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KenGen
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GEOTHERMAL MAPPING USING TEMPERATURE MEASUREMENTS

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ABSTRACT

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

1. INTRODUCTION

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

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

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

Results from heat loss survey are an important input in numerical simulation of the prospect if the reservoir is proven.

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

2. METHODOLOGY

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

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

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

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

It can be shown that temperature fluctuations due to periodic heating can be computed from the formula:
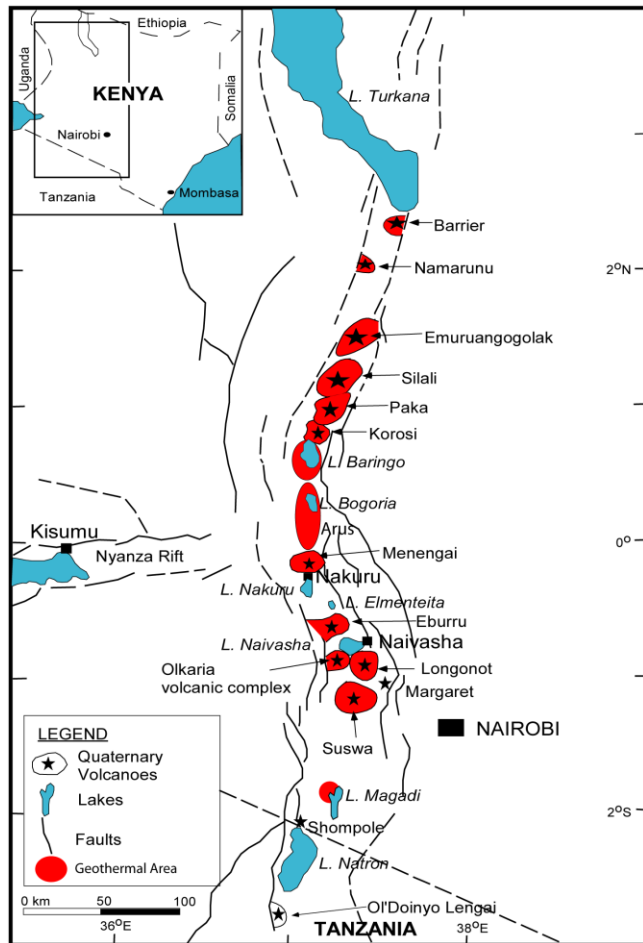
FIGURE 1: Geothermal prospects in the Kenya rift
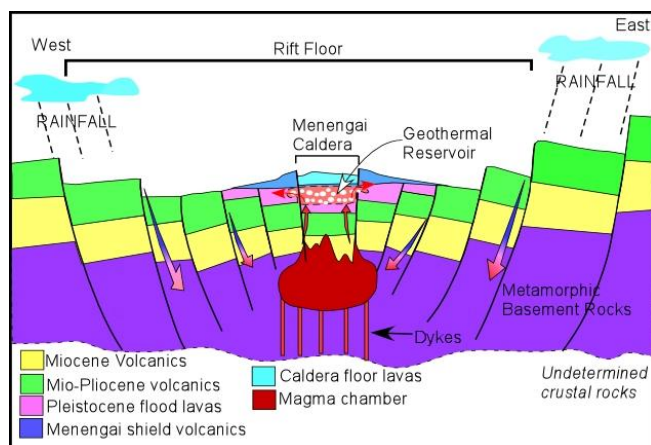
FIGURE 2: Model of a geothermal prospect in the Kenyan rift

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

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

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

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

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

2.1   Conductive heat loss measurements

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

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

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

2.2   Convective heat loss measurements

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Heat flow was then computed using equation (7).

2.3 Reliability check

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

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

The highest deviation was 4% on surface temperature in areas of low thermal activity and 0.1% for anomalous areas. At 100 cm depth, the deviation was 0.35% for cold areas and 0.1% for thermally active areas. This indicates negligible sun effect on temperature readings at 1-meter depth hence the method is reliable for delineating hot grounds.

2.4 Down-hole temperature and pressure measurements in boreholes

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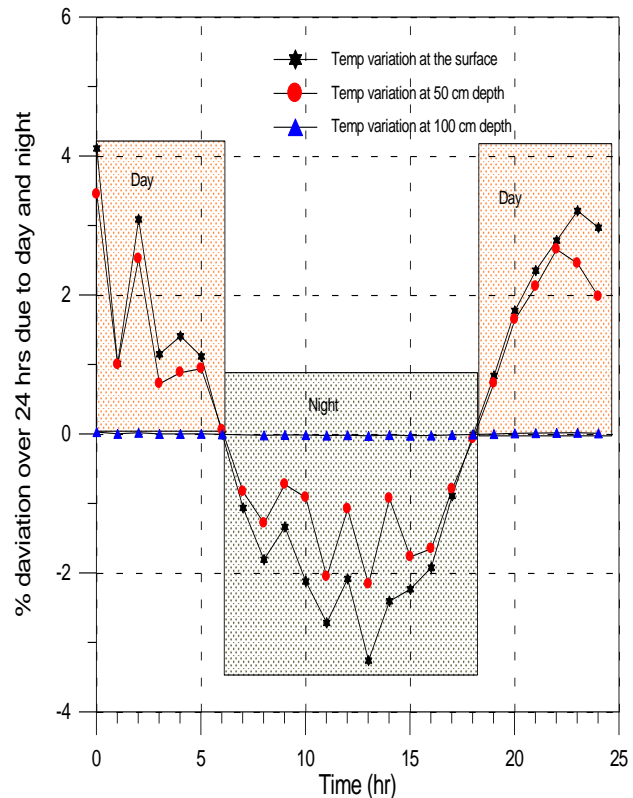

FIGURE 3: Temperature variation due to effect of daytime heating and cooling at night

3. RESULTS FROM MENENNGAI TO PAKA GEOTHERMAL PROSPECTS

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

3.1 Menengai geothermal prospect

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

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

3.2 Discussion

It was difficult to make holes in areas with fresh lava flow cover. Because of this, temperature gradients and areal extent in certain zones have been extrapolated from temperature contours. For all practical purposes, this is considered well enough for field measurements.

Control points indicated no significant changes in ground temperature at 1 m depth due to seasonal variation.

Orientation of the high temperature areas is in a NNW-SSE direction and suggests that a major fault/fracture zone could be in this direction and allows deep hot fluids to travel close to the surface causing localised heating. Another possible structure seems to occur in NE-SW direction as can be observed from the orientation of the high temperature areas in the Caldera.

Total heat loss estimated from the Caldera alone is in excess of 2,690 MWt indicating possibly a big hot body underneath which can be explored further for production of steam.

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

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

FIGURE 4: Heat loss results from Menengai prospect

3.3 Conclusions

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

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

3.4 Arus and Bogoria geothermal prospects

Arus and Lake Bogoria prospects are located to the north of Menengai and are not associated with any central volcano. Heat loss survey was done from 14th February to 8th July 2005 in an area of about 2,000 km². Earlier work at Lake Bogoria prospect was done in 1973-1974 under the sponsorship of United Nations covering an area of 31 Km². This study was regional starting from Turkana in the north to Lake Natron in the south. Other fields incorporated in the survey included Eburru, Olkaria and Lake Magadi. Infrared aerial photographs were taken over the named prospects. At Bogoria, the
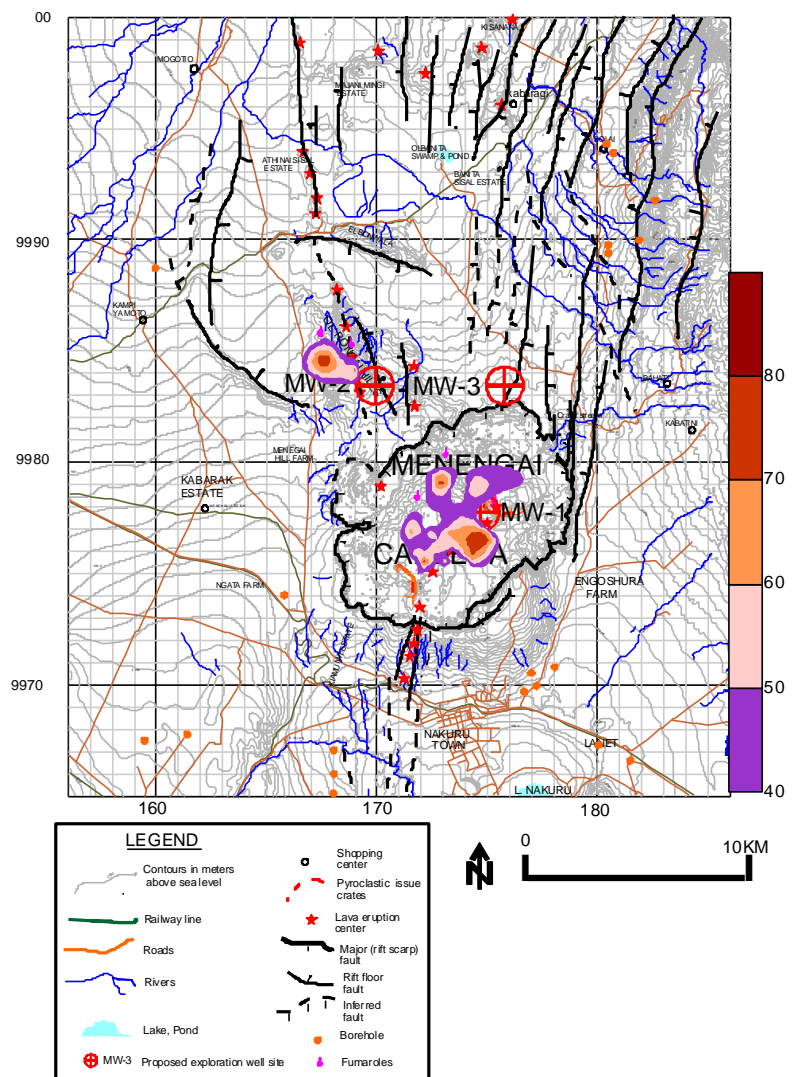
survey was localized around the lake where numerous geothermal surface manifestations are located. 40°C isotherm was used to delineate the thermally active area resulting in a total heat flow of 353 MW$_t$ (Crane and O'Connell, 1982).

3.5 Discussion

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

Figure 5 shows distribution of temperatures at 1 m depth in Lake Bogoria and Arus geothermal prospects. Anomalous areas are enclosed by the 40°C isotherm.

Heat loss features are located on the southern shore of the lake. Some springs are submerged in the lake; therefore it is possible that anomalous temperatures at shallow depth can be obtained below the lake.

FIGURE 5: Temperature contours at 1 m depth

Heat loss features at Lake Bogoria are more active when compared to those at Menengai possibly due to better recharge or poor capping.

3.6 Conclusions

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

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

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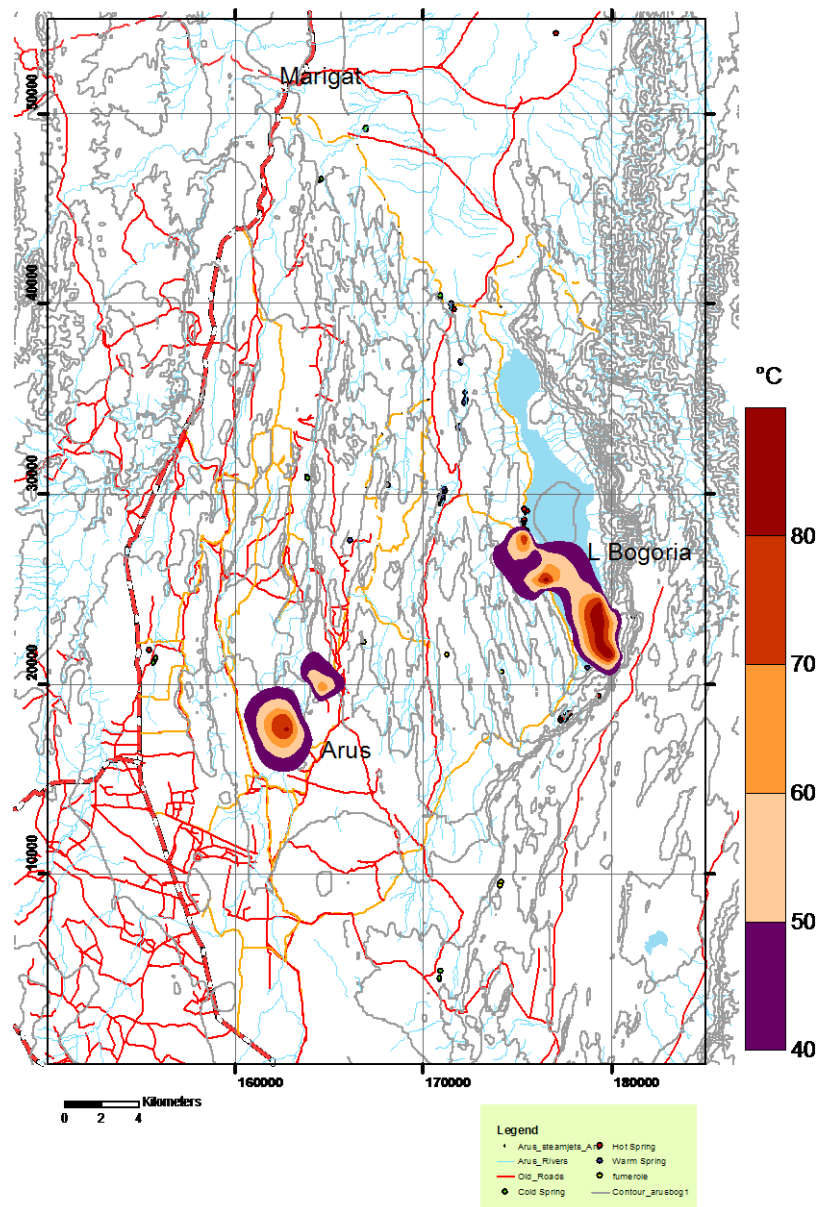
3.7 Lake Baringo geothermal prospect

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

3.8 Discussions

Figure 6 shows ground temperature contours at Baringo. The area is generally inactive as strong fumaroles and hot grounds were encountered only, in Kokwa Island and north of Kampi Samaki.

Hard rock covering the high lands and silt deposits in the low lands make it difficult to make temperature measurements. Silt cover lowers the natural heat loss as it acts as an insulator. Area covered by the lake could also be absorbing the natural heat flow underneath.
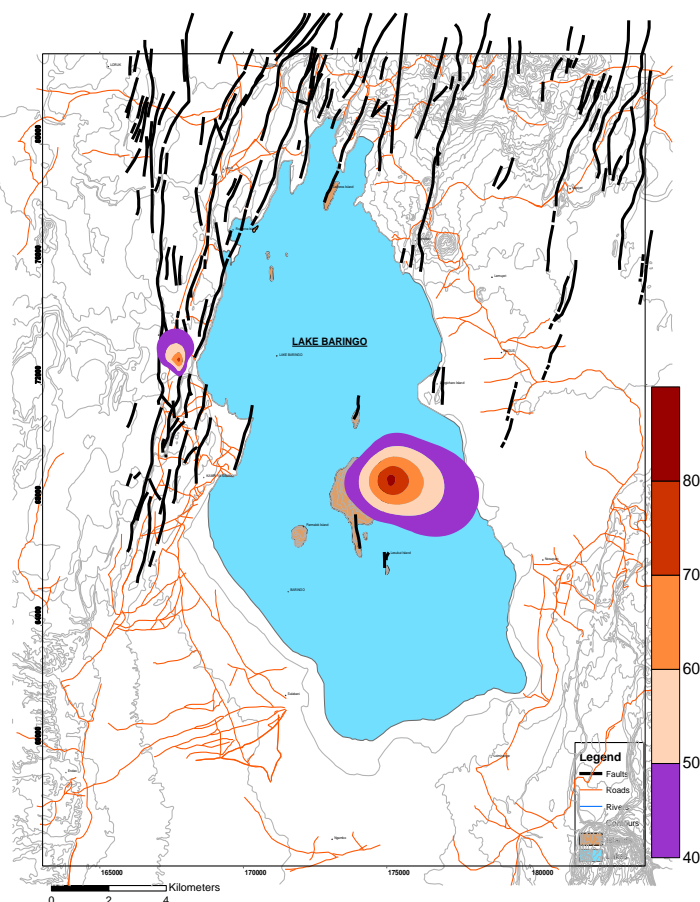

FIGURE 6: Temperature contours at Lake Baringo prospect

3.9 Conclusion

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

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

3.10 Korosi and Chepchuk

Surface exploration was done in these geothermal prospects from 11th October, 2005 to 24th March 2006 covering an area of about 900 km[2]. Earlier work at Korosi by British Geological Survey in 1993 identified geothermal surface manifestations as being hot grounds (altered grounds), steaming grounds

and fumaroles covering an area of 33 Km^2. A maximum surface temperature of 95°C was recorded. At Chepchuk the area covered by similar thermal features was estimated at 2.3 km^2 and a maximum surface temperature of 90°C was recorded (Dunkley et al, 1993).

3.11 Discussion

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

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

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

FIGURE 7: Temperature contours at Korosi & Chepchuk

3.12 Conclusions

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

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

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

3.13 Paka

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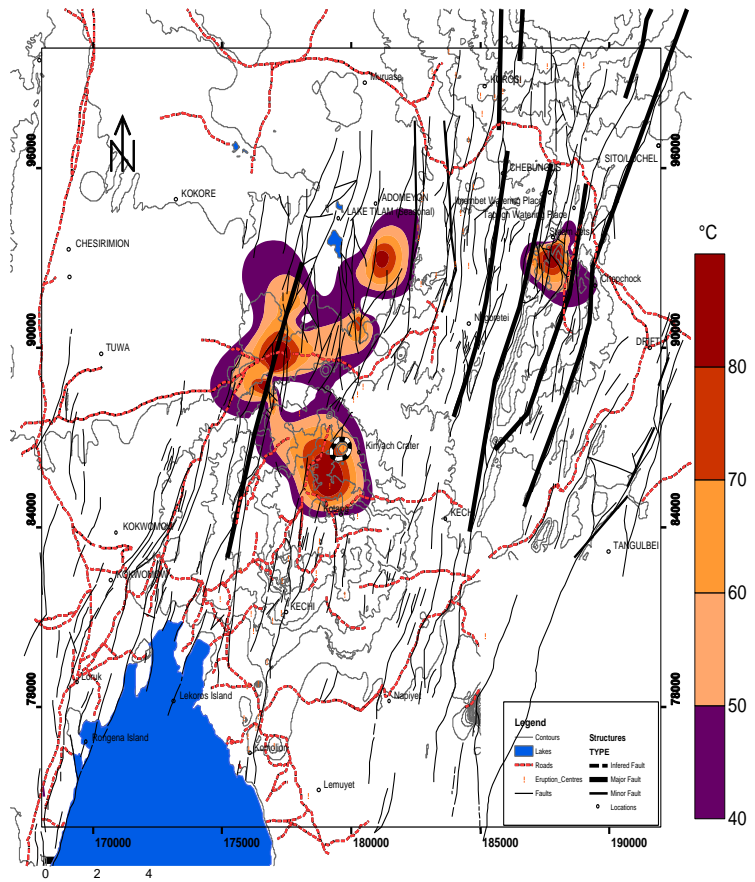
3.14 Discussion

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

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

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

FIGURE 8: Temperature contours at Paka, Chepchuk
& Korosi

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

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

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

3.15 Conclusions

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

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

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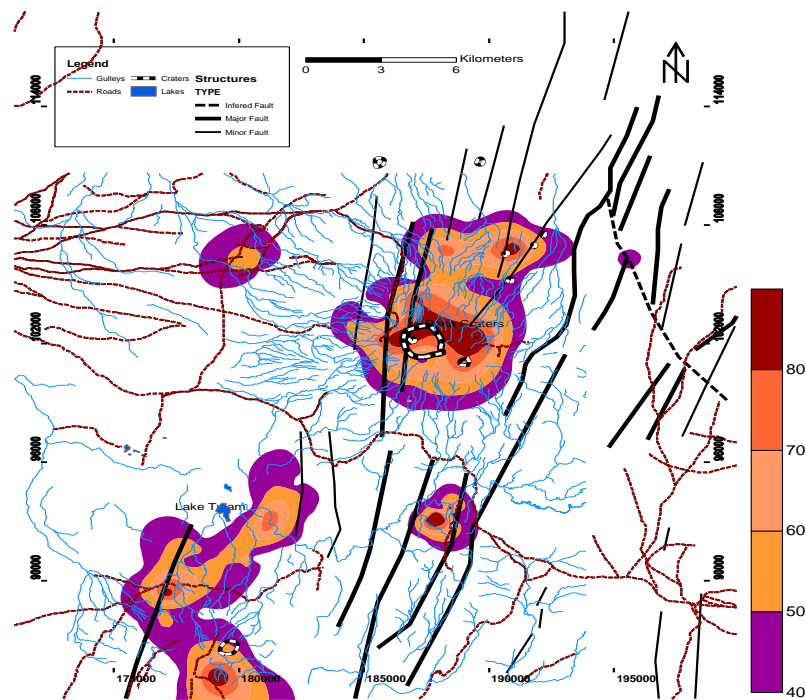
Another survey done by Williamson in 1975 covered western Kenya, the rift flanks and the floor and an area north of Lamu near the Kenya-Somali border. Borehole depth ranged from 66 m to 226 m deep. Terrestrial temperature gradient computed ranged from 0.01 to 0.08°C/m (Williamson, 1975).

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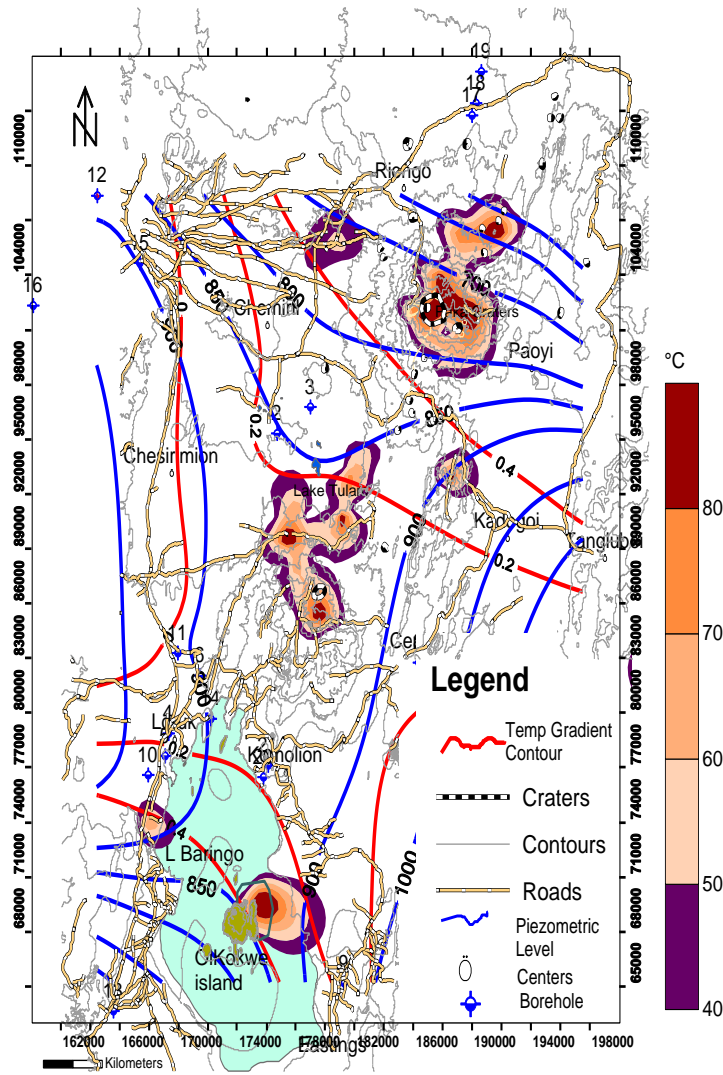

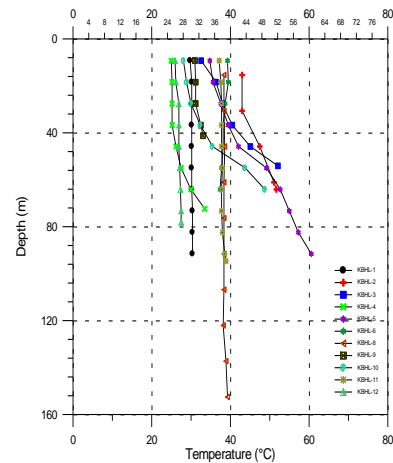FIGURE 9: Temperature gradient & piezometric levels
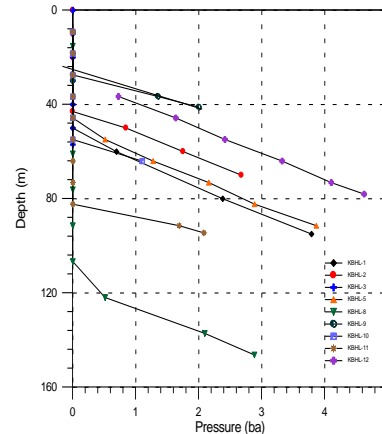

FIGURE 10: Down-hole temperature profiles

FIGURE 11: Down-hole pressure profiles

4.1 Discussion and conclusions

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

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

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

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

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

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

5. RANKING OF THE EXPLORED FIELDS BASED ON HEAT LOSS

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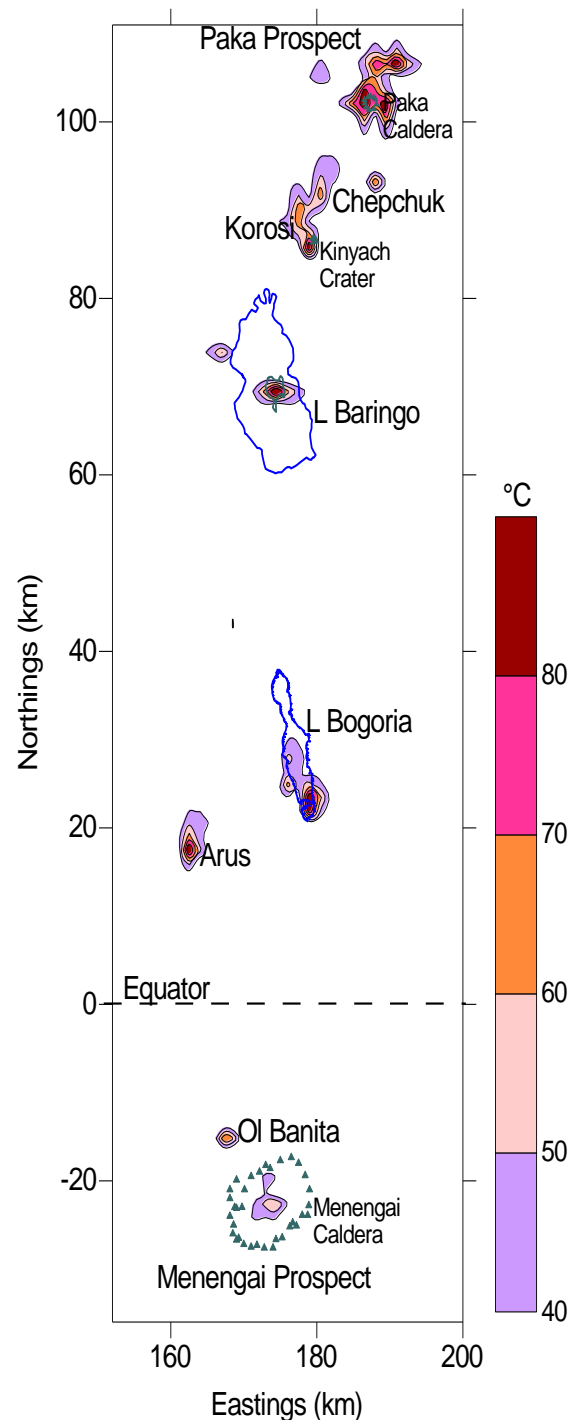

FIGURE 12: Explored Prospects in the North rift

TABLE 1: Ranking based on heat loss survey

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

ACKNOWLEDGEMENTS

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