EXPLORATION OF GEOTHERMAL RESOURCES USING MAGNETOTELLURICS CASE STUDY MENENGAI PROSPECT IN KENYA

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ABSTRACT

Geothermal energy sources are formed by heat stored in rocks at depth. In regions with high heat flow, like at volcanically active plate margins, high total thermodynamic energy is accumulated in the so called high enthalpy resources. Unaltered volcanic rocks generally have high resistivity which can be changed by hydrothermal activity. Hydrothermal fluids tend to reduce the resistivity of rocks by altering the rocks or by increasing salinity. Initial regional exploration for geothermal resources in Kenya indicated that the Quaternary volcanic complexes of the Kenya rift valley provided the most promising prospects for geothermal exploration. Consequently, detailed exploration for geothermal power has been concentrated around volcanic centres within the rift valley. Studies show that these centres have positive indications of geothermal resource that can be commercially exploited. The geothermal potential of the area is associated with these magma chambers that constitute the heat sources. Magnetotellurics (MT) data show that the heat sources are shallow beneath the volcanic centres. This abstract concentrates on the geophysical work that has been carried out in the Menengai Geothermal prospect using Magnetotellurics (MT). Data collected using magnetotellurics is used to determine the resistivity distribution within the earth to depths of many kilometers which is then interpreted in terms of lithology. The contrast in resistivities provides an excellent tool for identifying geothermal targets. So magnetotellurics is the standard method for mapping the alteration cap and via 3D inversion the underlying reservoir.

INTRODUCTION

Initial regional exploration for geothermal resources in Kenya indicated that the Quaternary volcanic complexes of the Kenya rift valley provided the most promising prospects for geothermal exploration. Consequently, detailed exploration for geothermal power has been concentrated around volcanic centres within the rift valley. Studies show that these centres have positive indications of geothermal resource that can be commercially exploited. The geothermal potential of the area is associated with these magma chambers that constitute the heat sources. Magnetotelluric (MT), seismic and magnetic data show that the heat sources are shallow beneath the volcanic centres. This abstract concentrates on the geophysical work that has been carried out in the Menengai Geothermal prospect. Static shifts of the resistivity curves have been removed by means of the MT response derived from TEM measurements at the same locations.

The Magnetotellurics (MT) technique, a natural electromagnetic method, has proved effective in mapping the characteristics of geothermal fields due to its lateral resolution and also greater depth of investigation. Magnetotellurics survey is more appropriate for difficult topography due to its simple logistics and low cost compared to seismic survey. MT provides useful information about the lateral and vertical resistivity variations in the earth's subsurface from surface measurement of two horizontal electric field and three magnetic field variations over a typical 10^{-3}-10^{3} Hz frequency range. MT results along a profile can be used to evaluate the resource potential of the area. Data collected using magnetotellurics is used to determine the resistivity distribution within the earth to depths of many kilometers which is then interpreted in terms of lithology. The contrast in resistivities provides an excellent tool for identifying geothermal targets. So magnetotellurics is the standard method for mapping the alteration cap and via 3D inversion the underlying geothermal reservoir. This resistivity survey identified three zones, separated by discontinuities, which are suitable for geothermal production.

The role of electrical resistivity

Unaltered volcanic rocks generally have high resistivities which can be changed by hydrothermal activity. Hydrothermal fluids tend to reduce the resistivity of rocks:-

- by altering the rocks,
- by increase in salinity or
- due to high temperature.

In high enthalpy reservoirs, i.e. fluid temperatures above 200 °C, hydrothermal alteration plays the predominant role (Figure 1.1). In a volcanic terrain the acid-sulphate waters lead to different alteration products depending on the temperature and thus on the distance from the heat source. With basalts as country rock smectite becomes the dominant alteration product in the temperature range from 100 °C to 180 °C. At higher temperatures mixed layer clays and chlorite become dominant

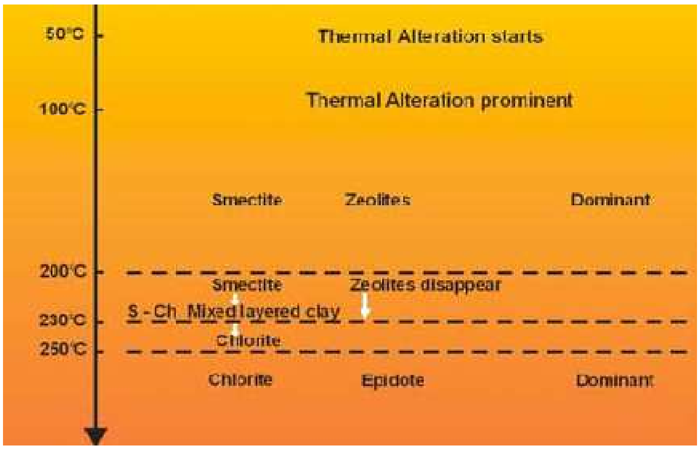


Figure 1: Alteration mineralogy with increasing temperature in basaltic country rock. In the temperature range 100°C to 180°C smectite becomes the dominant alteration product and generally forms a smectite/bentonite clay cap (source: Geological Survey of Iceland ISOR).

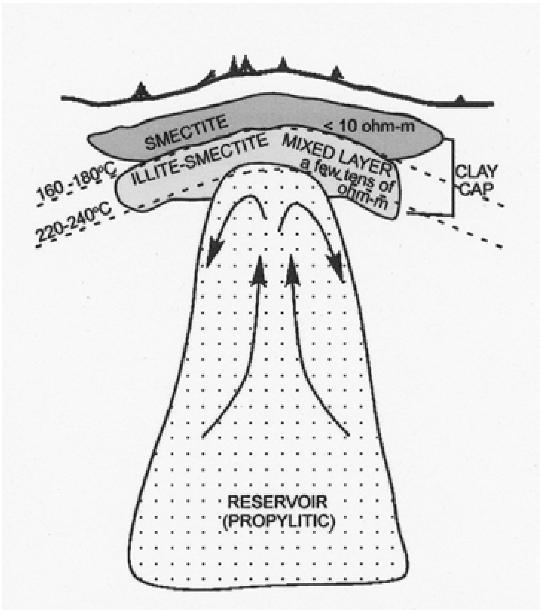


Figure 2: Schema of a generalised geothermal system. The smectite cap formed exhibits resistivities in the range of 2 Ohm*m, the mixed layer around 10 Ohm*m.

METHODOLOGY

MT Sounding

MT techniques measure over a frequency range. The lower the frequency, the greater the depth of investigation possible at a given site. MT techniques acquire data in frequencies ranging from about 400-0.0000129 Hz (over a period of about 21.5 hrs), and are suitable for deeper investigations. The survey was planned so that work crews could set up one or more sites each day (depending on the nature of the terrain), allowing the equipment to acquire data for a period of time and then retrieving the equipment to re-deploy it at another site. In this survey, the equipment was left to acquire data overnight and retrieval usually happened the next morning.

Although an MT can be used alone, best results are achieved when a remote or far remote site is available for noise-reduction techniques. Apart from the 50 Hz or 60 Hz grid frequency, electrical noise from human activities tends to vary considerably over distance. The natural magnetic signal, though, tends to be the same over large distances; the lower the frequency, the less variation. The MT equipment system employed took advantage of these characteristics by collecting data simultaneously at the survey (“local”) sites and at one reference (“remote”) site.

MT equipment and sensors must be calibrated before acquiring data. Calibration took place at the beginning of the survey, and was repeated in the course of the survey when equipment problems arose (e.g., damaged cables). The field layout comprised of two orthogonal electric dipoles to measure the two horizontal components, and two magnetic sensors parallel to the electric dipoles to measure the corresponding magnetic components. A third sensor measured the vertical magnetic component. Thus, at each station, five parameters were measured simultaneously as a function of frequency. By measuring the changes in the magnetic field (H) and electric (E) field over range frequencies, an apparent resistivity sounding curve can be produced, analogous to that produced for electrical resistivity sounding but measured as a function of frequency rather than inter-electrode separation. The data are displayed on log-log plots as apparent resistivity versus either frequency (f) or period ($1/2\pi f$)

DATA PROCESSING AND ANALYSIS

Resistivity

Both MT and TEM data can be analysed in different ways according to the manner in which they have been acquired. Measured parameters may be plotted as profiles or as gridded and contoured maps on which anomalous zones can be identified. These approaches tend to be qualitative and of first order interpretations. The data was processed, inverted and produced in apparent resistivity plots in form of contours maps at various elevations. The aim was to locate a possible sub-surface resistivity anomaly on the basis of relevant parameters such as apparent resistivity values, shape and size.

Time series processing included visual inspection of the recorded data and excluding disturbances and heavily noise affected parts of the time series. Although very time consuming this approach proved to be the best means to extract maximum information from the noise contaminated time series. These preconditioned time series were then transformed into the frequency domain by a FFT using adapted window lengths. With a coherency based algorithm the Fourier spectra were thenaveraged and the impedancetensor estimated. The impedance tensor has been rotated mathematically by a constant angle derived from the swift angle at low frequencies. This results in a data set with consistent orientation with one axis approximately along the valley which is taken as direction for the E-field. Static shifts of the resistivity curves have been removed by means of the MT response derived from TEM measurements at the same locations.

Figure 1.3 shows the map of the areal distribution of the resistivity soundings from the greater Menengai prospect area. Since resistivity of the subsurface varies with depth as well as horizontally, several iso-resistivity maps were constructed at elevations from 1800 masl to 5000mbslas shown in Figures 1.4,1.5,1.6,1.7,1.8,1.9, and 2.0 respectively.

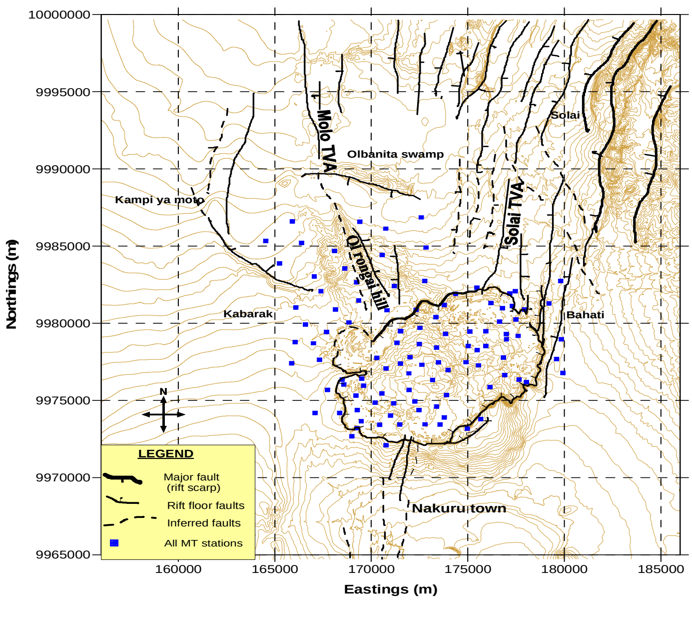


Figure 3: The areal distribution of MT resistivity soundings from the Menengai prospect area

Resistivity at 1800 masl

At 1800 masl(Figure 1.4), most of the area is covered with moderately high resistivity values particularly the Menengai caldera and to the North-west towards the Ol' Rongai area, except for localized low resistivity appearing in the north west towards the direction of KampiYa Moto and another in the south-east of the caldera. Relatively lower resistivity discontinuity can also be seen in the central part of the caldera. The high resistivity is probably as a result of un-altered rocks near the surface.

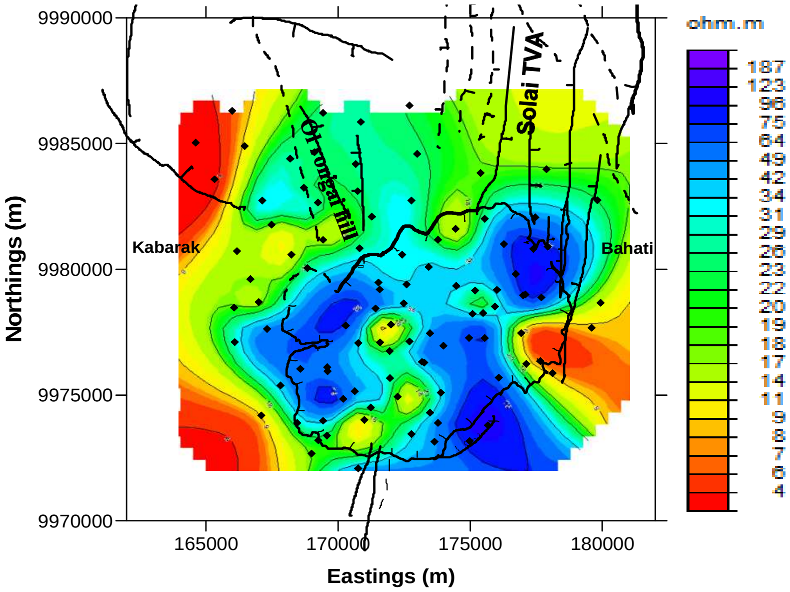


Figure 4: Resistivity distribution at 1800 masl. within Menengai prospect

Resistivity at 1400 masl

Deeper down, at 1400 masl (Figure 1.5), the high resistivity is still dominant within the caldera and to the Ol' Rongai hill except the low resistivity discontinuity that appears in the centre of the caldera and localized low resistivity anomalies in the north-west and south-east of the caldera as seen in the layer 400m above.

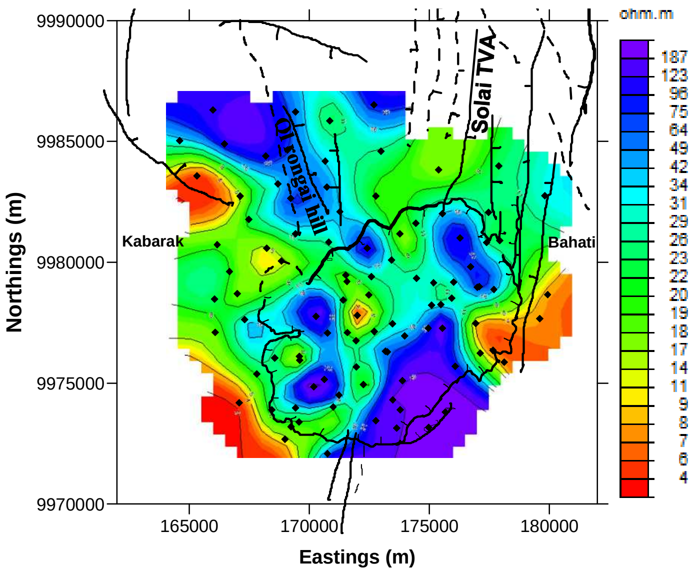


Figure 5: Resistivity distribution at 1400 masl. around Menengai

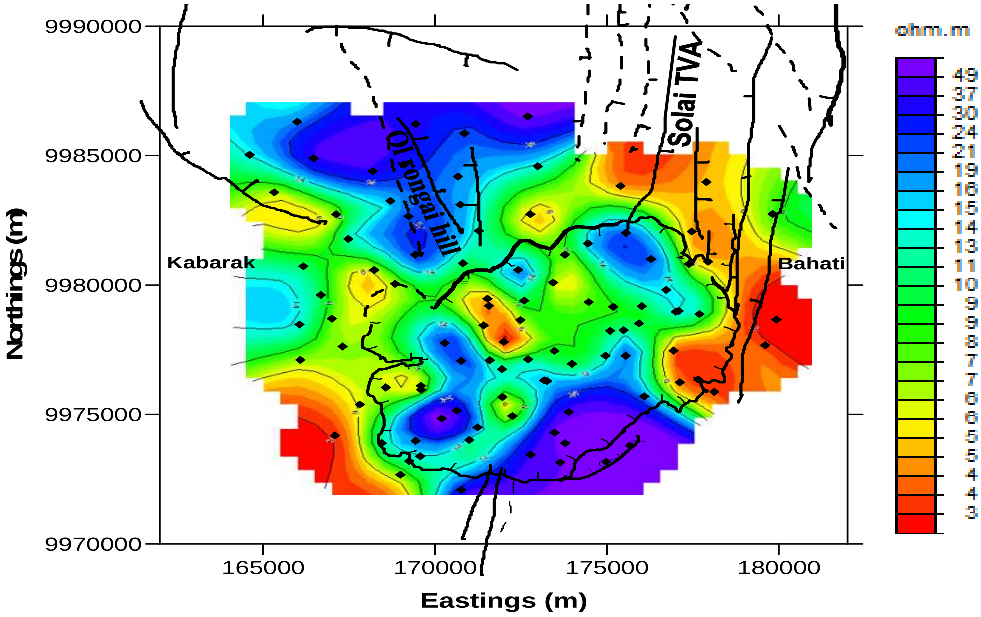


Figure 6: Resistivity distribution at 1000 masl within Menengai prospect

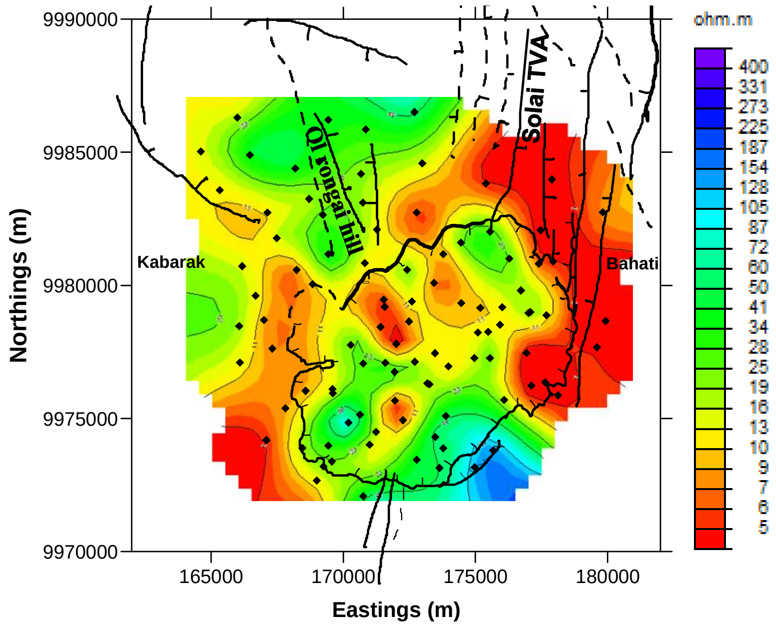


Figure 7: Resistivity distribution at 800 masl. in the Menengai prospect

<u>Resistivity at 1000 masl and 800 masl</u>

At 1000 masl (Figure 1.6) three distinct low resistivity (≤ 10 Ωm) areas are clearly seen; one large region to the east of the caldera towards Bahati area, one to the west of the caldera and a small low resistivity anomaly in the central portion of the caldera. High resistivity values, just as in the previous higher elevations, are still present in the Ol' Rongai area and the other to the southern rim of the caldera.

At 800 masl (Figure 1.7), low resistivity is smeared out in almost the entire plot with more prominence in the eastern, western and central part of the caldera. These low resistivity zones could probably be as a result of low temperature hydrothermal clay minerals like smectite and zeolite. On the other hand, the south-east of the caldera and north-west area around Ol' Rongai area is characterized by high resistivities.

Resistivity at Sea level

At Sea-level (Figure 1.8), the general resistivity structure of the prospect indicate a moderate high resistivity (about 49 ohm-m) particularly within the caldera and in the north west in tha Ol' Rongai area. This high resistivity portion could probabaly be associated with high temperatures alteration minerals such as chlorites and epidotes. Some higher resistivity zones can be seen appearing from the South and of the caldera and another in the North-East portion of the caldera aligning in the NW-SE direction. Low resistivity seen in the previous levels towards Bahati and in the north east along the Solai TVA is still present here.

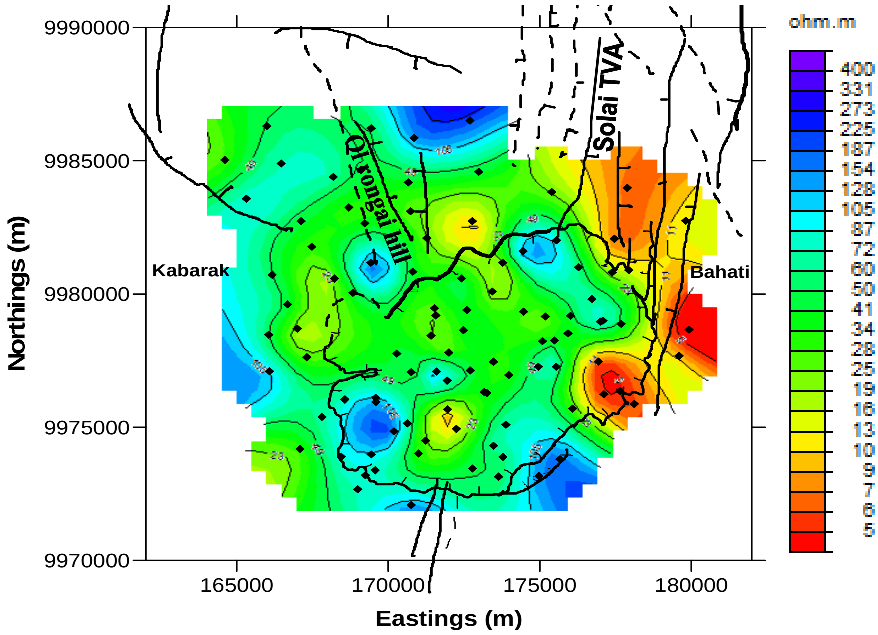


Figure 8: Resistivity distribution at sea level within the Menengai prospect

Resistivity at 3000 mbsl and 5000 mbsl

Figures 1.9 and 2.0 shows resistivity at 3000 mbsl and 5000 mbsl respectively. These figures reveal low resistivity bodies at depth that could be related to magmatic heat sources. Three distinct low resistivity anomalies can be seen in the prospect area, one in the central part of the caldera, the other in the Ol' Rongai area and the third towards Kabarak.

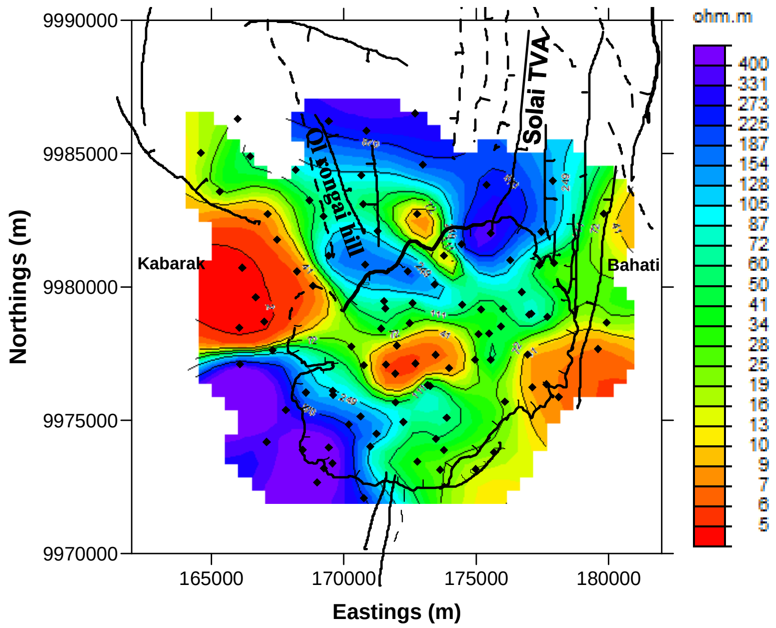


Figure 9: Resistivity distribution at 3000 mbsl within the Menengai prospect

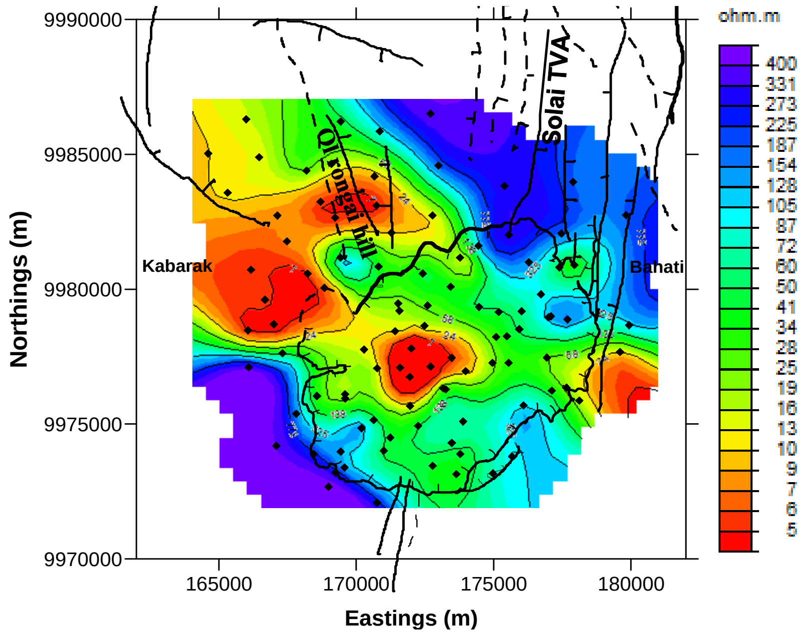


Figure 10: Resistivity distribution at 5000 mbsl within Menengai Prospect

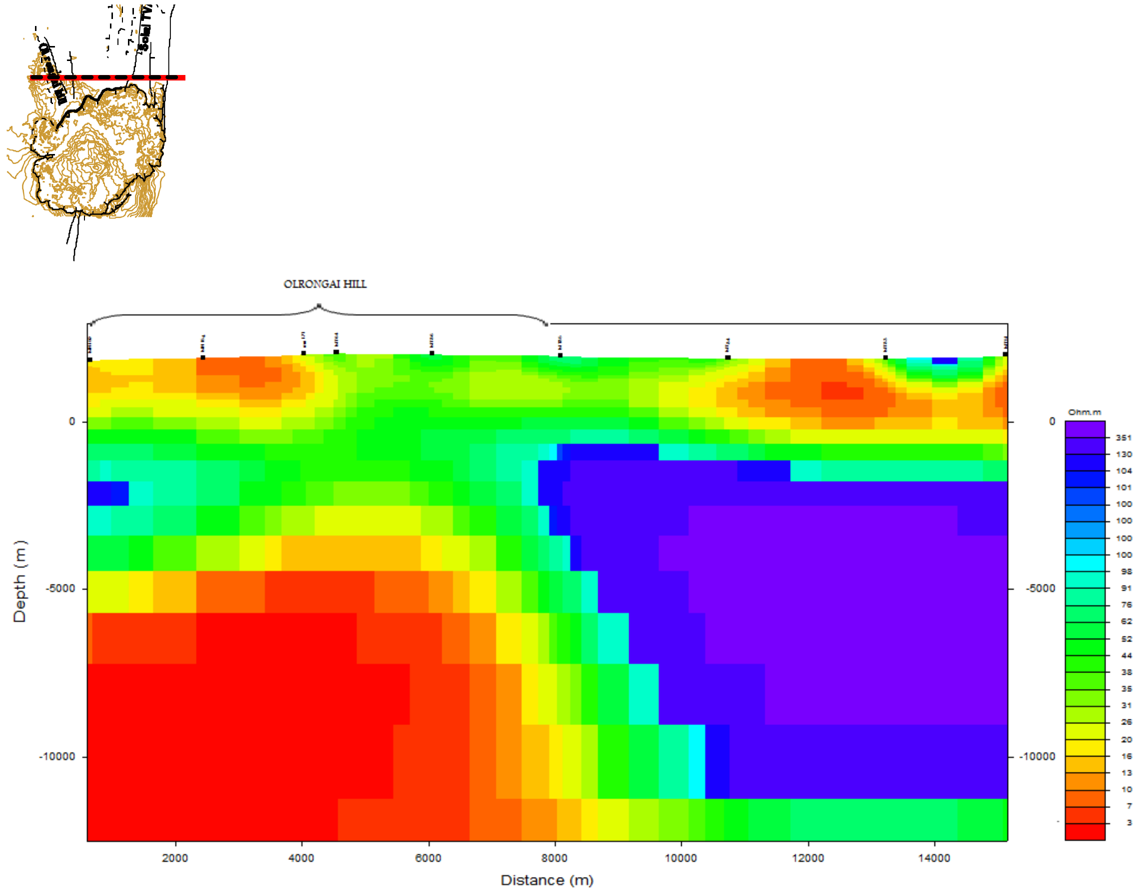


Figure 11: 2D East-west MT resistivity cross-section

<u>Resistivity cross-section through Ol' Rongai area</u>

Figure 2.1is the cross section through the Ol' Rongai area north of the caldera. It shows a low resistivity layer that is about 1.5 km deep below Ol' Rongai area. This shallow low resistivity layer on this profile defines a combination of conductive sediments and alteration zones around Ol' Rongai area. Below this zone a higher resistivity layer is seen overlaying a low resistivity starting at about 6 km below the surface. This is probably a magmatic heat source for the Ol' Rongai area.

<u>Resistivity cross-section passing through the Menengai caldera</u>

Figure 2.3 shows MT resistivity cross-section E-W 2 passing through Kabarak, the caldera and Bahati. This profile shows generally higher resistivity near the surface which is probably due to un-altered rocks in the near sub-surface. Underlain is a low resistivity layer about 1 km thick which run accross the entire cross-section. This shallow low resistivity layer on this profile defines the clay layer formed due to hydrothermal alteration at the upper zone of the geothermal system in Menengai prospect and the outflow zones. A localized low resistivity anomaly is also observed at a depth of about 4 km. This low resistivity body could be associated with magmatic intrusion which is a probable source of crustal fluids for this Prospect.

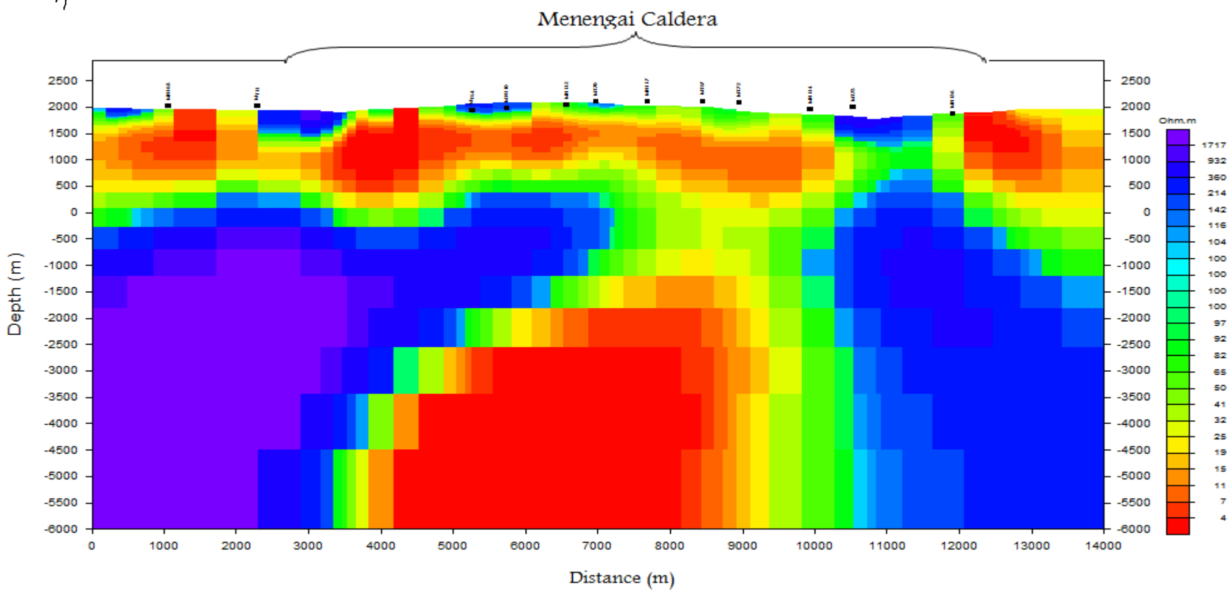


Figure 12: 2D East-west MT resistivity cross-section

DISCUSIONS

This resistivity survey has identified three zones, separated by discontinuities, which are suitable for geothermal production. These are:

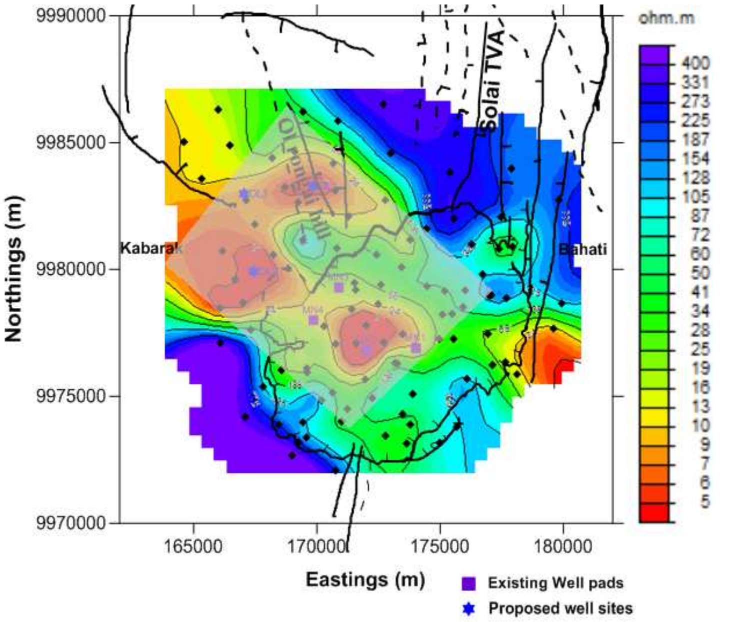
(1) The central part of the caldera which shows a low resistivity (< 10 Ωm) anomaly at depth.
(2) The Ol' Rongai area where steaming and dry hot wells are located also with low resistivity at depth.
(3) The western domain towards Kabarak which is separated from the central one by a structural discontinuity has a homogenous electrical response and low resistivity (<10 Ωm). The low resistivity is attributed to primary (lithology) rather than secondary alteration, probably due to intense hydrothermal alteration. However, the top of the resistive basement is shallower.

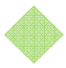
The total heat estimated from the caldera alone is in excess of 2690 MWt. This high heat flow from the Menengai caldera could be indicative of a big hot body underneath, which can be explored further for production of steam. Areas around Ol' Rongai and Ol' Banita are also interesting even though the overall heat flow estimated is low. The low heat flow could be due to the fact that they are older systems. The orientation of the high temperature areas is in a NNW-SSE direction. This suggests that a major fault/fracture zone could be aligned in this direction and allows deep hot fluids to flow close to the surface causing localized heating of the shallow fluids. Another possible structure seems to occur in NE-SW direction as can be observed from the orientation of the high temperature areas within the caldera.

CONCLUSION

It is recommended that four deep directional exploratory wells be drilled in Menengai caldera as was initially proposed and three more to be drilled on Ol' Rongai and Kabarak area as indicated in the findings**(**Figure 2.4**)**. The resource area based on the anomaly is about 84 km^2 which can yield about 1260 MWe based on the world average of 15 MWe/km^2

Figure 13: Menengai proposed exploratory well sites and resource area



 Resource area