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GEOPHYSICAL SURVEYS OF HIGH TEMPERATURE FIELDS – A CASE FOR OLKARIA AND MENENGAI GEOTHERMAL FIELDS, KENYA

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ABSTRACT

The occurrence of surface manifestations in the country's rift valley regions encouraged various people to carry out various geophysical investigations to establish the subsurface structure with a view of establishing its geothermal potential. Various levels of success have been achieved with each of the techniques. The activities resulted in drilling geothermal wells at Olkaria. Eburru and Menengai Geothermal fields. Power plans have been commissioned at Olkaria and Eburru. Changes in technology have seen the deployment of modern geophysical techniques that included transient electromagnetics (TEM) and magnetotellurics (MT) which made it possible for shallow and deep conductors to be accurately imaged and thus more accurate geothermal models developed. This article provides a general introduction to the most important methods of geophysical exploration that have been employed at both Olkaria and Menengai Geothermal fields, Kenya, the results obtained and recommendations made.

1. INTRODUCTION TO GEOPHYSICAL METHODS

For earth scientists, a wide range of geophysical, geo-chemical and geological surveying methods exist for geothermal energy investigations. For each of these methodologies, there is a typical physical/chemical property to which the technique is sensitive to. For geophysics, location of a geothermal reservoir may be determined by use of seismic velocity, electrical conductivity, magnetic or/and gravity methods. Effects of exploitation of a geothermal reservoir can be monitored using micro-seismic, micro-gravity, geo-chemical and temperature/pressure techniques. Though these may require complex methodology and relatively advanced mathematical treatment in interpretation, much information may be derived from simple qualitative assessment of the survey or monitoring data. Often many of these methods are used in combination to obtain a plausible inference. At the interpretation stage, ambiguity arising from the results of one survey may often be removed by consideration of results from a second or third survey method. A wide range of geophysical surveying methods have been employed for exploration for geothermal energy in Olkari and Menengai, as well as the monitoring of geothermal reservoirs under exploitation in Olkaria (Ndombi, 1981; Mariita, 1995; Simiyu and Keller, 1997). The type of physical property to which a method responds dictates the application. In both fields, these methods include seismic, gravity, magnetics, electrical resistivity, Transient Electromagnetic (TEM) and Magnetotelluric (MT). The end results are geared to obtaining information on whether a resource exists and propose sites for exploratory drilling, and develop a geothermal conceptual model of the area.

2. GEOPHYSICAL SURVEYS IN OLKARIA GEOTHERMAL FIELD

Olkaria Geothermal Field covers an area of about 256 km2 divided into seven fields based on structure and reservoir characteristics (Figure 1). These are; the East production field (EPF), North East (NEF), Olkaria Central (OCF), Olkaria West (OWF), Olkaria South East (OSE), Olkaria South West (OSW) and Domes (Olkaria 4). This is the first geothermal field to be developed in the Kenyan part of the East African Rift Valley where over 150 wells have been drilled. The field has been assessed to have total potential of 500 MWe. Drilling and reservoir studies have been going on for the last 30 years and research has reached a stage where the system characteristics are well understood. A conceptual reservoir model for the Olkaria geothermal field has been developed, and is reviewed from time to time as new data is obtained. Over the years, it has been possible to strengthen the model and add confidence to the understanding of the characteristics of the field and reservoir. Much of this information has been collected by use of Geophysical methods.

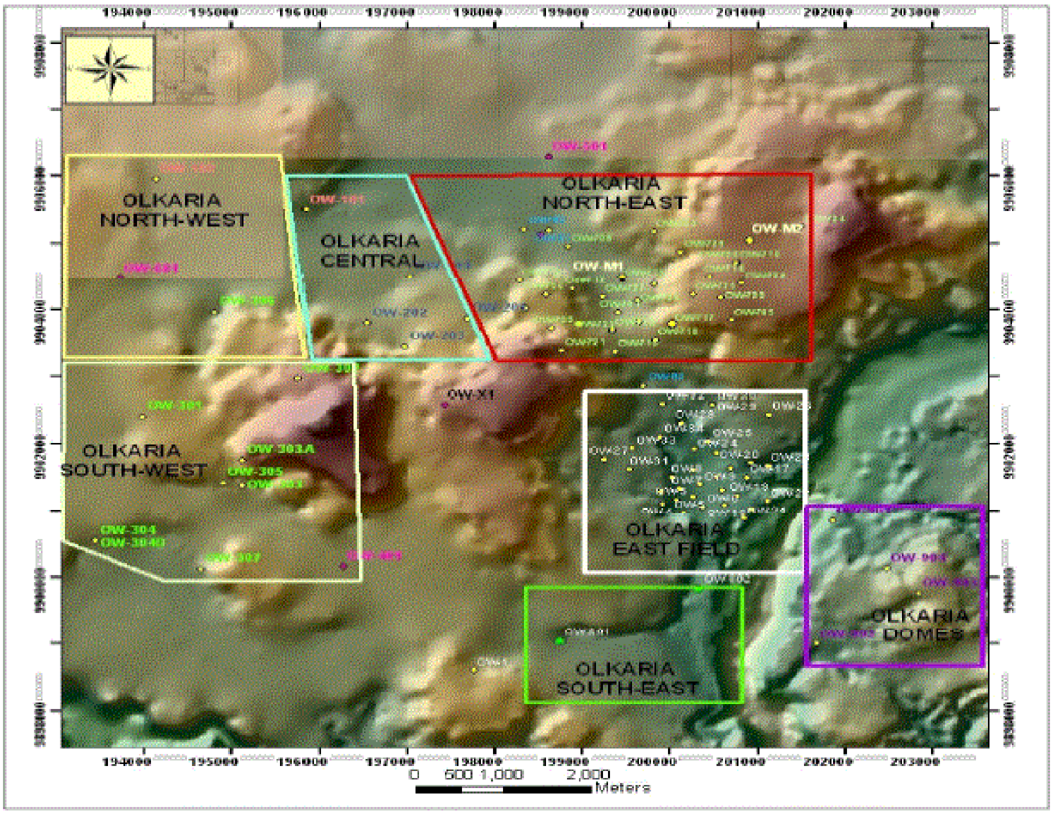

FIGURE 1: Sectors of the Greater Olkaria Geothermal field

2.1 Previous works

Exploration efforts for Geothermal Energy in Kenya before the 1970s is discussed in detail by Tole (1996) and JICA (1983). In the early fifties two wells (X1 and X2) were drilled at Olkaria (Figure 2). The results were not encouraging. In 1960's, more geophysical work was carried out between Lake Bogoria and Olkaria under the UNDP project. They identified several areas of low resistivity and positive gravity anomalies associated with Quaternary volcanic complexes. These areas that were found suitable for geothermal exploration were found to be associated with surface manifestations and they have been targets for detailed geothermal exploration.

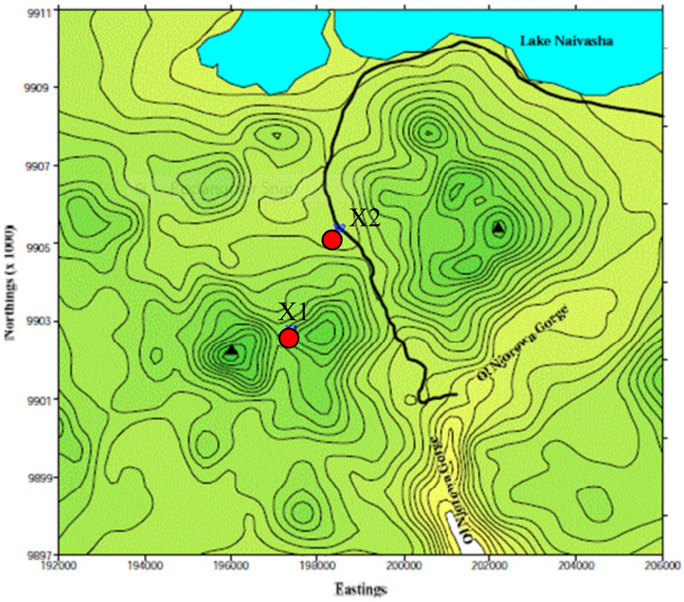

FIGURE 2: Location of the first 2 geothermal wells (X1 and X2) to be drilled in Kenya

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

2.2 Resistivity measurements in Olkaria geothermal field

At Olkaria, direct current (DC) resistivity methods have been used for many years to carry out reconnaissance mapping, location of faults for drilling targets and to define the boundaries of geothermal reservoirs. Interpretation of DC Resistivity data from the Olkaria geothermal field shows that the low resistivity (less than 20 Ωm) anomalies at depths of 1000 masl that define the geothermal resource boundaries are controlled by linear structures in the NE-SW and NW-SE directions. The near surface difference in resistivity is caused by contrasts in the subsurface geology. Drilled wells show that the low resistivity anomalies at 1000 masl define a geothermal system with temperatures in excess of 240°C. Some of the high resistivity regions coincide with recharge areas associated with NE and NW trending faults that act as conduits for cold water flow from the Rift Valley scarps. The geothermal fluid up-flow zones occur at the intersections of these regional faults in the vicinity of a heat source.

In recent years, Transient Electromagnetic (TEM) and Magnetotelluric (MT) have been favoured against the DC sounding methods. This was mainly due to logistical considerations and the depth of penetration.

Transient electro-magnetics (TEM)

Of the DC resistivity measurements, the Schlumberger array was the most preferred configuration for good vertical resolution at depth down to 1 km. However due logistic constraints this technique was abandoned and TEM method was introduced in the mid-1990s. The TEM method serves the same purpose as Schlumberger but it gives better resolution at depth. The depth of penetration is dependent on how long the induction in the receiver coil can be traced in time before it is drowned in noise. However, for the Olkaria situation the depth of penetration of TEM is limited to about 700 m depth depending on the resistivity structure. This is similar to that of Schlumberger soundings with a maximum distance of 3 km between the current electrodes.

Over one hundred TEM sounding stations have been covered in the greater Olkaria area. The method involved the passage of a large current through an ungrounded loop of wire measuring 300mx300m square. An EM receiver at the centre of the square measured the ground TEM response. The data was processed, inverted and produced in apparent resistivity plots in form of contours maps at various elevations. The data shows that the low resistivity anomalies are controlled by linear structures in the NE-SW and NW-SE directions and that the geothermal resource is confined within an area with a low resistivity value of less than 15 Ωm at an elevation of 1400 Masl (Figure 3).

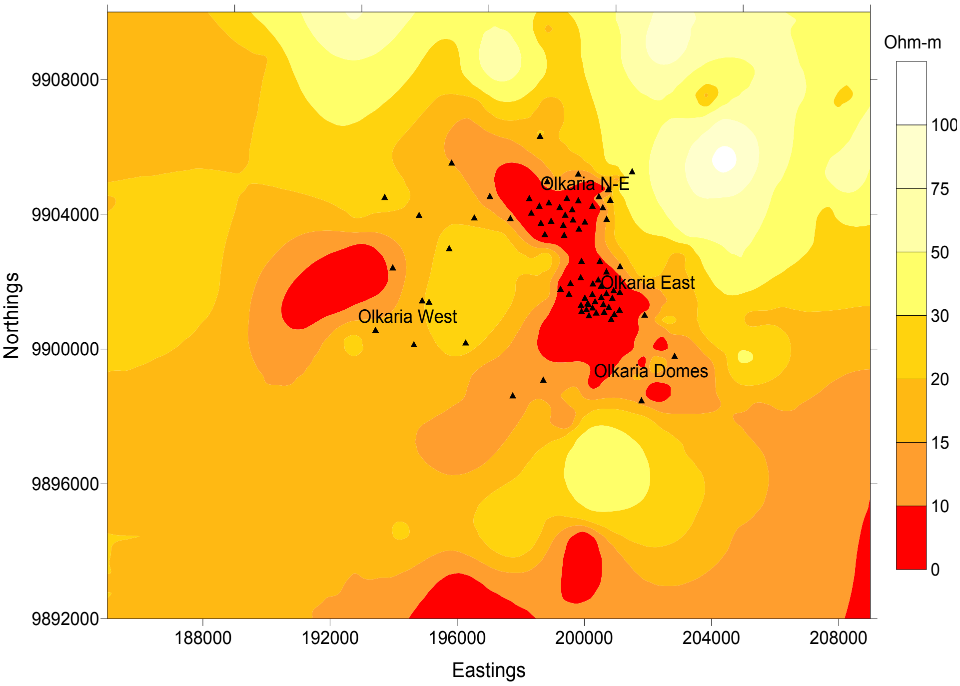

FIGURE 3: Resistivity distribution at 1400 masl from TEM measurements at Olkaria

The resistivity is lower around Olkaria West Field (OWF) than the area around East (EPF) and North East Fields (NEF). The near surface difference in resistivity is caused by contrasts in the subsurface geology. An altered thick surficial layer of pyroclastics occurring in the Olkaria West field is the cause of the near surface low resistivity in the field (Omenda, 1994, 1998). A thicker layer of pyroclastics up to an elevation of 1500 masl covers the Olkaria West area. Drilled wells show that the low resistivity anomalies at 1000 masl define a geothermal system with temperatures in excess of 240°C. Some of the high resistivity regions coincide with recharge areas associated with NE and NW trending faults that act as conduits for cold water flow from the Rift Valley scarps. The geothermal fluid upflow zones occur at the intersections of these regional faults in the vicinity of a heat source (Onacha, 1989, 1993).

Magnetotellurics (MT)

The magnetolluric resistivity technique is the latest method that has been acquired for geothermal energy exploration in Kenya. The method uses natural current fields induced in the earth by time variations in the earth's magnetic field. Both the electric and magnetic fields are measured. Due to this, the technique does provide more information on subsurface structure, as its depth of penetration is much larger than TEM. The depth is dependent on frequency and the resistivity of the subsurface. Consequently, depth penetration increases as frequency decreases and the apparent resistivity varies with frequency. The calculation of the apparent resistivity for a number of decreasing frequencies thus provides resistivity information at progressively increasing depths.

Though the MT method has the capability for probing several tens of kilometres, the data may be affected by galvanic distortions manifesting as frequency-independent static shifts of the apparent resistivity curves when small-size surficial heterogeneities are present, as can be expected in the weathered and volcanic-covered basement terrain of Olkaria. The TEM technique provides a logical shallow-depth (< 1 km) compliment to MT and also serves for correction of MT static shifts. The combined TEM-MT approach has therefore been selected as the technique with optimum potential in Olkaria. Preliminary analysis of MT data from the region suggests the presence of significantly enhanced conductivities below Olkaria (Figure 4); however, no quantitative modelling of the data has been undertaken and the actual physical parameters of the suggested zone of enhanced conductivities are not known.

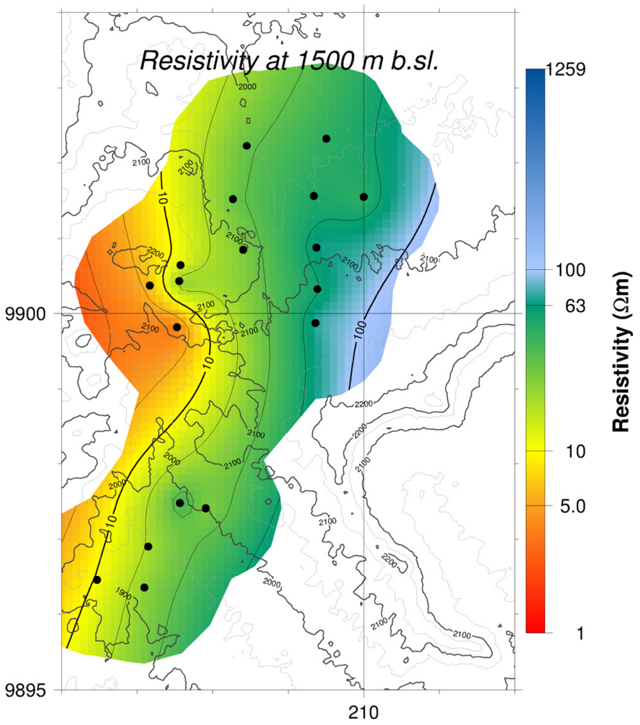

FIGURE 4: Resistivity distribution at 1500 mbsl from MT measurements at Greater Olkaria Area

2.3 Potential field measurements in Olkaria geothermal field

Gravity survey of the shallow crust beneath Olkaria indicated a volcanic zone of three layers that appears down-faulted in the Olkaria West area and showing low density (Ndombi, 1981). Gravity further revealed the presence of dense dike material along the Ololbutot fault zone. However, it is now known from geology that the N-S Olkaria Hill fault marks a major east-dipping fault that has down-thrown the Mau formation to more than 3 km in the eastern area. The developed eastern graben was later in-filled with late Pleistocene - Holocene volcanism that was dominated by trachyte, basalts and rhyolite lavas and relatively minor pyroclastics, thus resulting in higher gravity (Omenda, 1994, 1998). A Bouguer anomaly map using a density of 2.5 g/cm^3 (Figure 5).

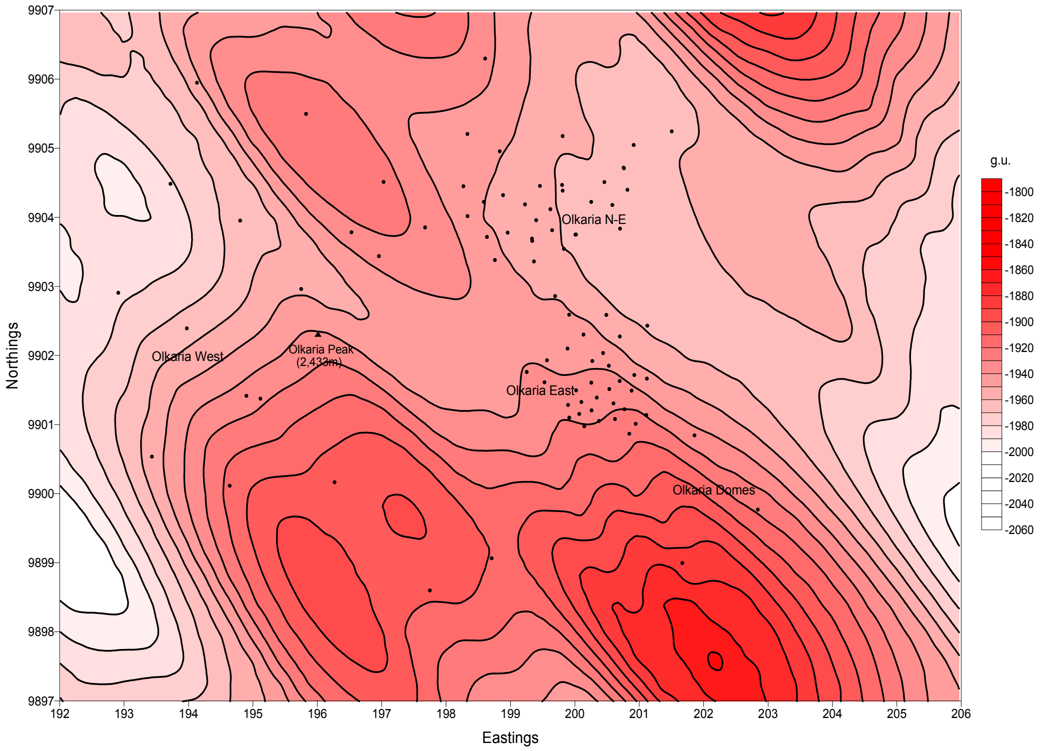

FIGURE 5: Directionally filtered gravity data of the greater Olkaria geothermal field. Note the NW-SE trend of the gravity anomaly through Olkaria, corresponding to the regional geological structure in the central rift segment. A low gravity anomaly occurs in the west with towards the Mau escarpment. Another gravity low occurs in the eastern Olkaria Domes area and extends to Longonot volcano.

In Olkaria, both ground and aero-magnetic data have been used to investigate the presence of a geothermal resource in combination with gravity. From the aero-magnetic maps several of the anomalies can be clearly correlated with surface expressions of volcanism such as craters, domes or cones, localised basaltics lavas or plugs (Figure 6). From these maps most of the volcanic centres tend to lie in areas with magnetic highs (positives). Sometimes a superimposed magnetic low (negative) exist; but this is generally weak or zero.

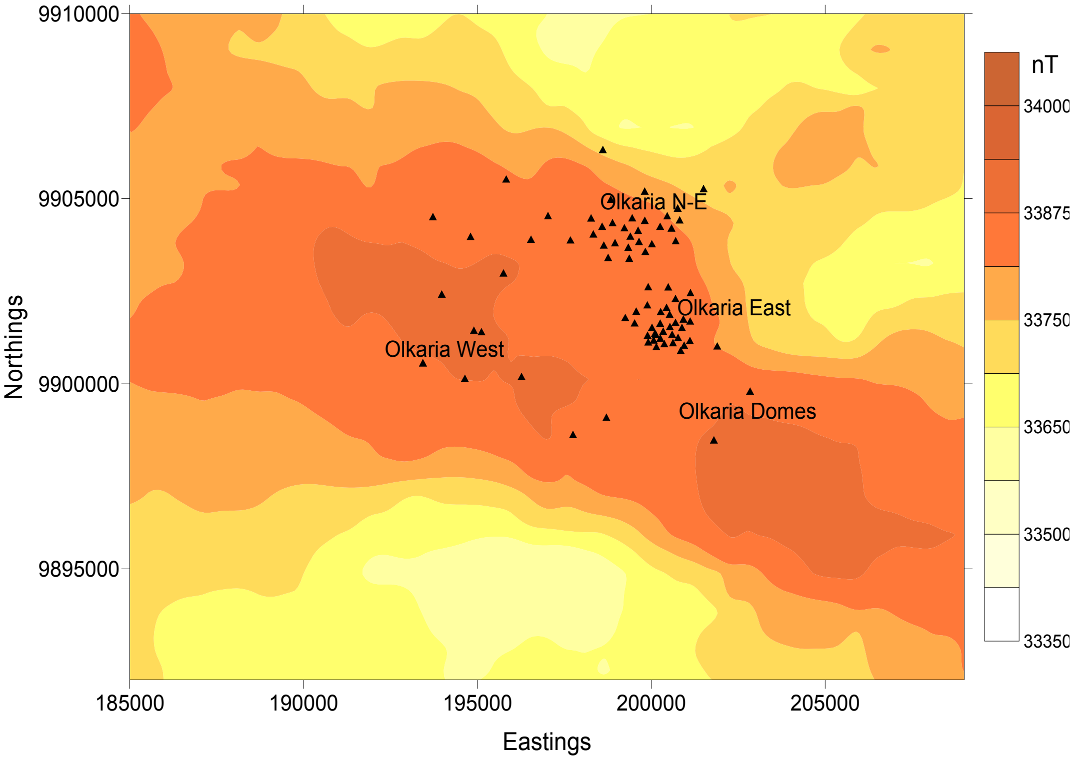

FIGURE 6: Total magnetic intensity over Olkaria and surrounding areas

Bhogal and Skinner (1971) analysed residual draped aeromagnetic data flown at 300 m above ground surface within the Olkaria area. Their results showed that the central geothermal area had a positive magnetic anomaly trending NW-SE. This anomaly is superimposed on a broad regional negative anomaly that covers the entire southern Lake Naivasha region and corresponds to normally magnetized rocks. The positive anomaly oriented NW was interpreted to occur in a demagnetized zone corresponding to the main heat source with a temperature above the curie point of magnetite (575°C) and a depth of about 6 km. A minor trend in the magnetic anomaly is in a NE-SW direction corresponding to the Olkaria fault zone.

2.4 Seismic measurements in Olkaria geothermal field

Both passive and active source seismic studies have taken place in Olkaria. These were contacted by the United States Geological Survey (Hamilton et al., 1973) using an eight-station network. They located 87 events of magnitude 2 and less restricted mainly within a 4 km wide zone parallel to the NS trending Ololbutot fault zone. Time distance plots indicated that the area is characterized by a three layer volcanic sequence of about 3.5 km thick underlain by a granitic layer with a P-wave velocity of 6.3 km/s.

A 2-year seismic monitoring program was carried out in Olkaria between 1996 and 1998 (Simiyu 1999; Mariita et al., 1996). The main objectives were to carry out analyses of the wave parameters so as to determine earthquake location and to relate these locations to the presence of structures that allow reservoir fluid flow patterns. During this period more than 4800 local earthquakes originating within the study area were recorded (Figure 7).

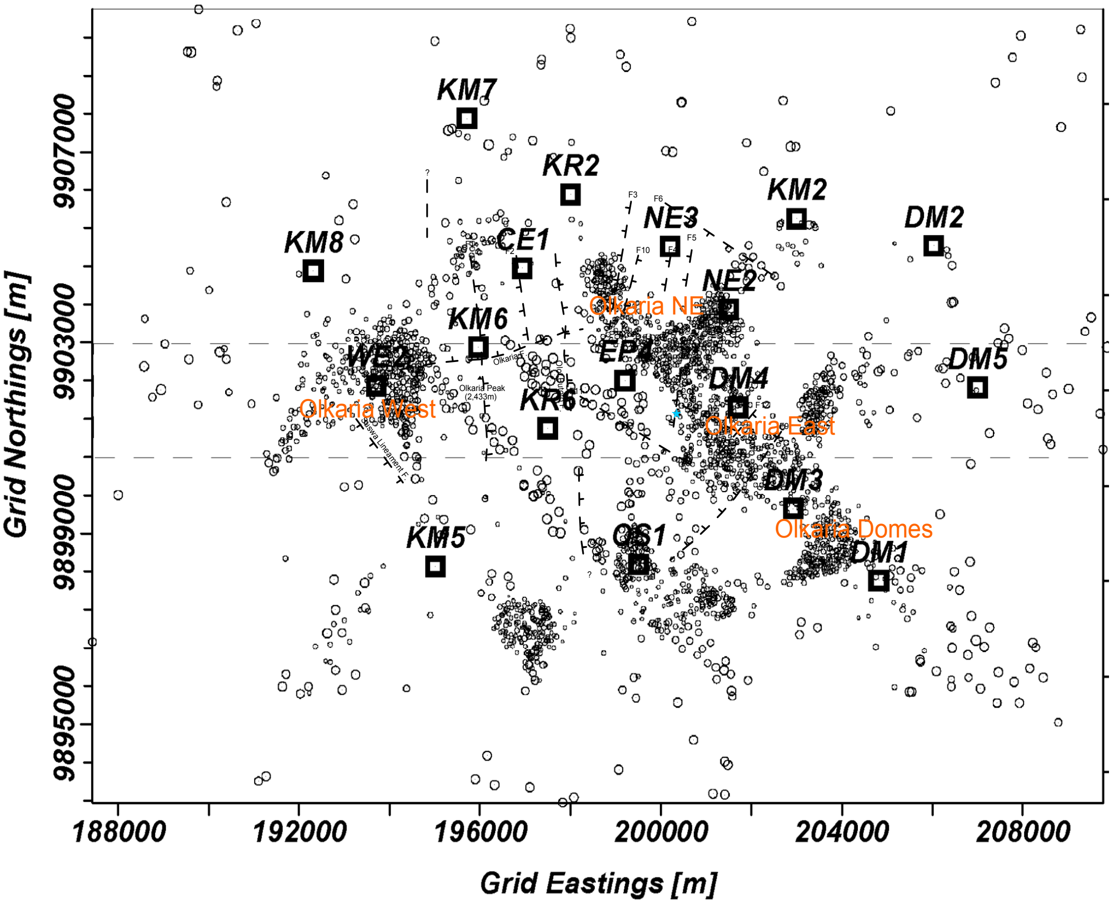

FIGURE 7: Micro-earthquake event location around Olkaria. Thick square boxes represent the locations of seismic receivers

The results show that seismicity is more intense in the centre of the field where temperature is high, with smaller and shallower events. On the periphery and outside of the field, where drill holes show low temperature, events are large and deeper.

Outside of the geothermal field, earthquakes deepen to the northwest, north and northeast away from the geothermal system. Seismic gaps were mapped within the Olkaria field (OWF and NEF) and found to mark zones of hot magmatic intrusions that have raised the temperature above 450°C. Anomalous low S wave amplitudes beneath the young volcanics of the Olkaria geothermal area were determined and then back projected to map the position of attenuating anomalies in the region by using source-receiver ray path overlap density. It was possible to image an attenuating (possible heat source) body directly beneath the Olkaria geothermal area that also showed a gap in seismicity above it.

2.5 Integration of geophysical data for Olkaria geothermal field

Many of the geophysical methods used at Olkaria have aided in understanding reservoir conditions. The Olkaria geothermal system is closely associated with the Quaternary silicic volcanism in the segment of the rift which was active from late Pleistocene to Holocene. Results from seismics and magnetics indicate the presence of attenuating bodies at 6-10 km depth which are also demagnetized within the Olkaria geothermal field thus, corroborating geological. The seismic data is also in agreement with recent geological models that indicate that the bodies are discrete; fault controlled and experienced different evolutionary histories.

The gravity survey of the shallow crust beneath Olkaria shows a general gravity high trending NNW and in line with the regional geological structure in the area. However, there are local highs that trend NE in line with the recent fault trends. These local gravity highs are interpreted as dike intrusions which are heat sources in some areas while in others, e.g., along the Ololbutot fault zone they act as hydrological barriers between fields. The occurrence of magnetic and gravity anomalies at the intersections of NE and NW rift faults, is an indication of distinct near surface heat sources controlling the reservoir characteristics of the geothermal systems.

Micro-earthquake monitoring for epicentre and hypocentre locations show that Olkaria is a high temperature geothermal field characterized by a relatively high level of micro-earthquake activity. The Olkaria West area has shallow high frequency events and deep low frequency events. The shallow events occur at the intersection of the Olkaria and Suswa faults. The shallow events are associated with an up-flow zone in Olkaria west. Shallow high frequency tectonic events and deep low frequency volcano-tectonic events occur within the EPF and NE Olkaria along a NW-SE linear trend. The shallowest high frequency events related to shallow fluid movement and volcano-tectonic events occur at the intersection of the Ololbutot fault zone and the Olkaria fault. Deeper to medium depth events occur along the Ololbutot fault zone and they are interpreted to be due to fluid movement at depth. The Ololbutot fault zone has also been modelled as a recharge zone from resistivity, down-hole temperature measurements and geochemical signatures. The deep events occur away from the up-flow zones and signify tectonic movements along the main faults.

At Olkaria, the resistivity methods have been the most consistent and extensively used geophysical method with very good results. Initially the DC resistivity type was employed. However, this has been abandoned in preference to TEM and MT methods due to the efforts required to penetrate depths greater than 1 km. Resistivity methods have been capable of mapping the reservoir itself and that makes them more attractive to use.

An integrated E-W cross sectional plot through Olkaria geothermal field incorporating gravity, DC, TEM and MT data (Figure 8) shows high resistivity and low gravity anomalies in the western escarpment which is interpreted as the recharge for the geothermal system. However, a deep low resistivity occurs in close proximity of Olkaria Hill and is postulated as the heat source for the Olkaria West geothermal system. A major dike intrusion is modelled to occur along the Olkaria Hill fault and the zone shows as a high resistivity zone.

3. GEOPHYSICAL SURVEYS IN MENENGAI GEOTHERMAL FIELD

3.1 Previous works

The Menengai-Olbanita area is located in a region of intra-continental triple junction where the Nyanza rift joins the Kenya rift and is considered to overly a mantle plume. The surface is comprised of several eruptive volcanoes with caldera collapses and concentration of tectonic grid faulting. The Menengai complex is dominated by a central volcano with a large caldera of about 12km in diameter. The Olbanita volcanic complex consists of the remnants of an old caldera 8 km north of Menengai. The surface in both areas is covered by mainly pyroclastics, tuffs and minor occurrence of trachyte and basalt. Although there are few surface manifestations, shallow boreholes in this area have encountered steam at depths of about 70 m. Pyroclastics and tuffs cover the area outside the caldera. The floor of the caldera is covered by post caldera collapse trachytes. The northern rim of the caldera is cut to the west by NS trending faults, which form a small graben, and to the east by NNE trending faults that form the Solai tectono-volcanic axis. Geothermal manifestations occur on the floor of the caldera and along the NS trending faults (Dunkley et al., 1993). The Menengai Geothermal Field has a rugged terrain and very few geothermal manifestations, which makes it quite difficult in terms of exploration using both geophysical and chemical methods. The few geothermal manifestations present

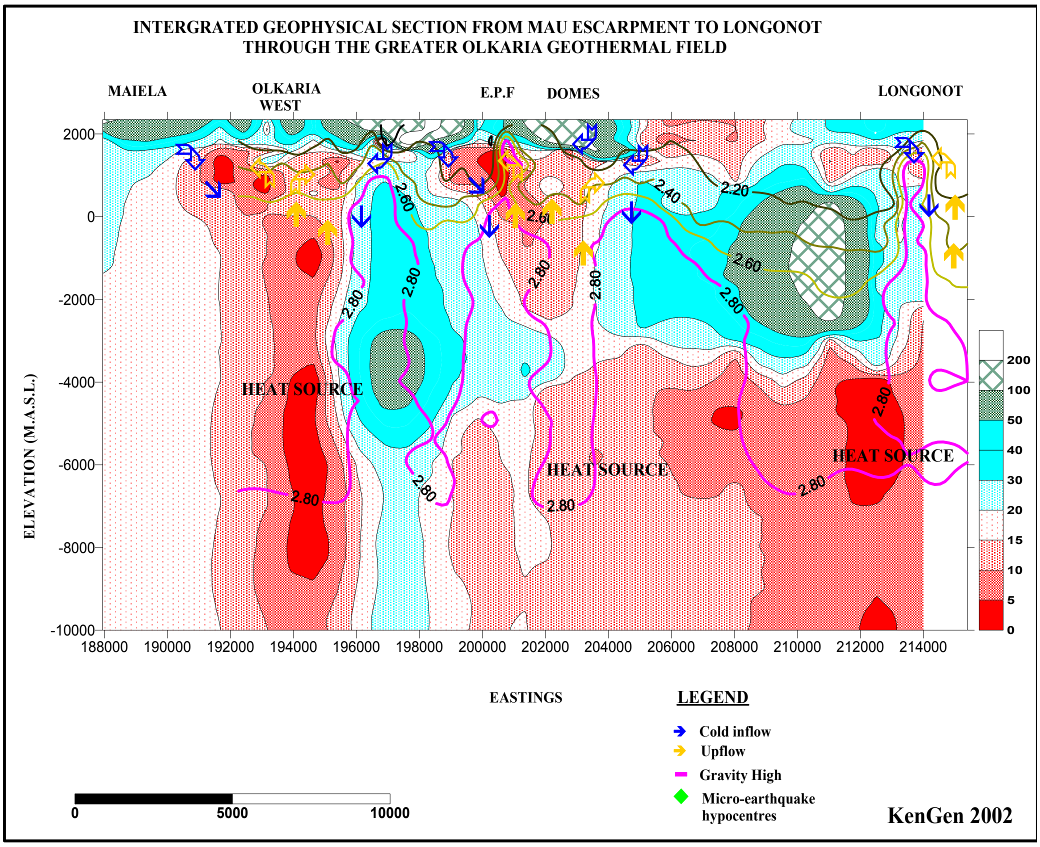

FIGURE 8: Integrated geophysical model across Olkaria

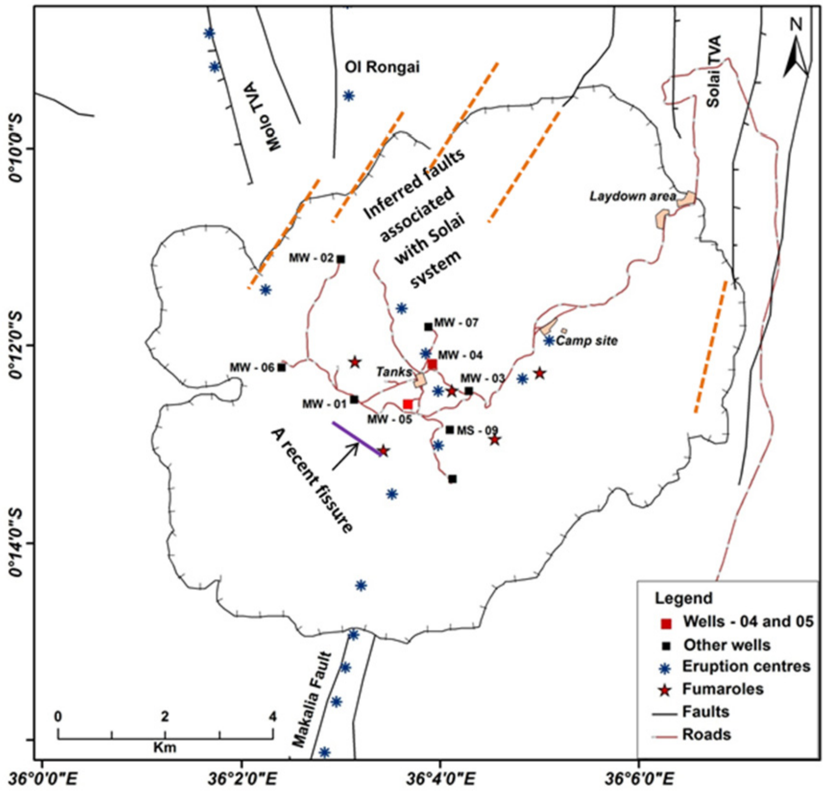

FIGURE 9: Menengai structural map and surface manifestations

Several Geophysical Methods have been used in Menengai, namely Resistivity, Seismics and Potential fields. The resistivity methods have been Schlumberger, MT and TEM. Previous geophysical investigations of this area were carried out by Geotermica Italiana Srl, (1987), the British Geological Survey (Dunkley et al., 1993) and Ministry of Energy in 1985-1986 under the auspices of the United Nations Department for Technical Development (DTCD). The work covered the area from Menengai caldera to Lake Bogoria to the north. The work involved gravity and resistivity measurements. Later in 2004 more geophysical work using (resistivity, gravity and heat flow) better methodologies were done by KenGen through funding by the Ministry of Energy. The Menengai caldera has extensive young lava flows and boreholes drilled to 300 m depths have recorded temperatures of 4°C to 60°C. Heat loss features encountered are hot grounds and fumaroles. No hot springs were encountered.

3.2 Heat flow measurements in Menengai geothermal prospect

Results from Heat flow work done by KenGen in 2004 using shallow gradient holes is shown in Figure 10. It is demarcated by the 40°C isotherm. Observation of the results indicate a high temperature anomaly in a NNW-SSE direction, suggesting a major fault/fracture zone in this direction allowing deep hot fluids to travel close to the surface causing localised heating. Another possible structure seems to occur in NE-SW direction. Areas around Olongai and Banita have low heat flow possibly because the geothermal system in this area is older.

Total heat loss estimated from the Caldera alone is in excess of 2,690 MWt indicating possibly a big hot body underneath which can be explored further for production of steam. From the heat flow measurements it was concluded that over 3,536 MWt of natural heat loss occurs in the Menengai/Olbanita geothermal prospect. 2,690 MWt is lost from the Menengai Caldera out of which 2,440 MWt is by convection through fumaroles. It was concluded that this large heat loss could be an indicator of a huge heat source underneath this prospect.

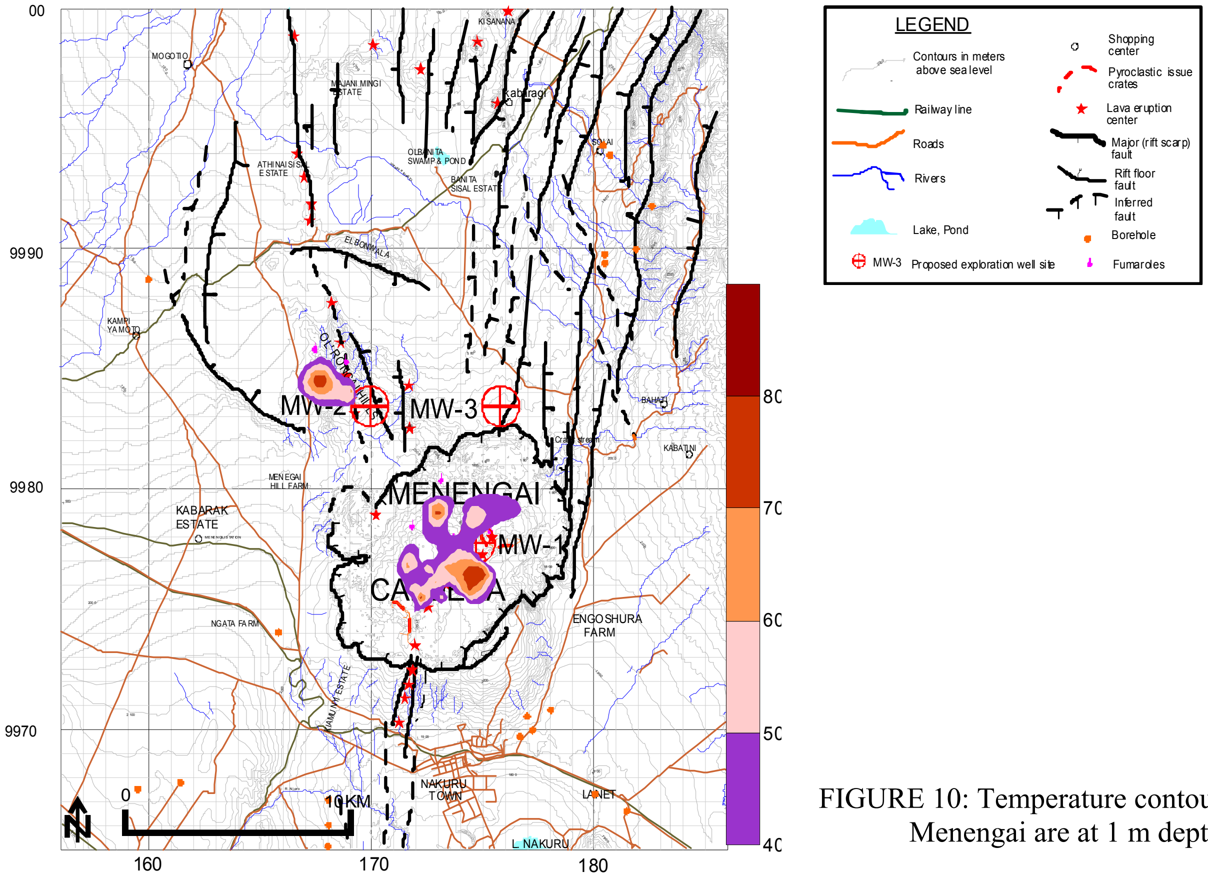

FIGURE 10: Temperature contour map of Menengai are at 1 m depth

3.3 Resistivity measurements in Menengai geothermal field

Geotermica Italiana Srl (1987), under the auspices of United Nations/Government of Kenya project KEN/82/002, carried out resistivity studies using the Schlumberger method. These studies were aimed at providing data for interpretation of the geothermal system. KenGen in the year 2004 and GDC in 2011 and 2012 have used Magnetotullics in conjunction with Transient Electromagnetics. Figure 11 is Iso-resisitivity Map at Sea Level of Menengai area from the MT/TEM data. Figure 12 is a cross-section across the caldera.

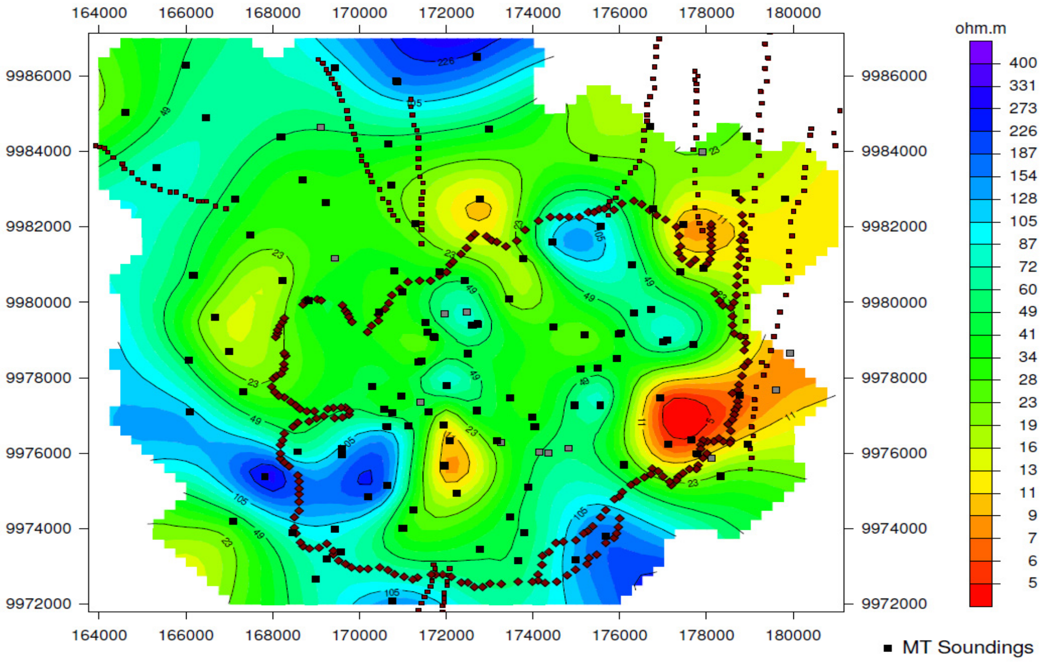

FIGURE 11: Iso-resisitivity Map at Sea Level of Menengai area from MT/TEM data analysis

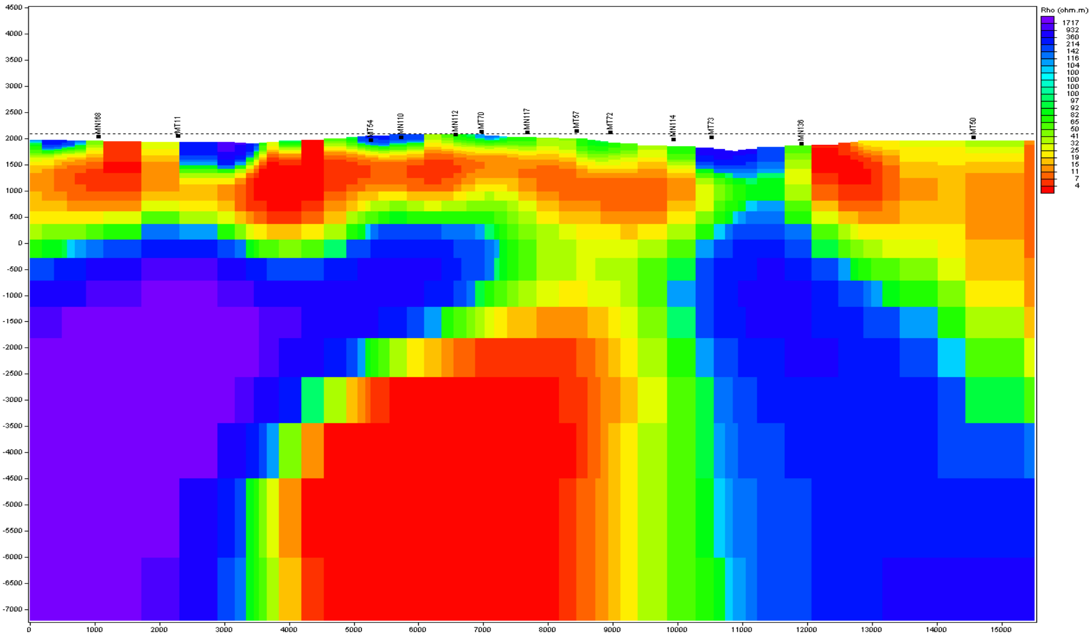

FIGURE 12: Resistivity cross-section across Menengai caldera.

3.4 Potential field measurements in Menengai geothermal field

A sizable amount of gravity data has been collected over the area. Interpretation of this data has been done in conjunction with aeromagnetic data from the Kenya National Oil Corporation. Gravity studies by Geotermica Italiana (1987) under UN/GOK project KEN/82/002 collected some 1400 data points. Analysis of this data showed a large positive anomaly, located in the central part of the area. They interpreted this anomaly to be related to a dense body located some 3.5-4 km deep and a density of 2.8 g/cm^3 that could be a heat source for the geothermal system. This anomaly coincided with the Molo Volcanic Axis, which is intruded by a series of dikes (Simiyu and Keller, 1997; Simiyu 1998). Gravity data interpretation by KRISP (Simiyu, 1998) along a regional profile that runs across Menengai, show a gravity high with an amplitude of 40 mGal and an EW wavelength of 35 km. This anomaly was modeled as an intrusive body, about 13 km wide and coming to within 4 km of the surface.

3.5 Seismic measurements in Menengai geothermal field

The Kenya Rift Seismic Project (KRISP) set up a Seismic work in this area in 1990. Results from the effort indicated the presence of high velocity material lying directly beneath the north of Menengai Caldera. Simiyu (1996) modeled this body with a P-wave velocity of 6.8 km/s in an area of 6.05 km/s basement velocity Micro-seismic monitoring show that some events originate from the Menengai-Olbanita area along the Solai axis. These seismic results together with geology showed that the Solai axis is still the most tectonically active system characterized by normal grid faulting with blocks generally tilting towards the east.

3.6 Integration of geophysical data for Menengai geothermal field

The Geophysical data from the three methods discussed above were integrated in order to infer the presence or absence of a heat source, reservoir and permeability. Results indicate the presence of deeper denser bodies. Seismic data from KRISP experiments suggest the presence of high velocity/high density material within the upper 10 km of crust along the rift axis located below the volcanic centres and low resistivity areas. The seismic activity confined to within 4 km imply that a magma body exists at shallow depth and may be forming the heat source for the area. This investigations culminated in recommending that the field be put under exploratory drilling. Figure 13 shows the initial proposed exploratory wells.

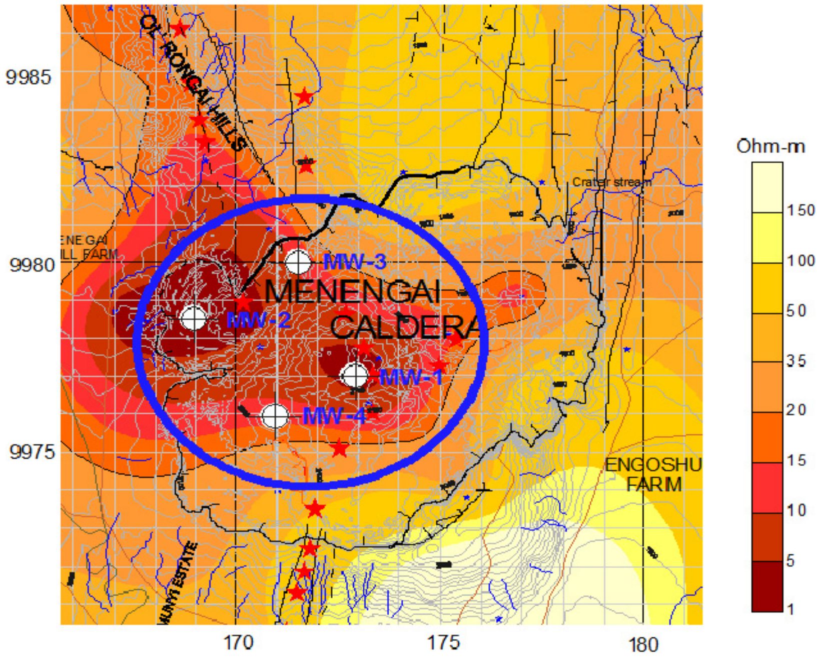

FIGURE 13: Initial proposed best well sites based on integrated geophysical studies

4. CONCLUSIONS AND DEVELOPMENT FOR MENENGAI FIELD

The Menengai geothermal field has a potential for existence of geothermal system(s), giving priority to caldera for further exploration since it represents the most recent volcanism and existence of centralized magma body, which is assumed to be the heat source.

The formation of the Geothermal Development Corporation in January 2009 by the Kenyan government has accelerated the development of the geothermal resource at Menengai. The company has carried out several investigations in Menengai which have involved Structural Mapping; geophysical surveys; geochemical surveys and heat flow measurements. All these methods have indicated an exploitable resource. The Comprehensive Geothermal Conceptual Model developed and currently in use to site productive wells in this field, recommends that 4 exploratory wells be drilled within the Menengai caldera and step out subsequent wells to delineate the resource area.

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