# GEOTHERMAL MAPPING USING TEMPERATURE MEASUREMENTS

Martha Mburu

Reservoir Engineer
Kenya Electricity Generating Company (KenGen)
P.O Box 785 Naivasha, Kenya
Tel: +254 50 50916, Fax: +254 50 2021223
mmburu@kengen.co.ke

## ABSTRACT

Geothermal energy is the heat from the earth's inner core which is always moving outward to the surface or near the surface. The geothermal heat manifests itself on the surface in form of hot ground, hot springs, geysers and fumaroles.

Geothermal mapping using temperature measurements commonly referred to as heat-loss measurements, employ the principle of heat transfer to quantify the heat energy lost to the surface naturally. The normal conductive temperature gradient is about 0.03°C per meter but the presence of a hot body, "near" the earth's surface, results in an elevated temperature gradient. Elevated temperature gradient can also result from thinning of the earth's crust as is the case in the floor of the East African Rift Valley. Although geothermal temperature gradient varies from place to place, it averages 25-30°C per km).

Heat-loss survey methods, together with other geo-scientific studies have been used during the geothermal surface exploration stages to map two existing geothermal fields and in other six geothermal prospects within the Kenyan Rift Valley. This paper discusses the use of heatflow measurement during geothermal surface exploration and shows some examples of heat-loss survey work done in the Kenyan part of the East African Rift Valley and how this has been used in the development of geothermal conceptual models.

## 1.0 INTRODUCTION

Geothermal energy has been around for as long as the earth has existed. The earth is an oblate spheroid composed of a number of different layers, the core, the mantle and the crust (Fig 1). The core, which is approximately 7000 kilometers in diameter, is located at the earth's center. The mantle surrounds the core and has a thickness of 2900 kilometers. The top layer of the mantle is a hot liquid rock called magma and the crust floats on top of the mantle. The crust is composed of basalt rich oceanic crust and granitic rich continental crust. The crust, is rigid and very thin and brittle compared with the other two. Beneath the oceans, the crust varies little in thickness, generally extending only to about 5 km. However, thickness of the crust beneath continents is much more variable but

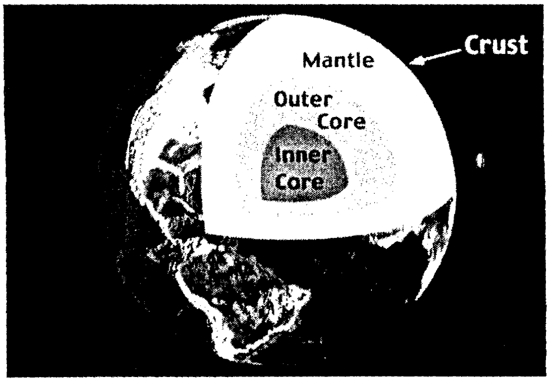


**Figure 1: The Earth's structure**

averages about 30 km. However under large mountain ranges, the base of the crust can be as deep as 100km.

## 2.0 CONTINENTAL RIFTING:

There has been considerable discussion on continental rifting over the years. Some have ascribed it to up-doming of the crust over a hot-spot; certainly parts of the E African rift system are very elevated, compared with other sectors, suggesting that the doming reflects an underlying hot low-density mantle plume. In other cases, geophysical models suggest the asthenospheric mantle is rising to high levels beneath the rift.

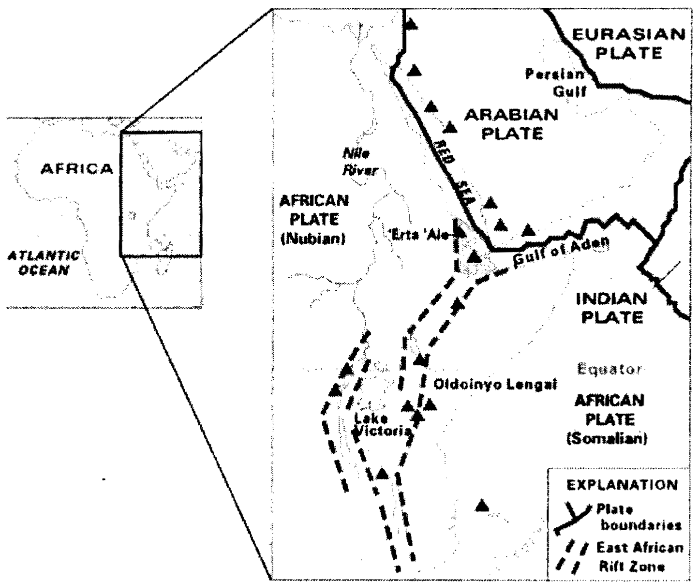


**Figure 2: Map of East Africa showing some of the historically active volcanoes (red triangles)**

The associated geothermal activity and spreading at the East African Rift has caused the lithosphere to thin to a mere 20 km thickness. The volcanic activity at the rift area and unusual concentration of hotspots has produced the volcanic mountains like Mount Kilimanjaro, Mount Kenya, Mount Karisimbi, Mount Nyiragongo, Mount Meru and Mount Elgon as well as the Crater Highlands in Tanzania (Figure 2)

## 3.0 THE EARTH'S TEMPERATURES

The earth is a hot planet. Although relatively cool on the surface, the temperatures at the centre of the earth reach several thousand degrees Celsius. Scientists have measured rates of increase in temperature with depth (geothermal gradient) in deep boreholes at many locations around the world and have found that, while regionally variable, the ground temperature increases by about 15°C to 30°C per kilometer depth. In geothermally active regions, temperature increases more rapidly with depth. Typically, these high geothermal gradient regions are associated with higher than normal heat flow that results from geological causes such as recent volcanic activity.

Because we can only access heat energy from the very near surface of the Earth, it is to our advantage to seek out areas that have high geothermal gradients if we are interested in high temperature resources. Alternatively, if low temperature resources are sought, the relative stability of ground temperatures beyond a few meters depth allows us to access earth energy at a fairly constant temperature year round. Heat from the earths gets to the surface either as a result of temperature difference between the hot core and mantle and the cooler crust (heat conduction) or through movement of fluid particles (heat convection). It is therefore necessary to understand these phenomena when dealing with heat-flow measurements.

Heat transfer mechanism is the science that studies the transfer of thermal energy from a hot surface to a cold surface. This phenomenon can be grouped into 3 broad categories, namely: conduction, convection and radiation.

## 3.1 Heat Conduction

Conduction is the transfer of thermal energy through free electron diffusion or phonon vibration, without a flow of the material medium. Conduction occurs mainly in solids, where atoms are in constant contact. In liquids and gases, the particles are further apart, giving a lower chance of particles colliding and passing on thermal energy. Metals are the best conductors of thermal energy. This is due to the way that metals are chemically bonded: metallic bonds (as opposed to covalent or ionic bonds) have free-moving electrons and form a crystalline structure, greatly aiding in the transfer of thermal energy.

To quantify the ease with which a particular medium conducts, engineers employ the conduction coefficient, known as the conductivity constant or thermal conductivity, k. The main article on thermal conductivity defines k as "the quantity of heat, Q, transmitted in time t through a thickness L, in a direction normal to a surface of area A, due to a temperature difference ΔT [...]." Thermal conductivity is a material property that is primarily dependent on the medium's phase, temperature, density, and molecular bonding.

## 3.2 Heat Convection

Convection is a combination of conduction and the transfer of thermal energy by circulation of the heated material medium. Because of this, convection typically occurs from or to a fluid. Convection can either be natural or forced.

In natural convection, fluid surrounding a heat source receives heat, becomes less dense and rises. The surrounding, cooler fluid then moves to replace it. This cooler fluid is then heated and the process continues, forming a convection current. The primary driving forces for natural convection are buoyancy and gravity. Forced convection, by contrast, occurs when pumps, fans or other means are used to propel the fluid and create an artificial convection current. In many heat transfer systems, both natural and forced convection contribute significantly to the rate of heat transfer, and the effect of each may be found using the superposition principle.

To total the amount of convection between two objects, engineers employ the convection coefficient, h. which is based on the geometry, temperature, velocity, and other factors of the system in which convection occurs. Therefore, the convection coefficient must be derived or found experimentally for every system analyzed.

## 3.3 Heat Radiation

Radiation is transfer of heat through electromagnetic radiation in the heat spectrum. Hot or cold, all objects radiate heat—unless they are at absolute zero, which is unattainable. No medium is necessary for radiation to occur; radiation works even in and through a perfect vacuum. The temperature difference between two material mediums determines the amount of thermal energy radiated. Thermal energy is transported from surfaces of higher to surfaces of lower temperature.

# 4.0 THEORY OF HEATLOSS SURVEY

Heat loss analysis involves evaluation of heat transfer in a geothermal system through both conduction and convection within the earth's crust. This takes place as a result of existent of elevated temperature gradient due to geothermal activity. The discipline of heat transfer is concerned with only two things: temperature, and the heat flow. Temperature represents the amount of thermal energy available, whereas heat flow represents the movement of thermal energy from place to place. On a microscopic scale, thermal energy is related to the kinetic energy of molecules. The greater a material's temperature, the greater the thermal agitation of its constituent molecules (manifested both in linear motion and vibrational modes). It is natural for regions containing greater molecular kinetic energy to pass this energy to regions with less kinetic energy.

## 4.1 Importance of heat loss measurements

Heat-loss measurements in geothermal prospects assists in:

- Estimation of the amount of heat being lost by the prospect naturally
- Analysis of distribution of the heat loss features
- Comparing the prospect with others already explored for rating and prioritization.
- The results can be used as an indicator of the heat source size and as an input into the reservoir model if the geothermal resource is proven and is to be exploited.
- Approximating the magnitude of recharge to the geothermal system in place as well as extent of leakage through the capping. Identification and location of areas of high thermal activity can serve as a guide in locating hidden fracture zones.

## 4.2 Data Collection And Analysis

Heatflow data collection and analysis involves ,

- Conductive heat transfer analysis
- Convective heat transfer analysis

Table 1 and figure 3 below shows a sample data collected from shallow gradient holes at Korosi Geothermal prospect located within the Kenyan Rift valley. Such data is used to calculate conductive heat loss from the prospect.

Table: 1 Sample calculations for conductive heat loss

| Name | East (Km) | North (Km) | $T_s$ (°C) | $T_{50}$ (°C) | $T_{100}$ (°C) | $Grad_{50}$ (°C/m) | $Grad_{100}$ (°C/m) | Average (°C/m) | Mean (°C/m) | Area (m2) | Heat flow ($MW_t$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| KH-1 | 190.9 | 91.0 | 24.3 | 28.4 | 28.4 | 4.1 | 4.1 | 4.1 | 14.6 | 5000 | 73 |
| KH-2 | 188.4 | 93.5 | 95 | 95 | 95 | 0 | 0 | 0 | | | |
| KH-3 | 188.3 | 93.5 | 28 | 34 | 36.2 | 6 | 8.2 | 7.1 | | | |
| KH-4 | 187.9 | 93.4 | 61.3 | 97 | 97 | 35.7 | 35.7 | 35.7 | | | |
| KH-5 | 187.6 | 93.2 | 35.4 | 57 | 68 | 21.6 | 32.6 | 27.1 | | | |
| KH-6 | 186.8 | 83.2 | 23.1 | 28.8 | 29.7 | 5.7 | 6.6 | 6.15 | | | |
| KH-7 | 189.3 | 86.7 | 24 | 30.7 | 32.4 | 6.7 | 8.4 | 7.55 | | | |

$T_s$, $T_{50}$ and $T_{100}$ refer to temperature at the surface, 50 cm and 100 cm depth. Grad refers to temperature gradient in (°C/m) while **KH** refers to identification of shallow hole. Figure 4

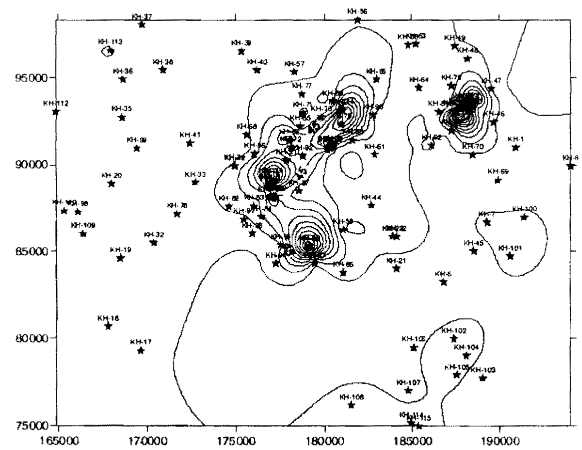


**Figure 3: Shallow gradient holes at Korosi geothermal prospect**

### 4.2.1 Conductive Heat Loss Measurements

Conductive heat transfer refers to the mode of heat transfer where heat energy frows from hot to cold particles as a result of the temperature gradients. The particles must be adjacent to each other. Natural heat loss by conduction is estimated by obtaining temperature gradients from shallow 1 m depth holes drilled manually using 1 inch diameter by 1 m long fabricated spikes. Temperatures are measured at the surface, at 50 cm and at 100 cm depths by a digital thermometer (thermocouple) with a hardened penetrating probe. Location of these holes is obtained by use of a portable Global Positioning System (GPS). Thermally active area is then mapped by considering 40°C isotherm at 1 m depth. The holes are drilled at an interval of 100 m – 1 km in an area of high thermal activity and at 1 - 4 km in an area of low activity. With the area of hot ground and average temperature gradient known, conductive heat flow is then calculated using one dimensional heat conduction equation (equation 1), assuming that the soil's thermal conductivity is constant at 2 w/m °C.

$$Q = Ak\frac{dT}{dy} \qquad \text{(Equation 1)}$$

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

### 4.2.2 Convective Heat Loss Measurements

Convective heat transfer involves transfer of heat energy by fluid. This process is faster than conduction. Natural convective heat loss from a geothermal system occurs from hot springs and fumaroles (steaming grounds). In Menengai prospect area, no hot springs were encountered and so the convective heat flow was solely obtained from the steaming grounds. The convective heat loss was estimated by measuring flow velocities of fumaroles at different locations within a steaming area and using average values. The flow velocities were measured by use of a venturimeter and water manometer fabricated locally at KenGen's Reservoir Engineering workshop.

To collect steam from the ground surface, an inverted plastic trough of known diameter was used and the venturimeter placed on a conveniently drilled hole at the back of the trough. To seal for any leakages, wet mud was used. The differential height at the manometer was then read and the value used to compute volumetric flow rates. Having known the temperature of the steam, other parameters like density and enthalpy were obtained from steam tables, and mass flow rates and heat flow were calculated. The surface area of the steaming was estimated by taking the co-ordinates of the area . The following equation (Equation 2) is used to calculate flow rates.

$$V = C_d A_t \sqrt{\frac{2g\Delta H(\frac{\rho_w}{\rho_s} - 1)}{(1 - \frac{d_t^2}{d^2})}} \qquad \text{(Equation 2)}$$

Where V is the volumetric flow rate (m3/s), Cd is the coefficient of discharge (assumed to be 0.96), g is the acceleration due to gravity (9.81 m/s2), dt is the venturimeter throat diameter, d is venturimeter diameter at the high pressure tapping (m), ΔH is the differential height at the manometer (m), ρ is the density (kg/m3), At is the throat area (m2) and the subscripts w and s stand for water and steam, respectively. Equation 3 is used to calculate the convective heat flow.

$$Q_c = V\rho_s h \qquad \text{(Equation 3)}$$

Where **Qc** is the convective heat flow (watts) and **h** is the enthalpy of steam at the corresponding measurement temperature (J/kg).

Table 2 and Figure 4 below shows a sample data collected from fumaroles at Korosi Geothermal prospect located within the Kenyan Rift valley. The data is used in calculation of heat convective heat loss from the prospect.

**Table 2: Sample calculation for convective heat loss from fumaroles**

| Name | North (km) | East (km) | Man. height (mm) | Volumetric flow ($m^3/s$) | Heat flow ($kW_t$) |
|---|---|---|---|---|---|
| Diameter (venturi) | 0.0254 | m | Water density ($\rho_w$) | 1000 | $kg/m^3$ |
| Diameter (throat) | 0.00635 | m | Steam density ($\rho_s$) | 0.4753 | $kg/m^3$ |
| Throat area | $3.16532E^{-05}$ | $m^2$ | Steam enthalpy ($h_s$) | 2670 | kJ/kg |
| Coef. of discharge | 0.96 | | Water enthalpy at ambient conditions ($h_o$) | 117 | kJ/kg |
| Gravity | 9.81 | $m/s^2$ | | | |
| KFMRL-1 | 177.0 | 89.2 | 9 | 0.000604765 | 0.767 |
| KFMRL-2 | | | 17 | 0.000831169 | 1.055 |
| KFMRL-3 | | | 9 | 0.000604765 | 0.767 |

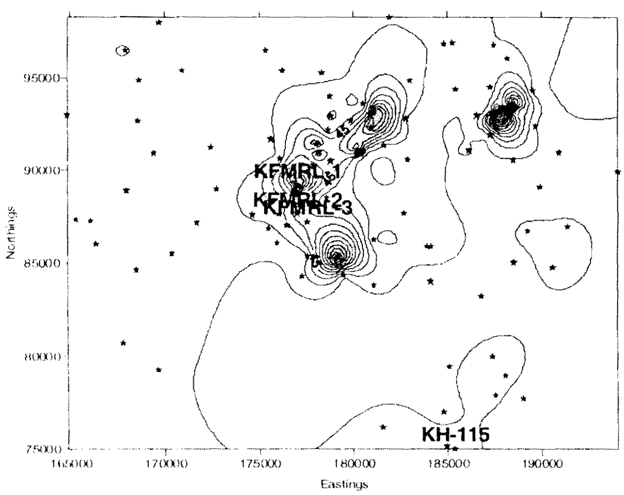


Figure 4: Location of some Fumarole at Korosi geothermal prospect

### Downhole temperature and pressure measurements in boreholes

Boreholes drilled within a geothermal prospect area can serve as very good temperature gradient holes which provides direct temperature information on the geothermal reservoir. Pressure measurements in these boreholes can be used to create the hydrological model of the area and hence give an indication on possible recharge, upflow and outflow zones.

## 5.0 FACTORS TO CONSIDER WHILE CARRYING OUT HEAT-LOSS MEASUREMENTS.

### 5.1 Distribution of gradient holes

The distribution of thermal gradient holes depends on the following parameters:

- Nature of surface thermal activity
- Surface area to be covered

- Time allocated for the fieldwork
- Available resources

But on average, in an area of high thermal activity, holes are drilled at a spacing of about 100m-1Km while in an area of low or no thermal activity, a spacing of about 1-4 km. The more resources available, the more gradient holes can be made within a short time.

### 5.2 Social Constraints

Some areas are no-go zones due to religious or cultural or social constraints. In such places gradient holes may not be made or may be widely spaced.

### 5.3 Previous data available

An area with previous data may require less gradient holes than an area where no previous work done. However, if the purpose of the holes is to map out an inferred structure, holes need to be drilled as close as possible.

## 6 TOOLS AND EQUIPMENTS USED DURING HEAT-LOSS MEASUREMENT

Table 3 below shows the tools and equipments used during geothermal heatflow measurements and their applications. Some of these tools are locally fabricated or modified to suit the needs while others are directly available in the market.

Table 3: Tools used in heatflow measurements

| Tools | Applications | Remarks |
|---|---|---|
| GPS | Determine coordinated and elevation of sites | Available in the market |
| Digital Thermometer | Temperature measurements | Available in the market |
| Metalspikes | Making shallow gradient holes | Locally fabricated |
| Hammer | Forcing the Spike into the ground | Available in the market |
| Panga | For clearing the pathway | Available in the market |
| Field note book | For recording the data | Available in the market |
| Graduated Metal rod | Measuring the depth of the shallow gradient holes | Locally fabricated |
| Field Map | For recording the data/location map | Prepared at GIS Lab |
| Satellite phones, mobile phones | For communication | Available in the market |
| Venturi or pitot tube | Fluid flow from fumarole | Modified |
| Plastic basins | Fluid flow from fumarole | Modified |
| Winch | Lowering KPT tools inside the boreholes | Modified |
| Kuster temperature tools | Temperature measurements in Boreholes | Available in the market |
| Kuster pressure tools | Pressure measurements in Boreholes | Available in the market |
| Jembe | Digging trenches where required | Available in the market |
| Spade | Scooping the earth where necessary | Available in the market |

## 7 GEOSCIENTIFIC CONCEPTUAL MODELLING

The heatflow measurement data obtained during geothermal surface exploration is analysed in conjuction with the data from other geoscientific disciplines. The combined data is used to prepare a comprehensive conceptual model (Figure 5) which is used to site the first exploration wells.

Analysis of the conceptual model helps in locating the first three exploration wells. The heatflow measurement data in particular is used in;

- Identification of active structures
- Quantifying the amount of heat lost to the surface
- Determining the reservoir temperature

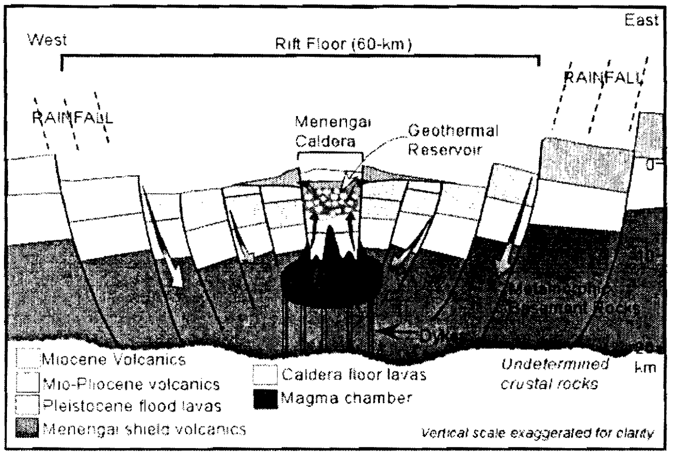


**Figure 5: Conceptual model of one of the geothermal prospect**

## 8 HEATFLOW DATA FOR THE KENYAN PROSPECTS

About fourteen (14) geothermal prospects have been identified in the Kenyan Rift valley (Figure 6). Their geothermal potential is estimated to be in excess of 3000 MWe. Wells have been drilled in only two of these sites , Olkaria and Eburru but exploitation is only at Olkaria geothermal field.

Preliminary heatflow measurements were carried out in Olkaria and due to heavy pyroclastic cover, the values obtained were very low (Mahon, W. A. J., 1989). Recently, more work has been carried out in four prospects and is ongoing in the fifth one. Values of conductive and convective heatloss in MWt are shown in table 4 below (Ofwona, 2004, Mwawongo, 2006).

Table 4: Heat flow data obtained from the Kenyan rift prospect

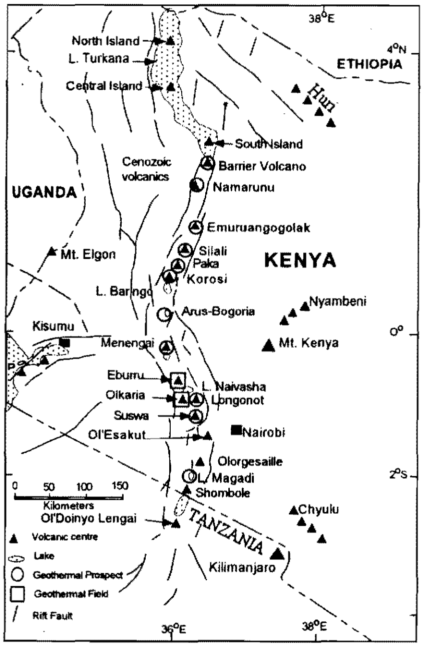


**Figure 6: Geothermal Prospects in The Kenyan Rift Valley**

| Prospect | Year | Conductive (MWt?) | Convective (MWt?) | Total | Remarks |
|---|---|---|---|---|---|
| Menengai-Olbanita | 2004 | 1060 | 2476 | 3536 | 2690 (Caldera) |
| Baringo | 2004 | 941 | 108 | 1040 | 105 (Olkokwa |
| Arus-Bogoria | 2005 | 1229 | 437 | 1666 | |
| Korosi-Chepchuk | 2006 | 2681 | 0.4 | 2681 | |
| Paka | Ongoing | | | | |

# 9 CONCLUSIONS AND RECCOMENDATIONS

- Heatflow measurement is an important method to be employed during the initial stages of surface exploration of a geothermal resource.

- Research should be carried out on better tools for heatloss measurements which are available in the market. This will significantly reduce time spent in the field and number of personnel required to do a certain task. This will effectually result to reduced cost of doing the work

- Heat-flow measurement method is simple, relatively cheap, and relatively fast way to profile a large area compared to the cost of drilling shallow slim holes.

# REFERENCES


Crane. K. and O'Connell. S.,1982. The distribution and implications of heat flow from the Gregory Rift in Kenya. Journal of Tectonophysics, pp 253-273.

Mahon, W. A. J., 1989. The natural heat flow from and the structure of the Olkaria geothermal system. Prepared by Geothermal Energy New Zealand Ltd., for the Kenya Power Company Ltd.

Mwawongo G.M., 2006. Heat loss assessment of Korosi-Chepchuk geothermal prospects. KenGen Internal report.

Ofwona C.O., 2004. Heat loss assessment of Menengai-Olbanita geothermal prospects. KenGen Internal report.

Ofwona C.O., 2004. Heat loss assessment of L. Baringo geothermal prospect KenGen Internal report.