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EXPLORATION HISTORY OF OLKARIA GEOTHERMAL FIELD BY USE OF GEOPHYSICS

Nicolas O. Mariita
Kenya Electricity Generating Company Ltd-KenGen
P.O. Box 785, Naivasha
KENYA
nmariita@kengen.co.ke

ABSTRACT

Olkaria Geothermal field is a high temperature geothermal resource in the Kenya Rift Valley which has been used for electricity generation since 1981. To date, 105 wells (96 by KenGen and 9 by IPP) have been drilled in Olkaria with a proven power potential of 157 MWe. However, it is estimated that the geothermal potential of the entire area could exceed 400 MWe. Olkaria geothermal area has been divided into seven development sectors out of which only three have been committed to development. The sectors (fields) are Olkaria East, Olkaria North East, Olkaria South West, Olkaria Central, Olkaria North West, Olkaria South East, and Olkaria Domes. The fields are named with respect to Olkaria Hill.

The geothermal resource is associated with an area of Quaternary volcanism in which rhyolites dominate. Geophysical exploration for the resource during the early stages of development included dipole, Schlumberger, electromagnetic, head-on, gravity, seismic and magnetics and various levels of success were achieved. It was noted that whereas resistivity was the most important in identifying the reservoirs, depth of penetration was low for dipole and Schlumberger while interpretation of head-on data was ambiguous.

Latest investigations at Olkaria have involved the use of transient electromagnetics (TEM) and magnetotellurics (MT) due to their ease of deployment and better depth of penetration of the latter. Combined MT and TEM models are more effective in characterizing the conductivity from near surface to deeper levels. Further information has been achieved by combining MT, seismics and gravity in regard to the heat sources.

1. INTRODUCTION

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

The activities resulted in the construction and commissioning of Africa's first geothermal power plant at Olkaria with 45 MW capacity between 1981-1985. Changes in technology saw the deployment of modern geophysical techniques that included transient electromagnetics (TEM) and magnetotellurics (MT) which made it possible for shallow and deep conductors to be accurately imaged and thus more accurate geothermal models developed. Further studies resulted in the development of the second, 70 MW geothermal power plant in Olkaria NE field. One small geothermal power plant has since been built with 12 MW Olkaria III plant in the Olkaria west field and another 2.0 MW at the nearby Oserian Farm in the Central field, Figure 2.

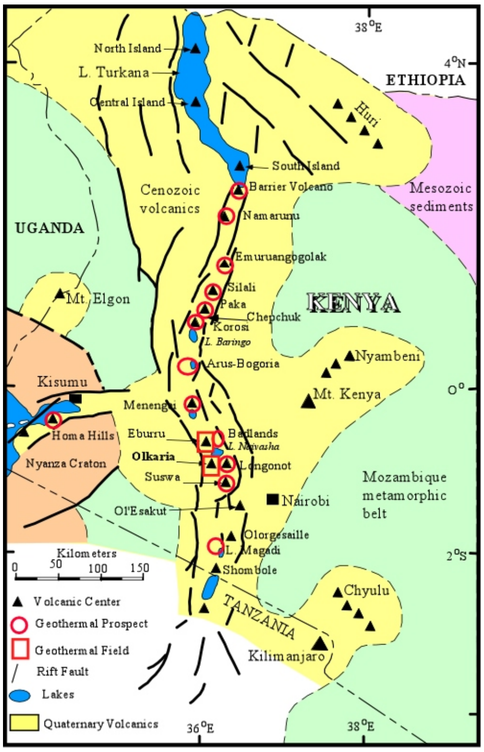

FIGURE 1: Location of Olkaria Geothermal Field within the Kenyan part of the East African Rift

2. GEOPHYSICAL EXPLORATION METHODS USED AT OLKARIA

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.

2.1 Seismology

The earliest seismic investigation in Olkaria involved passive and active source seismic studies and was undertaken by the United States Geological Survey using an eight-station network (Hamilton *et al.*, 1973). 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. Studies done by the Kenya Rift International Seismic Project (KRISP) using the 1985 and 1990 data revealed that the area immediately south of Lake Naivasha is underlain by a 5 layer upper crustal structure (Simiyu and Keller, 1997). Their interpreted model shows a structure with velocities higher than the rift's average.

A 2-year seismic monitoring program was carried out in Olkaria between 1996 and 1998 (Simiyu 1999; Mariita, 1995; Mariita *et al.*, 1996; Simiyu et al., 1998a, 1998b). The main objectives were to carry out analyses of the wave parameters so as to determine earthquake location and to relate these locations to the presence of structures that allow reservoir fluid flow patterns. During this period more than 4800 local earthquakes originating within the study area (t_s-t_p<3 sec) were recorded (Figure 3).

Average velocities for the upper crust were estimated to be 6.4 ±0.04 and 3.74±0.03 km/s for P- and S-waves respectively. The results also 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.

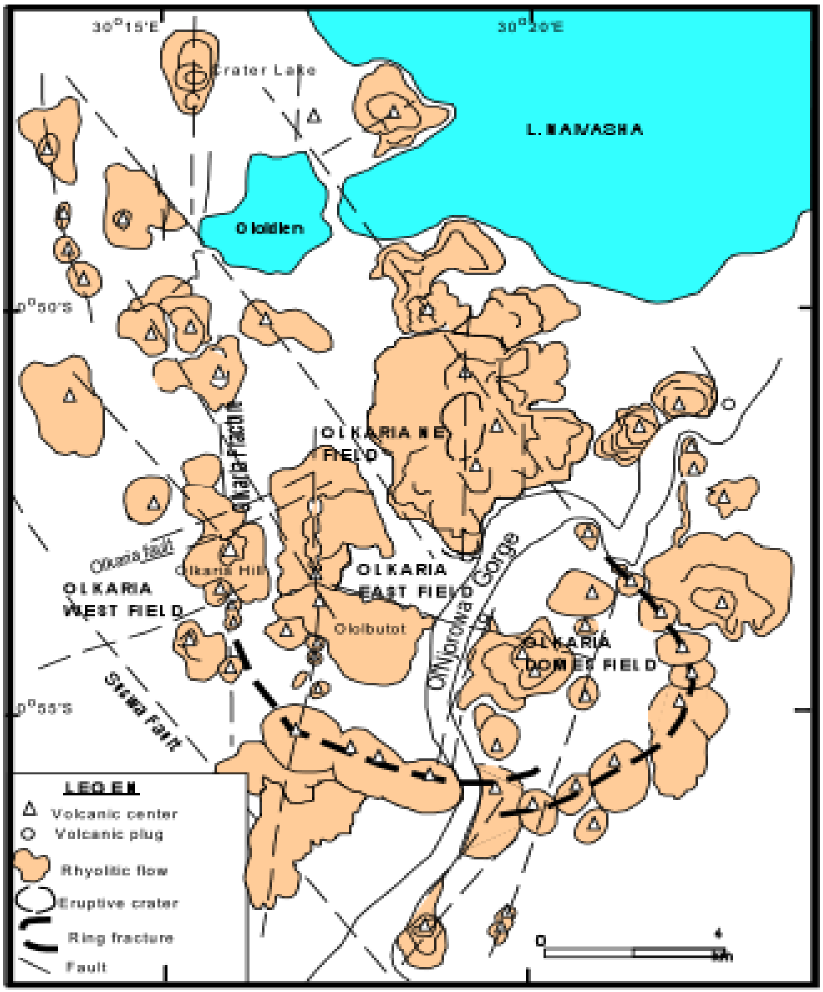

FIGURE 2: Geological map of the Olkaria volcanic complex

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^{0}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.

2.2 Resistivity

The objective of resistivity data interpretation is to delineate the resistivity variation with depth assuming that the earth is electrically homogeneous and the resistivity only varies with depth and relate them to hydrogeological and thermal structures associated with geothermal reservoirs. From several of these soundings a 2-dimensional model is constructed by use of computer inversion programs.

A resistivity survey of a geothermal field reflects the thermal alteration of the field, hence the temperature. Elevated temperatures lead to increasing alteration of minerals in the rocks of the subsurface leading to a lowering of resistivity.

At Olkaria, direct current resistivity methods have been used for reconnaissance mapping, location of faults for drilling targets and to define the boundaries of geothermal reservoirs. In recent years we have favoured Transient Electromagnetic (TEM) and Magnetotelluric (MT) sounding methods. In the TEM technique an artificial transient electromagnetic field is induced in the ground and secondary fields are measured at the surface. The sounding results are normally presented by late time apparent resistivity as a function of time, which is then used in an inversion computer program. The depth of penetration of TEM soundings is not very great, being limited by the frequency range that can be generated and detected. It is also dependent on the geology of the field under investigation and how long the signal received can be traced in time before it is drowned by noise. For the Olkaria situation our experience is that the maximum depth is about 500 m to 1 km.

Resistivity data interpretation 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^{0}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.

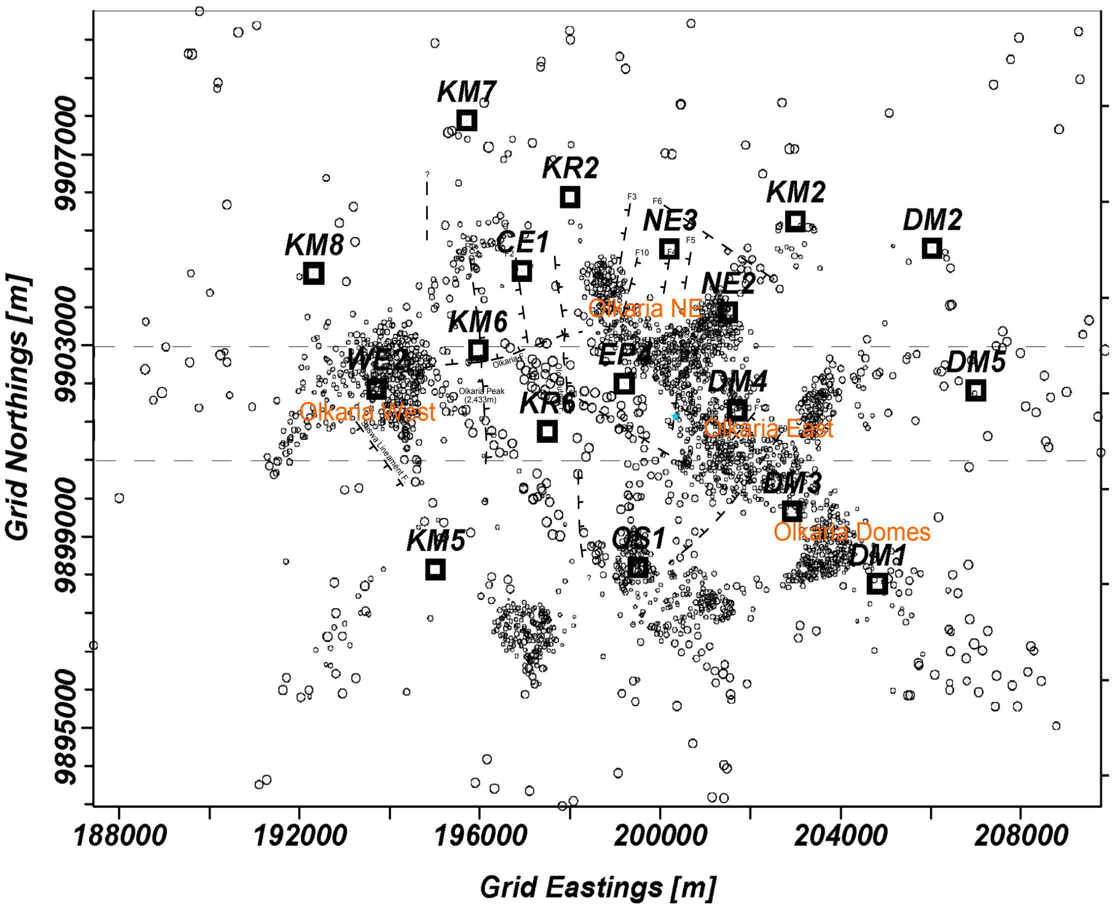

FIGURE 3: Micro-earthquake event location around Olkaria. Thick square boxes represent the locations of seismic receivers

2.3 Dipole

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

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

2.4 Schlumberger array

Since the early seventies a large number of Schlumberger vertical soundings have been carried out at Olkaria. Group Seven (1972) collected and modelled 21 Schlumberger sounding data in Olkaria with a view to exploring the resource potential in the area. The array was set with maximum spacing of 1 km and concentrated in the centre of the field in the vicinity of wells X-1 and X-2. Re-interpretation of these data in the early eighties (Hochstein *et al*., 1981; Mwangi, 1984) suggested that relatively shallow sediments and tuff in the eastern and north-eastern parts of Olkaria gave rise to the low resistivity anomalies seen in these parts of the field. These soundings had shallower penetration and so relatively higher resistivities were measured leaving undetected the main conductive part of the resource deeper down. The eastern and northern limits of the potential production area remained also undefined.

Later, in the early 1990's, a better Schlumberger equipment and longer cables were acquired. These increased the probing depth considerably. It was now possible to investigate depths down to 2 km. Results from these newer soundings highlighted the extent to which near surface resistivity features can influence apparent resistivity patterns and limit interpretations of deeper structures. For example, interpretation of this new data indicated that the Olkaria area is divided into two regions with markedly different resistivity structure by a north-south discontinuity which relates to a deep fault structures (Onacha, 1993). However, towards the end of the 1990s, this method was discontinued in favour of Transient Electromagnetic due to elaborate logistics and large number of people involved.

2.5 Electromagnetics

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

2.6 Head on resistivity

In 1982 it was proposed that the Head-on resistivity method be tried in Olkaria to see if it could be of any value in providing detailed information about the location and angle of dip of the fault zones near recommended well sites. This was based on the assumption that any fault zone containing geothermal fluids would be associated with low resistivities caused by the presence of both conductive fluids and hydrothermal alteration products. Similar work in China had been successful in locating and determining the dip of conducting zones. Mwangi (1982) carried out numerical modelling of Head-on resistivity data using Schlumberger data as constraints for near surface resistivity structures, Results from this work showed that there can be considerable ambiguity in modelling Head-on data, especially in the quantitative determination of the angle of dip and extent of narrow conductive features. The size of the electrode arrays used limited reliability of the information gathered to depths of between 200 and 400 m. Though it was possible to model vertical conductive features, possibly relating fault zones, it was difficulty to isolate the cause of particular Head-on resistivity anomalies to provide the resolution required to locate the faults zones for the siting of wells. This method was therefore abandoned for other more informative techniques such as Schlumberger.

2.7 Transient electromagnetics (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 dependant 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 4).

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).

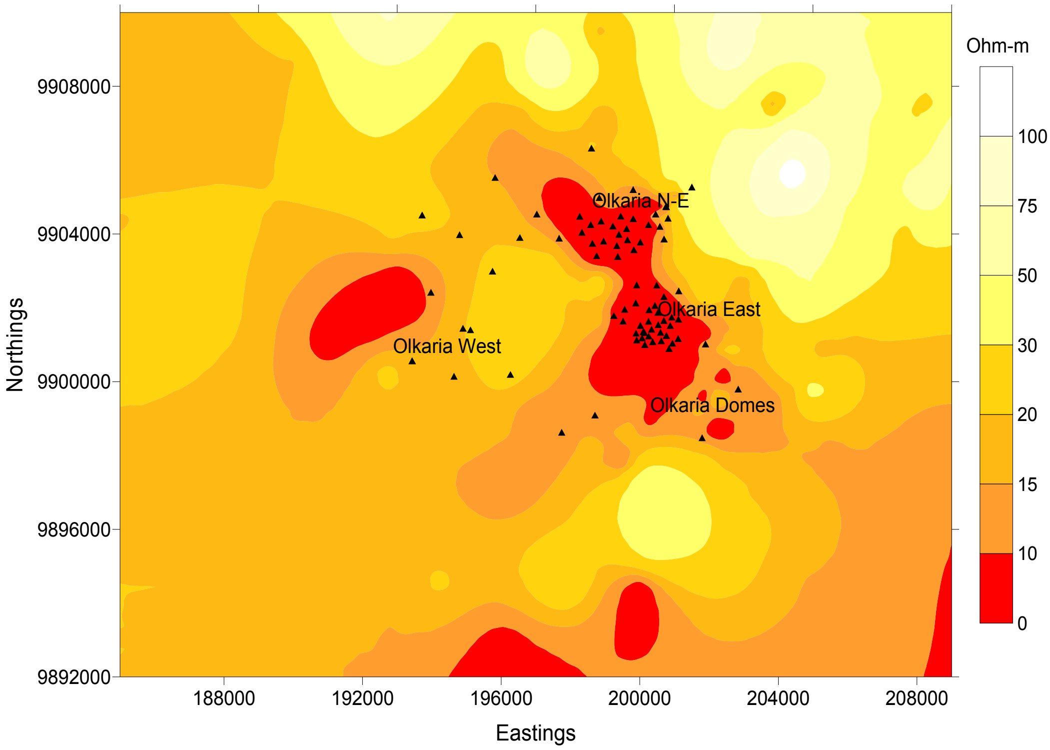

FIGURE 4: Resistivity distribution at 1400masl from TEM measurements

2.8 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 substrate. 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.

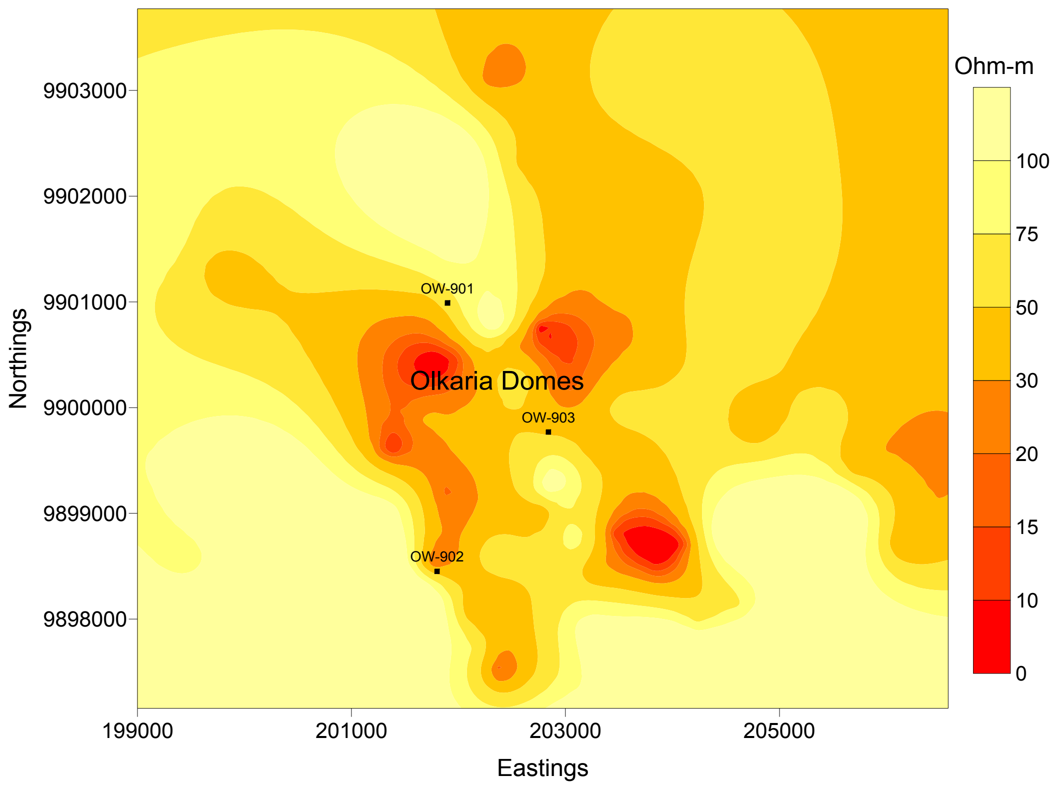

FIGURE 5: MT Resistivity distribution at 1000 mbsl at Olkaria-Domes geothermal field and its surroundings. In spite of the method being a relatively new technique, it has been used in several new prospects. Plans are underway to carry out soundings over the present production fields

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-Domes (Figure 5); 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.

2.9 Gravity

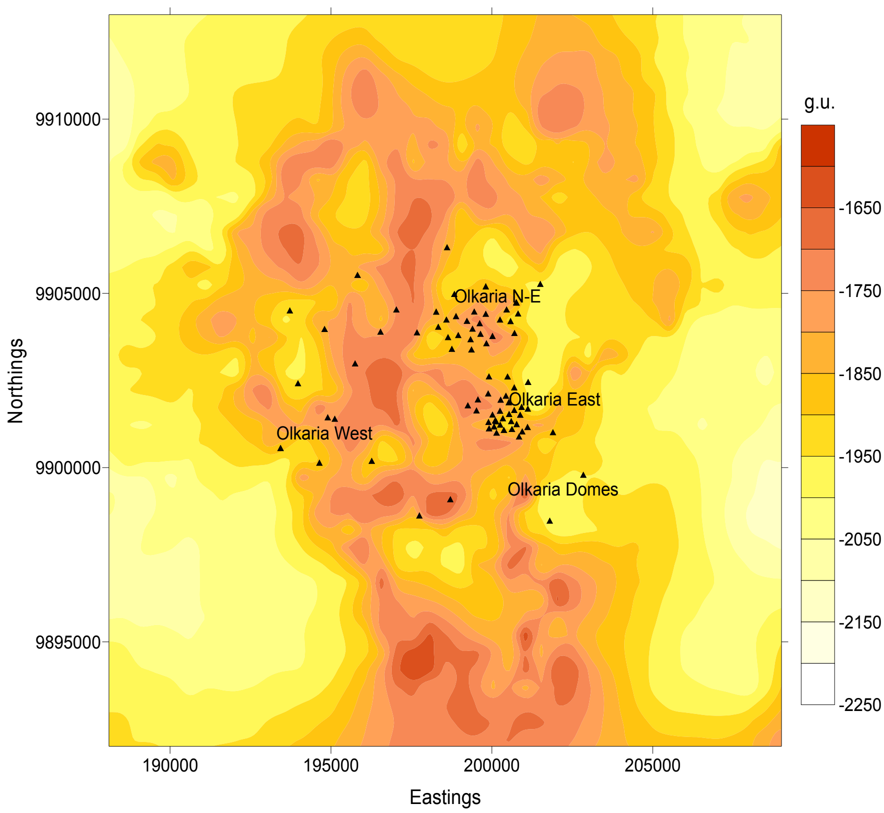

FIGURE 6: Gravity distribution at the Olkaria area

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 6) shows the following features:

1) A NW trending axial gravity high corresponding to the regional geological structure in the central rift segment.
2) 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.

Precision gravity surveys at Olkaria Geothermal Field began in 1983 to monitor gravity changes as a result of geothermal fluid withdrawal (Mwangi, 1983). A review of the observed gravity data over each benchmark indicates changes over the years during monitoring period (Mariita, 2000).

2.10 Magnetics

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 basaltic lavas or plugs (Figure 7). 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.

Bhogal and Skinner (1971) analysed residual draped aeromagnetic data flown at 300m above ground surface within the Olkaria area. Their results showed that the central geothermal area had a positive magnetic anomaly trending NW-SE. 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^{0}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. Mwangi and Bromley (1986) interpreted this to represent de-magnetized rocks due to alteration by chemical and thermal processes at reservoir depth. This magnetic anomaly trend is coincident with the deep resistivity conductor and a gap in the micro-seismicity.

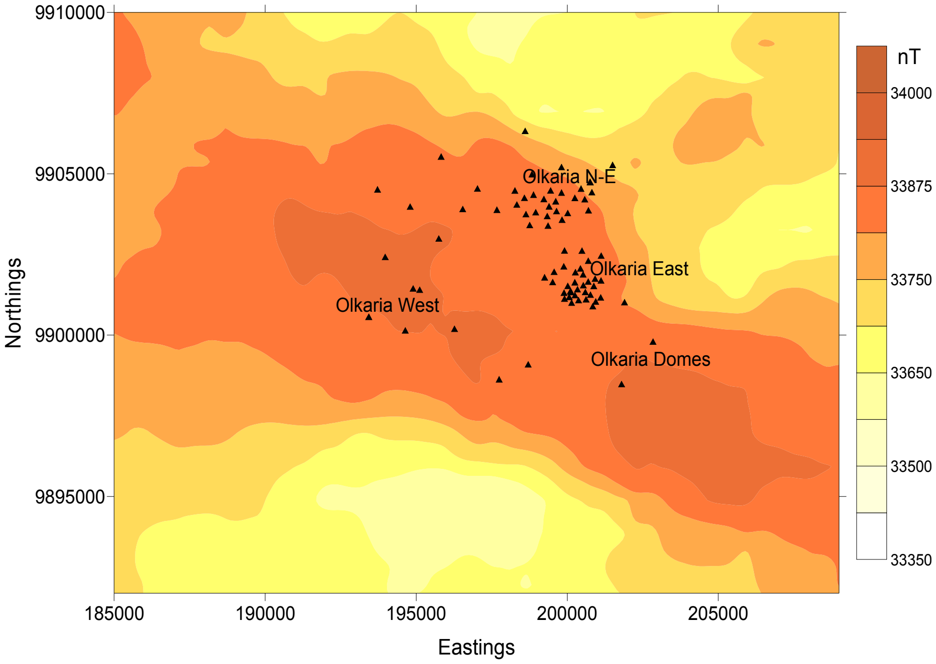

FIGURE 7: Total magnetic intensity over Olkaria

3. DISCUSSION

Many of the geophysical methods have been used at Olkaria to understand 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. The occurrence of late phase rhyolites (comendite) lavas and pyroclastics indicates the presence of shallow magma bodies since it has been established that they are products of protracted crystallization and crustal anatexis (Omenda, 2000, Macdonald et al. 1987; Black et al., 1997). Such processes have the potential to transfer large quantities of heat to the upper crust via the shallow crustal bodies. Results from seismics and magnetics indicate the presence of attenuating bodies at 6-10 km depth which are also demagnetized within the Olkaria geothermal field thus, corroborating geological models (Simiyu *et al.*, 1998a, Mwangi and Bromley 1986). The seismic data is also in agreement with recent geological models that indicate that the bodies are discrete; fault controlled and experienced different evolutionary histories (Black et al., 1997; Macdonald et al., 1987).

The gravity survey of the shallow crust beneath Olkaria shows a general gravity high trending NNW and in line with the regional geological structure in the area. However, there are local highs that trend NE inline with the recent fault trends (Figures 6 and 7). 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. Whereas some earlier geological studies suggested the presence of a caldera at Olkaria and marked by the eastern ring of domes (e.g., Naylor, 1972; Mungania, 1992; Clarke *et al.*, 1990), gravity and seismic data do not show any indications of the presence of a caldera structure at Olkaria (Simiyu et al., 1998a, 1998b, Ndombi, 1981). 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 hypocenter locations show that Olkaria is a high temperature geothermal field characterized by a relatively high level of micro-earthquake activity. The Olkaria West area has shallow high frequency events and deep low frequency events. The shallow events occur at the intersection of the Olkaria and Suswa faults. The shallow events are associated with an 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.

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.

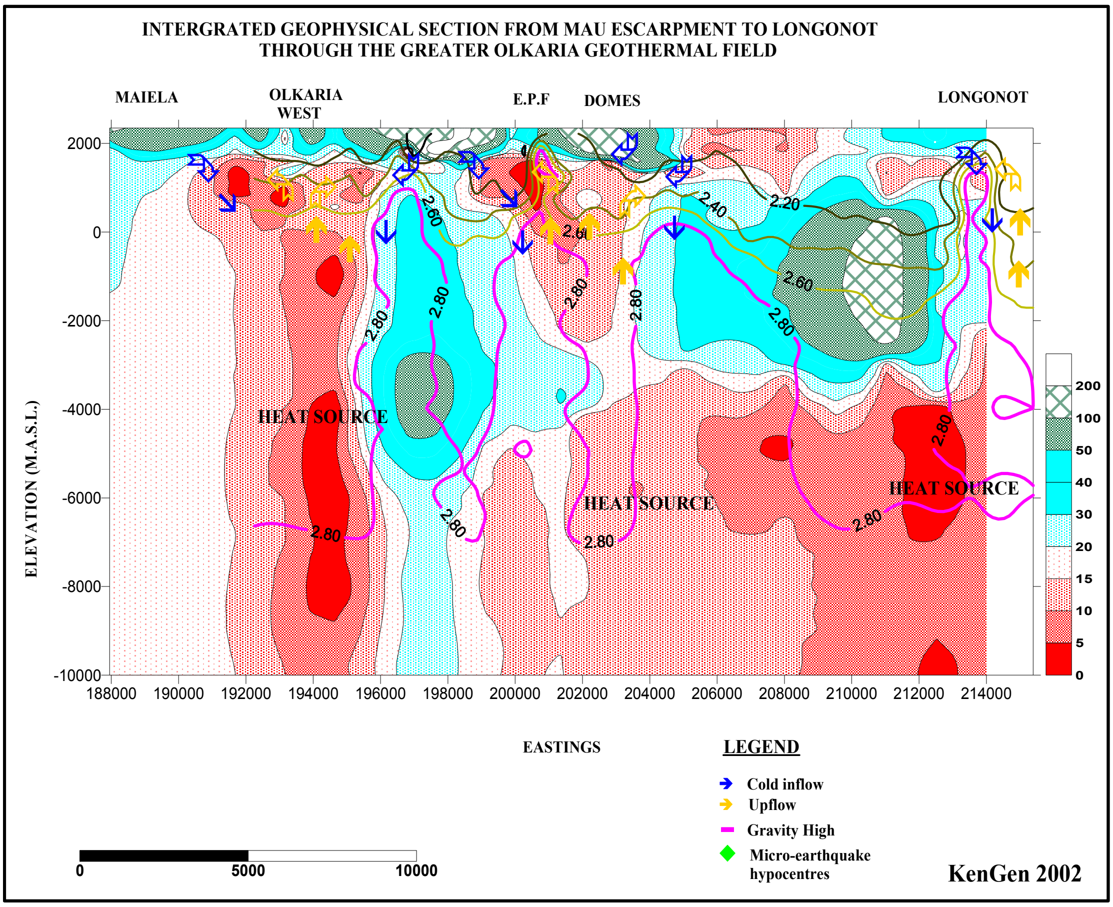

FIGURE 8: Integrated geophysical model across Olkaria

The reservoir in Olkaria is divided into the two regions defined by structures along the Olkaria Hill (Figure 9). The reservoirs in the western fields are hosted largely within the Mau Tuffs while in the eastern fields the reservoir is hosted within the flood trachytes. The difference in the structure between the fields has resulted in differences in the resistivity structure across this N-S discontinuity due to permeability, fluid type and degree of hydrothermal alteration. The lowest resistivity (<5Ωm) in Olkaria occurs in the western sector due to low pH fluids, extensive alteration due to tuffs and higher primary permeability (Muchemi, 1999). In contrast, the resistivity is relatively higher (>10Ωm) in the eastern fields where the reservoir is hosted within the flood trachytes. These trachytes are less susceptible to hydrothermal alteration except along secondary structures. The resistivity structure in the central and eastern areas of Olkaria, east of this discontinuity, suggests that the geothermal reservoirs supplying both the East Production Field and North East Field are the same and continuous.

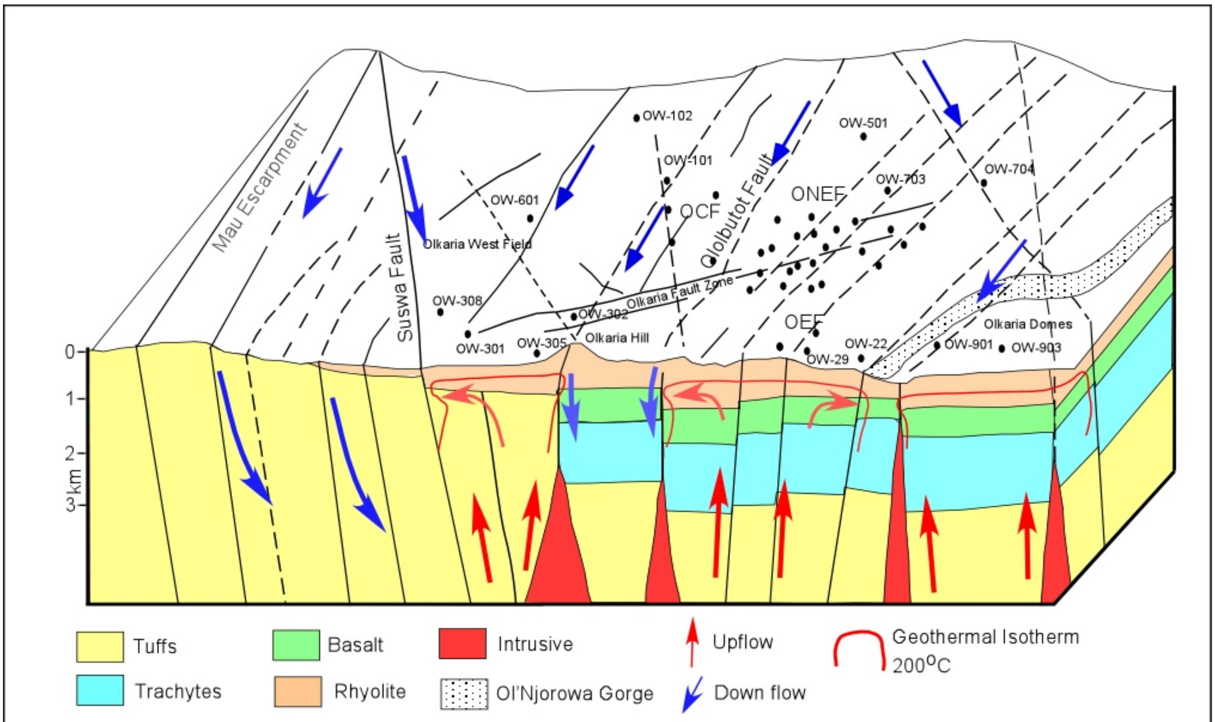

FIGURE 9: Geothermal model of the Olkaria system showing structures and fluid flow patterns

4. CONCLUSIONS

Kenya is the first African country to tap energy from the crust of the earth for electric power generation. At Olkaria, geothermal investigations started as long ago as 1956 when exploratory drilling was undertaken by a consortium of companies, which included the East Africa Power and Lighting Company Limited and Balfour Beatty and Company. Two wells were drilled without any marked success. It was not until the end of the next decade that interest in geothermal power revived.

In 1967, a resistivity survey was carried out in the Rift Valley between Lake Bogoria in the North and Olkaria in the South to determine the nature of the underground rocks and the possibilities of obtaining steam. The survey was encouraging and in 1969, the Kenya Government requested the United Nations to assist in financing further investigations.

A project was agreed upon and between 1970 and 1972 investigations were undertaken at Olkaria, Lake Bogoria and in the Eburru area. Further work, which produced positive results, was carried out on the two exploratory wells drilled at Olkaria in the fifties. On that basis, drilling started in earnest in 1973 and by 1975, four more wells had been drilled in the area. A feasibility study was then undertaken to evaluate Olkaria's potential for generating electricity from geothermal steam. The study found that the Olkaria Geothermal field covered some 80 km^2 and has a steam potential for 25, 000 MW years.

The Kenya Power Company (now Kenya Electricity Generating Company) subsequently took over the responsibilities formerly carried out by the East African Power and Lighting Company in the Olkaria project in 1977. Drilling was resumed in July 1978 and today 100 wells have been drilled with depths varying from between 180 and 2,600 meters below the earth's surface for exploration, production, monitoring and re-injection. Thirty three (33) wells are in the Olkaria East field alone. Initially, 23 wells were connected to the three turbines. However, with continued exploitation, the output of the wells decreased and new ones were drilled to maintain installed generation capacity at 45 MW. To date 29 wells are connected to the Power Station. These wells have a steam capacity of 49 MW. Two more wells were connected at the beginning of 2001 to ensure full load capacity to the year 2007. Two wells are currently being used for the re-injection of hot and cold wastewater.

Production drilling at the Olkaria Northeast field was completed and a 2 x 32 MW power station was commissioned in 2004. In this field, there is excess steam and therefore a third unit is planned to tap it.

Geophysical investigations at Olkaria continues with the purpose of obtaining a better understanding of the subsurface structure of the reservoir, delineating various fields, which can be developed for power generation to meet the projected power demand from this sector.

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