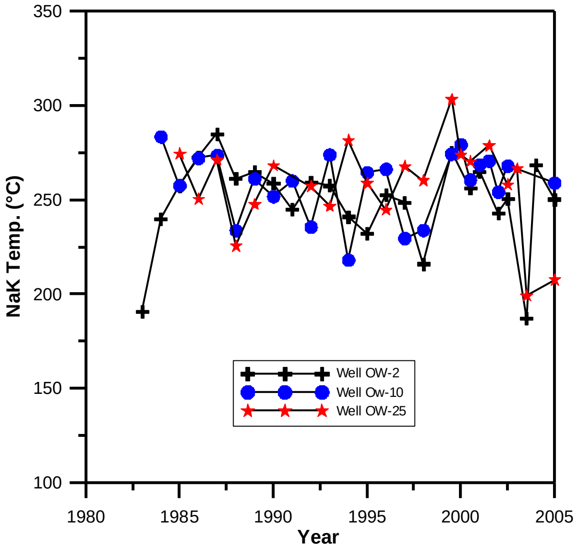

FIGURE 20: NaK geothermometer results

Only well OW-34 has had silica deposition problem on surface equipment but studies have shown that this problem is unique to this well and that this deposition has not affected the wellbore or its output.

4. FUTURE RESERVOIR DEVELOPMENT IN OLKARIA

Olkaria I plant and reservoir have been in operation since 1981 and have performed very well. Average plant availability factor and overall load factor has been over 96%. The plant is now approaching its design life of 25 years but is still in good condition. The only major repair done was replacement of unit 1 generator coil in 2003. Unit 2 generator coil is now being replaced. The wells currently have about 280 t/hr more steam than what is required to generate 48 MWe. The deep reservoir is still unexploited as has been proved by deepening of well OW-5 and has had very little pressure drawdown. There is also evidence that it has good recharge from the periphery and an area for expansion still exist to the south and to the east of the field. Currently, studies are being undertaken to find ways of optimizing the generation and the reservoir. After the optimization study, it will then be decided whether to increase production from the reservoir and by how much or to keep the current installed generation plants. However, because of the positive response of the reservoir during its production history, it is felt that it is underutilized and increased production is expected in the future. Production drilling in Olkaria Domes will also start soon and hot re-injection in Olkaria I will be enhanced.

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The United Nations University

GEOTHERMAL TRAINING PROGRAMME

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LECTURE 4

KENYA'S GEOTHERMAL PROSPECTS OUTSIDE OLKARIA: STATUS OF EXPLORATION AND DEVELOPMENT

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ABSTRACT

Implementation of the geothermal resource assessment program (GRA) has resulted in exploration studies being done in five other prospects in the Kenyan rift between 2004 and 2005. The same studies in all the geothermal prospects north of Lake Baringo will be complete by 2010. So far Menengai is ranked first followed by Longonot and Suswa. For prospects with no central volcano, L Baringo is ranked last after L Bogoria and Arus. Over 6,838 MWt is lost naturally from the already explored geothermal prospects in the rift. Areas of heat leakages in the rift are controlled by NW-SE trending faults. At Olkaria, over 84,800 GWH have been generated from geothermal resulting to a saving of over 4,900 million US$ in foreign exchange.

1. INTRODUCTION

Kenya is located in the eastern part of Africa with 14 geothermal prospects identified in the Kenya rift starting from Barrier in the north to L Magadi in the south with an estimated potential of over 2000 MWe (Omenda et al., 2000). Studies done in the rift in mid 1960 identified Olkaria as the most economical prospect to develop (KPC, 1994). Exploration and field development was then done leading to the establishment of sectors which form the Great Olkaria Geothermal area (GOGA) currently with an installed capacity of 130 MWe. Over 84,800 GWH have been generated from geothermal resulting to a saving of over 4,900 million US$ in fossil fuel cost.

Performance of Olkaria power plants indicate that geothermal power is cheap and feasible and for this reason the Government of Kenya (GOK) through KenGen implemented a geothermal resource assessment program (GRA) aimed at systematically exploring all the geothermal prospects outside Olkaria with the aim of ranking them for further development.

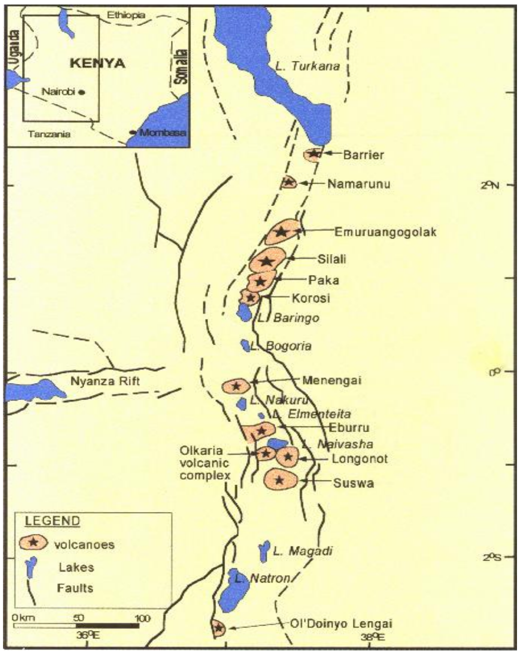

FIGURE 1: Geothermal fields in the Kenyan Rift

So far surface studies have been conducted at Eburru, Suswa, Longonot, Menengai, Lake Baringo, Arus and Lake Bogoria prospects with exploration drilling only done at Eburru. This paper presents the current status of exploration and development of other geothermal prospects outside Olkaria.

2. EBURRU

Eburru volcanic complex is located to the north of Olkaria. Structures in the prospect mainly have a N-S trend (Figure 2). Hot grounds and fumaroles in the area produce steam at 95°C. (JICA, 1980). Exploration drilling of 6 deep wells was done between 1989 and 1991 by Kenya Power Company for the GOK. Hydrothermal minerals assemblages suggest that the area had experienced temperatures of over 300°C possibly due to localized intrusives.

The lithology indicates that rhyolite is the most abundant together with basalts and trachytes. Resistivity indicates that the field is delineated by the 30 ohm-m anomaly with an outflow towards the NE towards Badlands volcanic field (Figure 3). The Badlands volcanic field was investigated together with Eburru and expansive low resistivity anomaly was detected. However, drilling has not been done to confirm its potential.

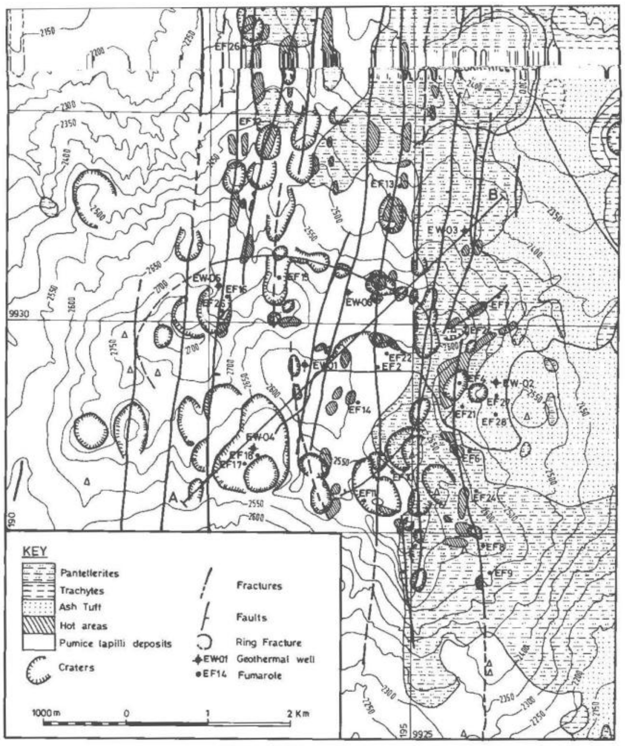

Figure 2: Geological map of Eburru (Omenda and Karingithi, 1993

Discharge fluid chemistry from the wells (EW-1) indicates that the reservoir is non-boiling with very saline brine and a high amount of non condensable gases (NCG), however scaling problem is not anticipated due to the low calcium and magnesium in the brine. Despite the almost similar geology, the chloride level of EW-I (956 to 1976 ppm) is higher than that of Olkaria. As compared to Olkaria, the reservoir permeability is moderate (KPC, 1990).

The maximum temperature was 285°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 is about 20 MWe (Omenda et al., 2000). The area has a fairly well established infrastructure and for this reason a 2.5 MWe binary plant for early generation will be commissioned in 2007. Additional studies will also be done to refine the field model prior to commissioning of the plant.

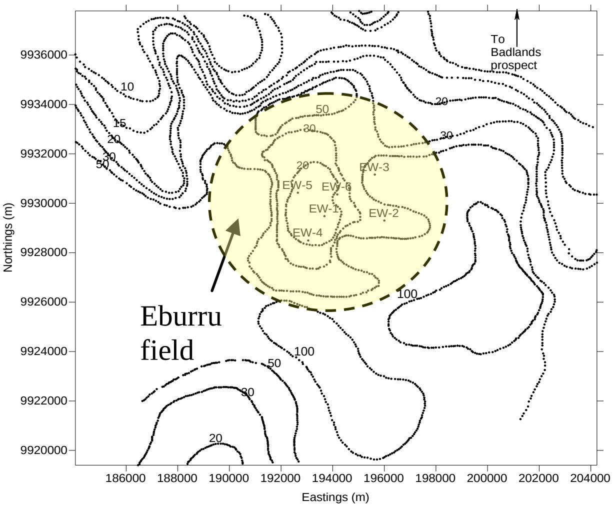

FIGURE 3: Resistivity at 1000 m a.s.l. in Eburru (Onacha, 1991)

3. MENENGAI

Menengai is a large caldera volcano on the floor of rift valley. Pervious studies of the volcano indicated probable occurrence of a high temperature geothermal resource (Omenda et al., 2000). The youngest eruptive activity is about 1400 BP. Surface manifestations are mainly steaming grounds at a temperature of 88°C. The Government of Kenya and KenGen carried out surface studies between January and May 2004 in an area of about 900 km^2 (Mungania et al., 2004). Integrated results of geological, geophysical, geochemical and heat loss surveys indicate existence of a hot, ductile and dense body under the caldera. It is modeled that the hot magmatic body resulted in the development of a geothermal system with an up-flow under the caldera and an outflow to the north (Figure 4).

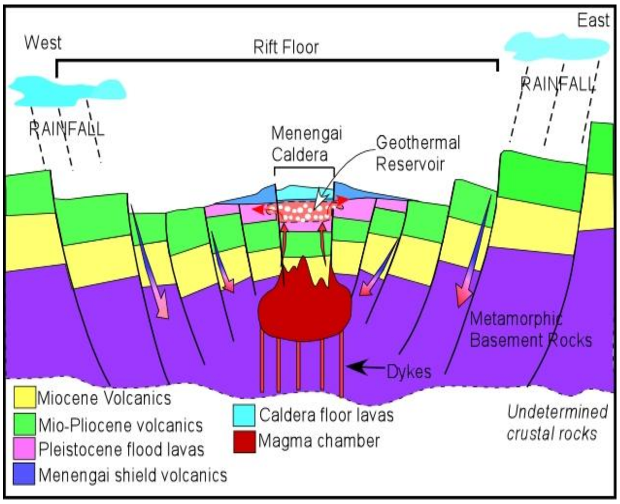

FIGURE 4: Conceptual model of Menengai

Gravity suggests that the dense body is 3.5 to 4 km deep (Omenda et al., 2000). Good permeability in the subsurface is shown by the shallow low resistivity of <15 ohm m at 1000 ma.s.l. Seismic studies indicate clusters of shallow micro-earthquakes under the caldera and from experience at Olkaria this is related to a high temperature geothermal field associated with shallow magma bodies (Simiyu and Keller, 1997). 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). Heat loss results from this prospect together with those obtained in others are plotted on Figure 5.

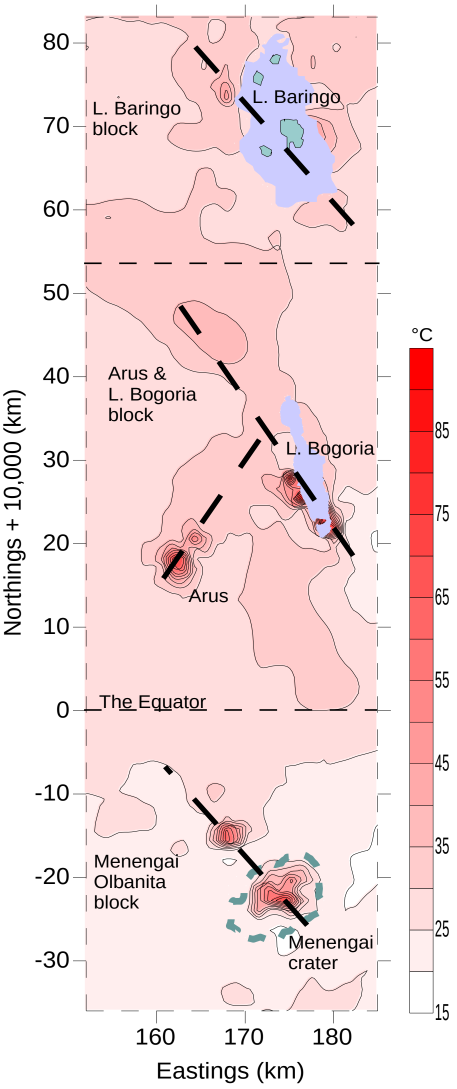

FIGURE 5: Ground temperatures at 1 m depth from Menengai to L. Baringo

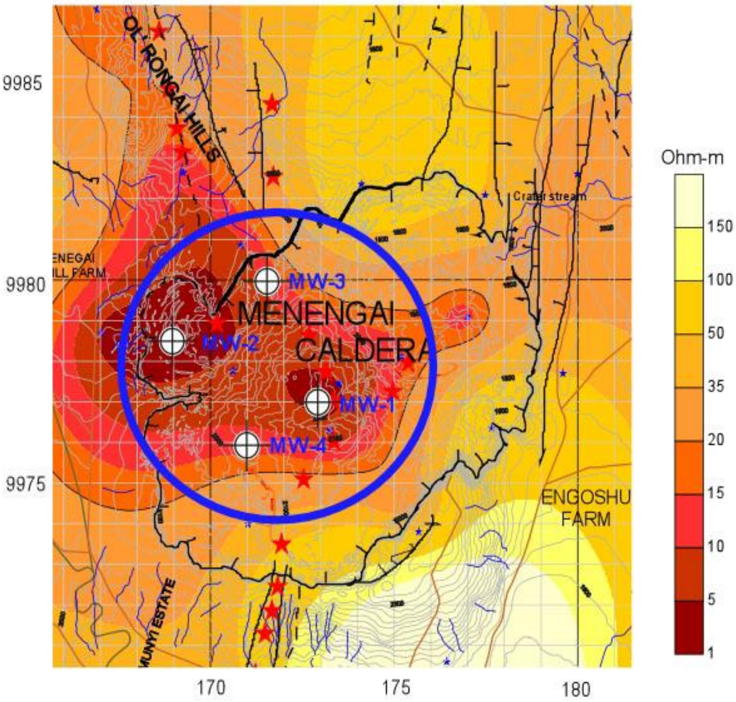

FIGURE 6: MT resistivity at 2000 m b.s.l. and proposed well site locations

The mapped potential area is about 40 Km^2 translating to over 700 MWe of electric power (Figure 6). 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. The reservoir rocks are expected to be trachytes 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. From geothermometric estimates, the reservoir is expected to be at more than 300°C.

4. LONGONOT

Longonot geothermal prospect occurs within the Longonot volcanic complex which is dominated by a central volcano with a summit crater of about 35 km^2 and a large outer caldera (Figure 7). Geothermal surface manifestations are mainly fumaroles. KenGen carried out surface studies at Longonot in 1998 and the results suggest that Longonot has a centralized magma chamber beneath the summit crater. Resistivity data shows a low anomaly that covers about 70 km^2 (Figure 8). The Geochemical analysis projected reservoir temperatures in excess of 300°C. CO_2 and Radon counts at Longonot and Olkaria are similar. These together with similar reservoir rocks expected, suggests that the reservoir characteristics of the two could be comparable. The heat source is expected to be at 6 km deep (KenGen, 1999). Three exploration wells have been sited and will be drilled soon. Estimated power potential is over 200 MWe (BCSE, 2003, Omenda et al., 2000).

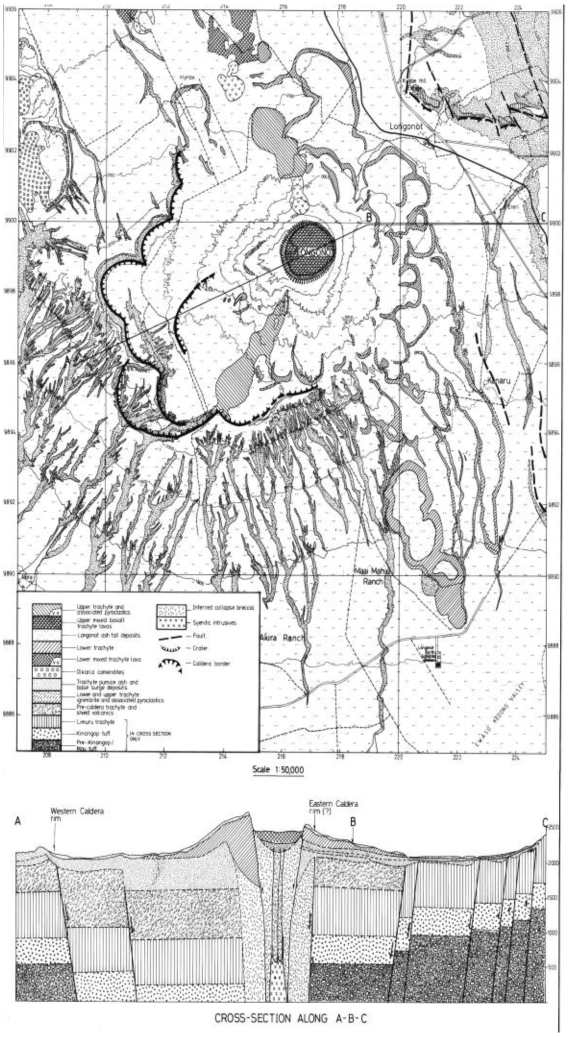

FIGURE 7: Geology of Longonot prospect (Lagat, 1998)

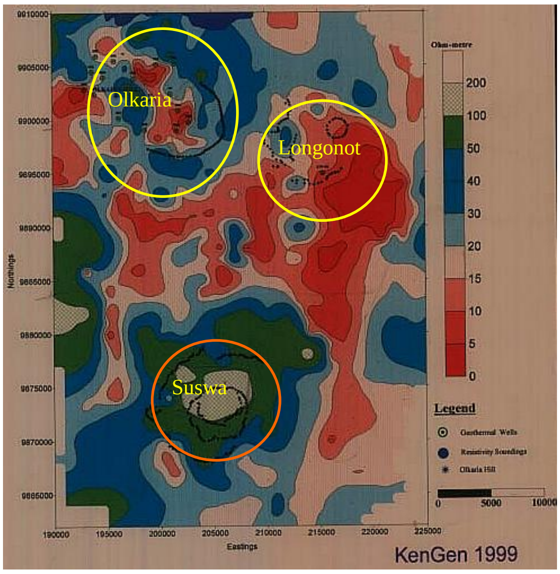

FIGURE 8: Resistivity map of Olkaria, Longonot and Suswa (KenGen, 1999)

5. SUSWA

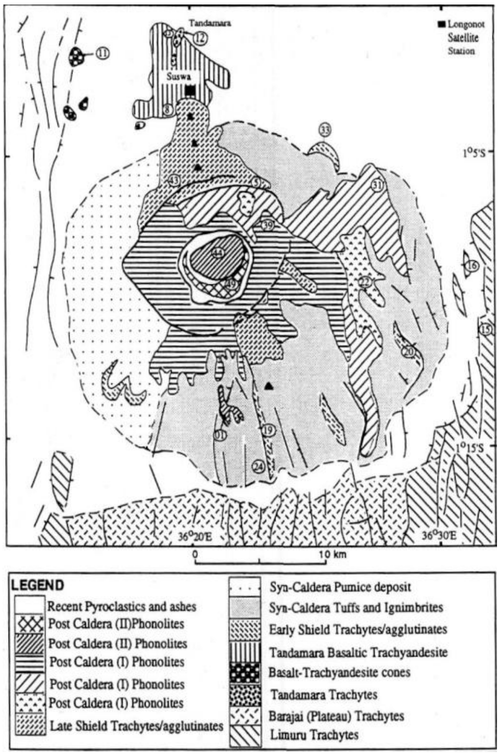

FIGURE 9: Suswa caldera (Omenda, 1997)

Suswa is a Quaternary caldera volcano in the southern part of the Kenya rift. The prospect has a central volcano with an outer and inner caldera (Figure 9). The inner caldera has a resurgent block with a trench around it. The diameter of the outer caldera is 10 km while that of the inner is 4 km. Volcanism at Suswa started about late Pleistocene and the earliest products overlie the faulted Plateau Trachyte of late Pleistocene epoch. The Plateau Trachyte Formation comprises of flood trachytes that erupted on the developing graben. The age of the recent volcanism is <1000 years and this resulted in the formation of the annular trench and the Island block while the oldest forming the outer caldera is 400±10 ka (Omenda et al., 2000). Surface manifestations occur around the margins of the outer and inner caldera, on the Island block and in the trench surrounding it. These include fumaroles, steam jets, steaming and hot grounds and solfatara with temperatures of over 93°C.

Results from detailed surface studies done by KenGen in 1993 and 1994 suggest reservoir temperatures of 220°C to 300°C which is comparable to that at Olkaria. High amount of $C0_2$ in the fumaroles sampled indicated high fracture density. Low amount of H_2S in the sampled steam suggests influence of steam condensate or shallow ground water on the fumaroles. Relatively high pH of the condensate supports this mixing hypothesis (Muna, 1994). Seismic and gravity studies show that the heat source under the caldera is at 8 to 12 km deep with a NE-SW bias. Resistivity at 1000 ma.s.l indicates a low (15-20 ohm m) anomaly under the island block and extends to the north out of the inner caldera. Another low was obtained to the NW of the inner caldera close to the wall of the outer caldera (Figure 8). This resistivity value is high compared to Olkaria and even Longonot where values of less than 10-15 ohm-m were obtained. This could possibly be due to low bulk permeability and low level of alteration. Lack of low resistivity at shallower depths suggests that the reservoir is deep. This suggests that the resource area at economical depth could be small.

Proximity of the resource to the rift flanks suggests good recharge but the lack of hot springs indicate a deep water table. It is postulated that dikes may be abundant in the prospects and hence act as hydrological barriers and may compromise reservoir permeability. Three exploration wells were sited within the anomalous region (KenGen, 1999). The power potential of the prospect is about 100 MWe (Omenda et al., 2000).

6. LAKE BARINGO

Lake Baringo geothermal prospect is in the northern part of the Kenyan rift. Surface manifestations include fumaroles, hot springs, thermally altered hot grounds and anomalous ground water boreholes. The Kenya Government and KenGen carried out surface studies in 2004 (Mungania et al., 2005). The geology indicate occurrence of trachyte and trachy-phonolites to the east and west while basalts occur to the north and alluvial deposits to the south (Figure 10). Lack of a centralized volcano or a caldera in this prospect suggests that its reservoir characteristics may be different from that of the prospects mentioned above. However geology of this prospect is expected to compare well with that of Lake Bogoria and so are the two reservoirs (see Section 9).

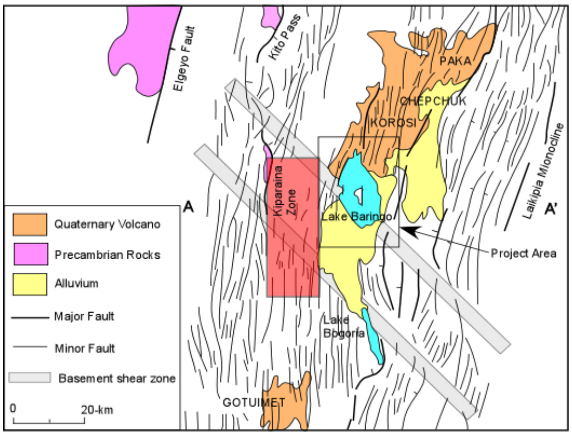

FIGURE 10: Geology of L. Baringo and L. Bogoria prospects (Mungania et al., 2005)

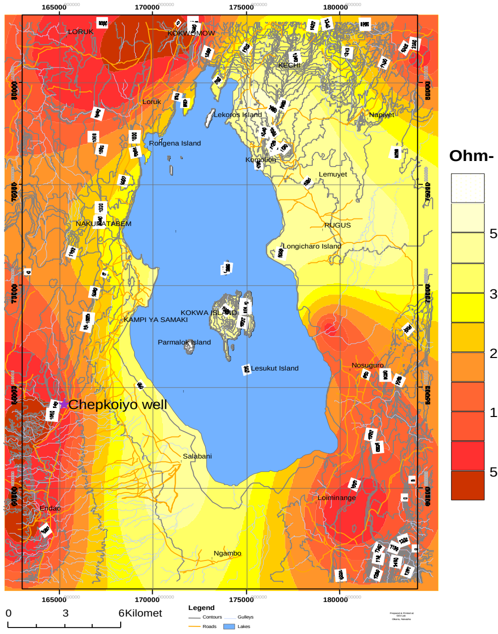

FIGURE 11: Resistivity at sea level at L. Baringo prospect

Resistivity at sea level indicates occurrences of fault controlled, discrete possible resource areas in the west of the Lake (Figure 11). Fluid geothermometry indicate reservoir temperature of over 200°C near the Chepkoiyo well, west of Lake Baringo. Heat flow surveys indicate that the prospect loses about 1049 MWt to the atmosphere with 941 MWt being the conductive component (Ofwona, 2004). Results of this survey are plotted in Figure 5. The prospect is not associated with a centralized volcano and the heat sources are probably deep dyke swarms along the faults. Drilling deep slim holes that can be geologically logged and be used to determine temperature gradients and reservoir permeability has been recommended for the prospect.

7. ARUS AND LAKE BOGORIA

Arus and Lake Bogoria is an area of volcanic rocks with no observable central volcano. Geothermal manifestations mainly hot springs, geysers, hot grounds, fumaroles and steam jets occur along the shore of Lake Bogoria and at Arus. One of the hot springs is used for heating at a near by hotel. Surface studies are still ongoing. Preliminary results suggest that the heat source could be due to intrusives. Geothermometry indicates moderate reservoir temperature (Karingithi, 2005). Heat loss survey indicates that L Bogoria area loses about 1199 MWt while Arus loses 467 MWt (Figure 5). Heat loss at Arus is mainly conductive with negligible convective component. Convective heat loss at L Bogoria is about 437 MWt (Mwawongo, 2000). From geological observations, reservoir characteristics of this prospect are expected to compare well with those at L Baringo (Figure 9).

8. OTHER GEOTHERMAL FIELDS

The prospects that occur to the north of Lake Baringo include Korosi, Chepchuk, Paka, Silali, Emuruagogolak, Namarunu, and Barrier volcanoes. Plans are underway to undertake surface studies at Korosi and Chepchuk from 2005 to 2006. The other prospects in the north will systematically be studied under the ongoing GRA exercise. It is believed that the caldera volcanoes in the north host large geothermal systems as manifested by the Kapedo hotsprings at Silali volcano that discharge fluid at 1,000 litres/sec at 55°C. Other prospects include Lake Magadi and Badlands.

9. DISCUSSION

Results from surface studies conducted under the GRA program are summarised in Table 1. Eburru prospect was included in the analysis for comparison purposes but not for ranking since the field has been proven by deep drilling. From geology central volcanoes are associated with Menengai, Longonot and Suswa. Trachytes as the expected reservoir rocks dominate the same prospects but Suswa has phonolites that were from recent volcanism. This may seal older faults making Suswa have low permeability compared to Menengai and Longonot. As for the age of volcanism, all the volcanoes have comparable ages of last activity. Higher reservoir temperatures are associated with young age.

From surface manifestations, areas covered by Suswa and Longonot are the same while smaller area covers manifestations at Menengai. This may suggests that resources at Longonot and Suswa are bigger than that at Menengai or alternatively the resource at Menengai is better capped.

The low resistivity anomaly at Suswa still has higher resistivity values (15-20 ohm-m) as compared to Longont and Menengai (10-15 ohm-m). This suggests a better resource in the later two. Gravity indicates a deeper heat source at Suswa followed by Longonot and the shallowest being at Menengai. Also shallow low resistivty at Menengai suggest shallow permeability as compared to Suswa and Longonot.

Geothermometry suggest low reservoir temperatures at Menengai compared to both Suswa and Longonot but lack of hot springs in the prospect make these results unreliable. Silica (quartz) geothermometer related to hot springs is more reliable than gas geothermometer. For this reason, the reservoir temperatures computed need to be treated with caution. Only deep drilling can give a good reservoir picture in these prospects.

Heat sources at Arus, L. Bogoria and L. Baringo prospects are associated with dyke swarms and not centralized volcanoes. Dykes are related to low temperature systems while centralized volcanoes most often results in high temperature reservoirs. This makes the prospects be ranked low as compared to the ones discussed above. When compared, L Baringo appears a smaller resource than both Arus and L Bogoria. From the active manifestations at L Bogoria, the same appears better than Arus. However, geology of the prospects suggests similar reservoir characteristics in terms of reservoir rocks and permeability.

Heat loss survey has not been conducted in all the studied prospects except at Menengai, Arus, L Bogoria and L Baringo (Ofwona, 2004a, Ofwona, 2004b, Mwawongo, 2005). It's important to note the limitations of this method in that high heat loss may not necessarily mean a big resource. Big reservoirs may have low heat loss due to sound surface cover like Olkaria with 400 MWt yet it is a proven big resource (Mahon, 1989).

The already explored prospects dissipate over 6,338 MWt naturally to the atmosphere. With the other prospects north of L Baringo yet to be explored, this figure is bound to rise. This is further evidence that power potential in the Kenyan rift is high. The high convective heat loss at Menengai suggests that the prospect is well recharged. High heat loss at L Bogoria suggests a larger resource compared to L Baringo.

Although Menengai is estimated to have a huge potential the mapped hot area is still smaller than that at Olkaria of over 80 km^2. However, the area may be extended when exploration drilling and subsequent development of the area starts. The Agro based industries close to Menengai can utilize geothermal heat for their processes. Space heating of greenhouses in the surrounding farmlands can also be enhanced. This will greatly increase direct utilizations of geothermal heat in Kenya which is currently low.

TABLE 1: Summarized results

RANK	Name of prospect	Geological setting	Age of last volcanism	Nature of geothermal activity	Area of activity (km2)	Max. measure surface T (°C)	Geothermometry (°C)		Geophysical indications	Heat source
							Range	Ave.		
3	Suswa	Central volcano with two calderas and N-S trending fissure zone. Volcano active between 400ka – Recent and dominated by phonolite. Dike swarms thus permeability compromised. Rocks are dominantly trachytes and phonolites	0.24 Ma-400 yr BP (est)	Fumaroles, steaming and altered grounds. Deposits of sulphur occur within the annular trench. Altered lithics (T>250°C) common.	3	93	230-310	265	High gravity in the south of caldera which is also the most seismically active. 15-20 ohm-m anomaly, strong magnetic anomaly, shallow attenuating bodies.	Large magma chamber at shallow depth (8-12 km) immediately below Caldera II.
1	Menengai	Central caldera volcano. The volcanic activity has been active since 0.2 Ma to present. The volcano is built dominantly of trachyte lavas.	1.4 ka 0.7-0.3 Ma	Medium strength fumaroles, steaming, and altered grounds. Scarce manifestations within Menengai caldera. Boreholes in the immediate neighbourhood discharge steam and warm water.	<2	90 67	170-220 170-220	200 200	Resistivity lows occur within the caldera floor with bias to the NE. High, shallow seismicity under the caldera. High gravity anomaly occurs superimposed on a regional low associated with the caldera.	The main heat source is associated with a magma chamber at 6km under the caldera as shown by seismics, MT and gravity.
4	L. Bogoria and Arus	No clear magmatic and volcanic association noted. However, the Plio-Pleistocene lavas that cover the area are extensively faulted.	<1.6 Ma	Hot springs, geysers, and steam jets common and occur along fault zones. The springs discharge at low temperatures. CO_2 gas emissions common. Hot water boreholes.	2	98	120	120	High gravity and positive magnetic anomaly. Intense, deep (>15km) seismicity on the east along Marmanet fault. Low resistivity occurs to the east of Lake Bogoria	No magmatic body anticipated. Heat probably associated with dike swarms.
NR	Eburru	The volcanic massif is built dominantly of trachytes, rhyolites and their pyroclastic equivalent. The eastern volcano which is more promising has a pseudo craters defining a small caldera structure.	28 ka	Fumaroles, steaming and altered grounds occur along crater walls and N-S faults. The hydrothermal zones in Eburru contain alteration minerals such as kaolinite, smectite, native sulphur, and sinter.	>3	93	285	285 (Actu.)	Low resistivity anomaly (15ohm-m) enclosed by the ring of craters define the resource. High gravity body under the volcano.	Centralized solidified dense body under the massif. No molten body expected at shallow depth.
2	Longonot	Quaternary caldera volcano with summit crater. Latest lava flow was inside the crater and along NW-SE volcano tectonic line. The rock types are mainly trachytes and mixed basalt-trachyte lavas.	0.4 Ma -400 BP	Fumeroles, hot grounds, altered grounds along walls of the crater.	2	93	300	300	Low resistivity anomaly (10 ohm-m) on the southern slopes of the summit volcano and extending southwards along NW-SE fault line.	Centralized magmatic body under the summit volcano at 6km depth.
5	Lake Baringo	No clear magmatic and volcanic association noted. However, the Plio-Pleistocene lavas that cover the area are extensively faulted.	<1.6 Ma	Weak fumaroles, altered ground, hotsprings and sulphur deposits. Hot water boreholes.	<1	98	280	280	N-S fault controlled low resistivity anomaly on the west side of the lake.	No magmatic body anticipated. Heat probably associated with dike swarms.

It is important to note that exploration drilling is currently lagging far behind surface investigations due to high cost of drilling as opposed to surface work. Proper ranking of these prospects and energy utilization strategy is only possible after exploration drilling. Therefore, lack of drilling is also discouraging development of geothermal resources in Kenya as well as speeding up diversification of utilization of geothermal energy.

Kenya has saved over 4.900 million US$ in fuel cost at GOGA through geothermal power generation hence proposed early generation at Eburru should be encouraged even in other prospects to start early revenue generation that could enhance studies and development of other resources. This practice will also greatly reduce the cost of well head maintenance in fields already with exploration wells.

Even after the recent studies done under GRA, Eburru development should proceed as planed due to the already existing drilled wells and infrastructure. As for exploration drilling, so far Menengai appears most promising as compared to Longonot and Suswa. Longonot appears better than Suswa.

10. CONCLUSIONS

Geothermal development in Kenya has been slow. With implementation of the ongoing GRA, surface studies of all the prospects in the rift north of Olkaria will be complete by 2010. Exploration drilling at Menengai should be of high priority. Longonot and Suswa reservoir characteristics may be similar to that at Olkaria while that at Arus, L Bogoria and L Baringo may be the same but different from Olkaria. Deep NW-SE crustal faults control occurrence of heat sources in the rift while thinning of the earths crust has resulted in high temperature gradients north of Menengai Kenya will save a lot in foreign exchange through development of its geothermal resources.

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LECTURE 5

GEOTHERMAL EDUCATION IN AFRICA – PAST EXPERIENCE AND FUTURE PROSPECTS

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ABSTRACT

Group training of candidates from developing countries in geothermal technology started at the International School at Pisa (Italy) and at Kyushu University (Japan) in 1970. In 1979, training started at the Geothermal Institute (Auckland) and UNU-GTP (Iceland). Since then, 1689 scientists and engineers have been trained worldwide. As at 2004, geothermal professionals trained at Pisa – Italy, Kyushu-Japan, GI-Auckland and UNU-GTP were 322, 385, 654 and 318 respectively. Of the 1689 geothermal professionals worldwide, Africa has 282 (approx. 17%). Training of these scientists and engineers from Africa on geothermal energy development technologies at the three institutions has been very useful. Graduates trained are among the leading specialists in geothermal research and development in their countries. This will continue to be as more countries diversify their power generation mix to include geothermal as an indigenous and environmentally friendly and renewable source of energy. Some countries are already ahead of others in manpower development and thus those still behind will require training to build up the necessary human capacity. All these training needs will be realised if UNU-GTP will continue with the current training assisted by the establishment of East African Geothermal Resources Centre for shorter courses and practical field training.

1. INTRODUCTION

Training in geothermal technology that started in 1970 at the International School at Pisa (Italy) and at Kyushu University (Japan) were non-degree overview type courses. These lasted between 9 and 2 months in Pisa and 4 months in Kyushu. This decade saw a rapid expansion of geothermal projects in developing countries sponsored by international and bilateral aid. Overview teaching, however, could not cope with demand for specialized and academic type training. At the request of the UN Development Programme (UNDP) and with the support of the NZ Ministry of Foreign Affairs (MFA), the Geothermal Institute (GI) was established in 1978 at the University of Auckland (UA). Its purpose was to offer a post-graduate, 10 months academic Diploma course for earth scientists and engineers (Hochstein, 2005). After this course started in Auckland, a 6-months training course began at Reykjavik (Iceland) in 1979 as part of a United Nations University training programme (Fridleifsson, 2005).

2. WORLD GEOTHERMAL RESOURCE USE

On a global scale geothermal resources constitute a small, yet rapidly growing, energy resource. It is a very important renewable energy source for many countries. In the year 2000 geothermal energy constituted about 0.25% of the annual worldwide energy consumption (Friðleifsson, 2001) and had been identified in more than 80 countries and utilisation of the resource had been recorded in 58 countries in the world. Geothermal energy, as natural steam and hot water, has been used for decades to generate electricity, in space heating and industrial processes. In 2005 a total of 24 countries were generating electric power from geothermal resources (Bertani, 2005) and 71 countries were using geothermal energy directly (Lund et al., 2005). The world installed electrical capacity from geothermal resources is 8,900 MWe (year 2005). In developing countries, where total installed electrical power is still small, geothermal energy still plays a significant role. Various countries have plans to increase the use of geothermal resources and by 2010, the total installed capacity is expected to reach over 10,000 MWe (Bertani, 2005). The thermal capacity of non-electrical uses (greenhouses, aquaculture, district heating and industrial processes) is 72,622GWh/yr (year 2004, Lund et al., 2005).

2.1 Geothermal use in Africa

Among African countries, Kenya has been generating electricity since 1981 and Ethiopia started in 1998. These are the only countries in Africa producing electricity from geothermal steam. Since Kenya commissioned its first 45 MWe geothermal power plant at Olkaria East in 1981, it has been producing electricity with an availability factor of over 95%. An Independent Power Producer (IPP) commissioned an additional 12 MWe as a pilot plant for Olkaria III. Olkaria II (70 MWe) was commissioned in 2003, and the extension of Olkaria II by 35 Mwe and Olkaria III by 36 MWe is expected to start soon. Oserian Development Company - a flower-growing firm, commissioned a small project with a 2.0 MW binary plant in September 2004 in Olkaria. Ethiopia commissioned its first 8.5 MWe geothermal plant in 1998 at Aluto in the Lakes District (Teklemariam et al., 2000). Exploration for high temperature resources (for electricity production) has also been conducted in Cape Verde, Djibouti, Eritrea, Tanzania, Uganda and Zambia (Fridleifsson, 2001).

Many African countries have made some direct uses of their geothermal resources. These countries are Algeria, Egypt, Ethiopia, Kenya, Tunisia, and Zambia. Tunisia, which is one of the world leaders in the use of geothermal energy for greenhouse heating and irrigation, is currently leading in Africa with about 110 hectares of greenhouses being heated with geothermal. This development has mainly taken place in oases (Kebili, Tozeur and Gabes) in the Sahara desert (Mohamed, 2005). In Kenya, Oserian Development Company, a flower-growing firm utilizes a steam well leased from KenGen, on the Olkaria field. A heating system was installed in May 2003 and carbon dioxide from the well is also used for the flowers photosynthesis. The system started off by heating 3 hectares, was expanded to 30 hectares and is now being expanded to 40 hectares. Greenhouse heating amounts to 79.1 TJ/yr and a capacity of 10 MWt. (Lund et al., 2005). Hot springs have also been identified in Burundi, Zambia, Cape Verde, Madagascar, Malawi, Mozambique, Uganda, and Zimbabwe (Fridleifsson, 2001).

3. WORLD TRAINING IN GEOTHERMAL ENERGY DEVELOPMENT

In order to realise faster development in geothermal resource utilization, Africa requires trained manpower. The main institutions that have taken a leading role in geothermal technology training are the UNU/GTP in Iceland, the Geothermal Institute at the University of Auckland in New Zealand, the International Institute for Geothermal Research in Pisa, Italy, and Kyushu University - Japan. By 1992, the school at Pisa had trained a total of 324 students from 68 countries in various courses. Of this total, there were 43 Africans, 117 Latin Americans, 113 Asians, and 49 Europeans (Hochstein, 2005). On the other hand, the Geothermal Institute at University of Auckland had trained 96 Africans out of a total of 638 by the year 2002. Similarly, 61 Africans (16%) out of a total of 385 had been trained in Japan by the year 2001. Of the 318 students trained by UNU-GTP by 2004, there were 140 Asians, 45 Latin Americans, 82 African and 51 European (Table 1.) Except for the Iceland training, all the other three have now been discontinued.

From Table 1, expansion in Total Geothermal Installed Generating Capacity over the years relates directly to geothermal human capacity that has been developed over the years. For Africa, geothermal installed capacity vis-à-vis human capacity expansion over the years has not been proportional due to lack and/or limited funding towards geothermal development. Asia is at the top in terms of geothermal installed capacity and trained geothermal professionals. It thus becomes a very good example when planning capacity building activities for geothermal professionals in the developing countries. This direct connection between increase in installed capacity and trained manpower is an excellent example of the impact of capacity building in geothermal energy technology on geothermal development.

TABLE 1: Student population at international geothermal training courses
and total installed capacity (MW)

Institution	**Continents**					
	Asia	**Latin America**	**Africa**	**Europe**	**Total**	**Ref.**
Kyushu, Japan (1970-2001)	165	120	61	39	385	1
Pisa, Italy (1970-1992)	113	117	43	49	322	1
Auckland (GI), New Zealand (1979-2002)	443	103	96	22	644	1
UNU-GTP, Iceland (1979-2004)	140	45	81	51	317	2
Total	**861**	**385**	**281**	**161**	**1688**	
Tot. inst. capacity by 2005 (MW)	**3291.3**[a]	**1377**[b]	**134**[c]	**921.2**[d]	**5723.5**	3
1 - Hochstein, 2005; 2 - Fridleifsson, 2004; 3 - Bertani, 2005						

3.1 Specialized geothermal training in Iceland

The Geothermal Training Programme of the United Nations University (UNU-GTP) was established in Iceland in 1978 when Orkustofnun (the National Energy Authority) became an Associated Institution of the UNU (United Nations University, 1979; Fridleifsson, 2003). Since 1979, a group of professional scientists and engineers from the developing and transitional countries have spend six months in highly specialized studies, research, and on-the-job training in geothermal science and engineering. Since the foundation of the UNU-GTP, 317 scientists and engineers from 39 countries have completed the annual six month specialized courses offered. Of these, 26% have come from Africa. In Africa UNU-GTP graduates are among the leading specialists in geothermal research and development.

Other international institutions that offered geothermal training to professionals from Africa include three international geothermal schools, which were established in Italy (Pisa in 1970), Japan (Kyushu in 1970), and New Zealand (Auckland in 1978). The Pisa school has not held its annual course since 1993 due to drastic cuts in government financing, but has occasionally held short courses (1-3 weeks) in developing countries. The International Group Training Course at Kyushu University was closed in 2001 and the Diploma course at Auckland University in 2003 due to withdrawal of government financing (see Fridleifsson, 2005, Hochstein, 2005). Auckland University will, however, continue admitting students to MSc and PhD studies in geothermal as part of its regular activities. Kyushu

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[a] Asia - China, Indonesia, Japan, Philippines & Thailand

[b] Latin America - Costa Rica, El Salvador, Guatemala, Mexico & Nicaragua

[c] Africa – Kenya & Ethiopia

[d] Europe – Austria, France, Germany, Italy, Portugal, Russia & Turkey

University started a new doctoral course (with Japanese Government Scholarships) entitled "International Special Course of Environmental Systems Engineering" in 2002 (Fridleifsson, 2005). The UNU-GTP is thus at present the only international graduate school offering specialized training in all the main fields of geothermal science and engineering.

During the 25-year period 1979-2004, 317 scientists and engineers from 39 countries have completed the six-month programme in Iceland (Fridleifsson, 2004). Of these, 44% are from Asia, 26% from Africa, 14% from Latin America, and 16% from Central and Eastern Europe. Among the 317 graduates of the UNU/GTP, by 2004, eighty one (81) of the Fellows came from ten African countries (Table 2). These are from Algeria (3), Burundi (1), Djibouti (1), Egypt (3), Eritrea (3), Ethiopia (22), Kenya (35), Tanzania (1), Tunisia (6), and Uganda (6). Most of the participants have been on fellowships from the UNU and the Government of Iceland, but some have studied on fellowships from UNDP and the International Atomic Energy Agency (IAEA).

They have had specialized training in the following fields

- Geological exploration: Practical training in basic geological and geothermal mapping, which is commonly the first step in the geothermal exploration of an area.
- Borehole geology: Making geological logs, analyses of drill cuttings and cores. The identification of alteration minerals (microscope and x-ray diffraction) and the interpretation of the alteration mineralogy form an integral part of the course.
- Geophysical exploration: Practical training in conducting geophysical surveys of geothermal areas and interpretation of such data. Emphasis is on the application of computers in the interpretation.
- Borehole geophysics: Essentials of geophysical measurements in boreholes used for geothermal investigations, with an emphasis on temperature and pressure measurements.
- Reservoir engineering: Methodology needed to obtain information on the hydrological characteristics of geothermal reservoirs and to forecast the long-term response of the reservoirs to exploitation.
- Environmental studies: Environmental impact assessments (EIA), laws and policies, the planning and execution of EIA projects and environmental auditing. Scientific methods suitable for environmental monitoring are assessed and biological impact, pollution and occupational safety considered.
- Chemistry of thermal fluids: The role of thermal fluid chemistry in geothermal exploration and exploitation, including sampling, analysis of major constituents and the interpretation of results.
- Geothermal utilization: Civil, mechanical and chemical engineering aspects of geothermal fluids in pipes, equipment and plants. The feasibility of projects and environmental factors are also considered.
- Drilling technology: Provides engineers with the information and on-site training necessary to prepare them for the work of drilling engineers or supervisors. The course deals with the selection of drilling equipment, well design and casing programs, cementing techniques, and the cleaning and repairs of production wells.

Since 2000, MSc degree courses were introduced in cooperation with the University of Iceland. These are geothermal professionals who had attended the six month course. Four Kenyans have already completed their MSc course in reservoir engineer, geology, geochemistry and environmental science. In 2004, an environmental scientist from Uganda started his MSc studies. In 2005, two more scientists from Kenya started their MSc studies majoring in geochemistry and environmental science.

3.2 Geothermal training for African professionals

Kenya is the leading country in geothermal research and development in Africa. Most of the geothermal specialists in the country have been trained in Iceland. With the advanced training of the MSc students (Table 2), the UNU-GTP is assisting Kenya in bringing geothermal research to a higher level. It is hoped that, in the future, Kenya will be in a position to assist neighbouring countries by training some of their scientists and engineers. At present, Kenya obtains about 10% of its electricity from geothermal energy. The government plans to increase this figure to 20-25%. The UNU-GTP will support this aim (Fridleifsson, 2005).

TABLE 2: Internationally trained geothermal professionals from Africa

Country	**UNU-GTP (1979-2004)**	**UNU-GTP (MSc) (2001-2004)**	**UoA (GI) (1979-2002)**	**Pisa, Italy (1970-1992)**	**Kyushu, Japan (1970-2001)**
Algeria	3				
Burundi	1				
Djibouti	1				
Egypt	3				
Eritrea	3				
Ethiopia	22				
Kenya	35	4	27	1	1
Tanzania	1				
Tunisia	6				
Uganda	6	1			
Total	**81**	**5**	**96**	**43**	**61**

4. FUTURE PROSPECTS

The three international geothermal schools have played a major role in geothermal manpower development for third world countries especially Africa. Countries like Kenya and Ethiopia now have the capacity to carry out surface geothermal exploration, drilling and reservoir monitoring, and environmental impact assessments. Other countries like Uganda, Eritrea, and Tanzania have not yet attained the capacity to carry out exploratory work.

4.1 United Nations University - GTP

The only remaining geothermal training institution – UNU-GTP would therefore continue to play a major role in assisting such countries attain the necessary capacity. With an assurance of UNU-GTP continuation with its core activity i.e. specialized six month training, more geothermal professionals from African countries will be trained. After 25 years of UNU-GTP operations, their experience strongly suggests that to make technology transfer successful and sustainable, it is necessary to build core group of at least ten geothermal specialists in a given country (see Fridleifsson, 2005). This gives further chance to expand Africa's geothermal specialist. Suggestions of starting regional geothermal resources facilities such as the East African Geothermal Resources Centre (training centre) in Kenya have been there. The proposed centre would be used for training people from the region, archiving important documents/data, and acting as a coordination centre for geothermal activities in the region (see Mwangi, 2003).

The Government of Iceland made a further commitment at the International Conference for Renewable Energies (in Bonn, June 2004) to provide the core funding for short specialized courses in geothermal development conducted in selected countries in Africa, Asia, and Central America. The courses will be set up by the UNU-GTP in cooperation with the local organizations. These are energy agencies/utilities and earth science institutions responsible for the exploration, development and operation of geothermal energy power stations. With longer term goals of the United Nations University and the UNU-GTP being to assist in the establishment of formal training centres with former UNU Fellows as main teachers in countries like China, El Salvador, Kenya, and Philippines; geothermal training in Africa stand to benefit immensely (see Fridleifsson, 2005).

4.2 Geothermal training under ARGEO

Among the planned new activities for UNU-GTP (2005-2008) will be to conduct short courses in Africa (Kenya, Ethiopia, Uganda) under the Renewable Energy Efficiency Partnership -REEEP initiative (established after the Johannesburg Summit in 2002) (Fridleifsson, 2005, Fridleifsson, 2003). The first course is to be held in Kenya in 2005 in collaboration with Kenya Electricity Generating Company (KenGen) and the UNEP/GEF African Rift Geothermal project (ARGEO) with participants from Kenya and neighbouring countries with geothermal resources. The teaching will be in the hands of former UNU Fellows in Kenya and the regular teachers of the UNU-GTP, but there will also be lectures by specialists from GEF and UNEP. Funding is partly provided by the Government of Iceland, but co-financing will be sought with energy utilities in the region as well as international development agencies (Fridleifsson, 2005).

The first short course in Africa is to be held at Lake Naivasha Simba Lodge in Kenya 12-18th November 2005 in collaboration with KenGen and the African Rift Geothermal Facility (ARGeo). ARGeo has recently been established by the United Nations Environment Programme (UNEP), the Global Environment Facility (GEF), several African countries, and aid agencies from several countries. Participants in the course will come from Kenya and neighbouring countries with geothermal resources suitable for electricity production (e.g. Djibouti, Eritrea, Ethiopia, Tanzania, and Uganda). A part of the objective of the course is to increase the cooperation between specialists in the respective African countries in the field of sustainable development and use of geothermal resources.

The first course in Kenya will be planned as an opening course in an ARGeo course series. The tentative title of the course is ‘Short Course for Decision Makers on Geothermal Projects and their Management’. It is obvious that many decision makers in the region are not aware of what geothermal resources can do for their respective countries. These decision makers therefore assign very little human and financial resources to geothermal development. This opening course will be aimed primarily at these potential prime movers of geothermal project activities in the ARGeo countries. The course will give an overview of the planning, financing and execution of geothermal projects. The course will include; preparation of documents needed for proposals for financing of geothermal projects at different stages of development, and the requirements and preparation of data for the leasing of geothermal fields to private investors.

4.3 Geothermal training centre in Kenya

There have been suggestions of starting regional geothermal resources facilities such as the Geothermal Training Centre in Kenya. The proposed centre would be used for training people from the region, archiving important documents/data, and acting as a coordination centre for geothermal activities in the region. It is suggested that this sort of centre can be started as part of the UNU under the UNU/GTP curriculum, and with Iceland’s support, to increase the yearly total number of trainees while cutting down on the travel costs. This can be done by the UNU providing the expertise, with additional assistance of available experts in the region. This would help in developing further the expertise in the region, and would provide training to the locals in their surrounding environment. This has the advantage of developing home-based solutions to problems. Olkaria in Kenya has been identified as the ideal site for a regional geothermal training centre in East Africa because KenGen has the basic manpower and facilities to provide hands-on training in all phases of geothermal development from geothermal exploration to operation of geothermal power plants. The training centre will initially start with short courses with emphasis on the practical training on i) field data collection and processing, ii) equipment repair and maintenance iii) laboratory sample handling and analysis, iv) providing graduates from neighbouring countries field experience and data in preparation for the 6 months UNU-GTC training in Iceland. KenGen has thus drafted a plan for a geothermal training centre at Olkaria with six weeks annual training courses. It is hoped that some of the trainees from this school would go to the UNU-GTP for advance training.

In addition to the formal training, three geothermal conferences have been held in Nairobi. During the last conference in 2004, it was agreed that the Nairobi conference be called Eastern Africa Conference and to be held in different countries in the region so as to reach many different participants. The next conference will be held in Addis Ababa, Ethiopia in November 2006.

5. CONCLUSIONS

Training of scientists, engineers and technicians from Africa in the field of geothermal energy development technologies has been very useful and will continue to be useful as more countries diversify their power generation mix to include geothermal as an indigenous and environmentally friendly source of energy. Some countries are already ahead of others in manpower development thus those still behind will require training to build up the necessary manpower. All these training needs will be realised if UNU-GTP will strive to attain its target of ten trained geothermal experts per country, continued UNU funded training in specialised areas for countries ahead in man power and the establishment of the East African Geothermal Resources Centre under ARGeo, which has recently been established by the United Nations Environment Programme (UNEP).

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