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Geophysical survey of a high-temperature field, Olkaria

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ABSTRACT

Olkaria Geothermal field is a high temperature geothermal resource in the Kenyan Rift Valley which has been used for electricity generation since 1981. 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.Moderm geophysical methods such as Magnetotelluric (MT) and Transient Electromagnetic (TEM) were used and great success has been achieved.

This paper presents the results of Olkaria Geothermal field geophysical data analysis and interpretation. MT and TEM data is continually collected in the area for the improvement of the geophysical model and also determine the extent of the resource. From the results of the joint inversion of MT and TEM data of the area, a fairly good correlation with the available geological information is noted and the following resistivity structure can be deduced as seen on cross-sections and iso-resistivity maps. Generally, the area is characterised by a thin shallow layer of high resistivity on the surface especially on higher grounds. This is interpreted as being caused by unaltered rock formations on the surface possibly due to the thick pyroclastic cover from the adjacent Longonot volcano. Underlying this layer is a low resistivity (<15Ωm) layer that extend to approximately 1000 m a.s.l. This layer is presumed to be dominated by low temperature alteration minerals such as smectite and zeolite and defines the clay cap. A deep high resistivity (resistivity core) layer with values greater than 100Ω m is observed underlying the clay cap. This is a zone where high temperature hydrothermal alteration minerals such as epidote, chlorite and actinolite are observed and is interpreted as the reservoir zone. The existence of a high resistivity core indicates reservoir temperatures exceeding 250°C, which has been confirmed by the drilled wells and this zone is probably dominated by pore fluid conduction. Further information has been achieved by combining MT, seismics and gravity in regard to the heat sources.

1. INTRODUCTION

Kenya is endowed with a huge geothermal resource due to the presence of the Kenya rift which is part of the East African rift system (Figure 1). Olkaria Geothermal field is located in the Kenya Rift about

110 km from Nairobi the capital of Kenya. The area is along the Kenya Rift valley and is characterized by numerous volcanic rhyolitic domes, some of which form a ring structure, which has been interpreted as indicating the presence of a buried volcanic caldera (Axelsson et al., 2013). The field is inside a major volcanic complex that has been cut by N-S trending normal rifting faults.

Exploration of the Olkaria geothermal resource started in 1956 with deep drilling commencing in 1973. A feasibility study in 1976 indicated that development of the geothermal resource was feasible and consequently a 30 MWe power plant (Olkaria 1) was constructed (Ouma, 2010). Three power plants and several well head units are currently in-stalled in the field and producing electricity.

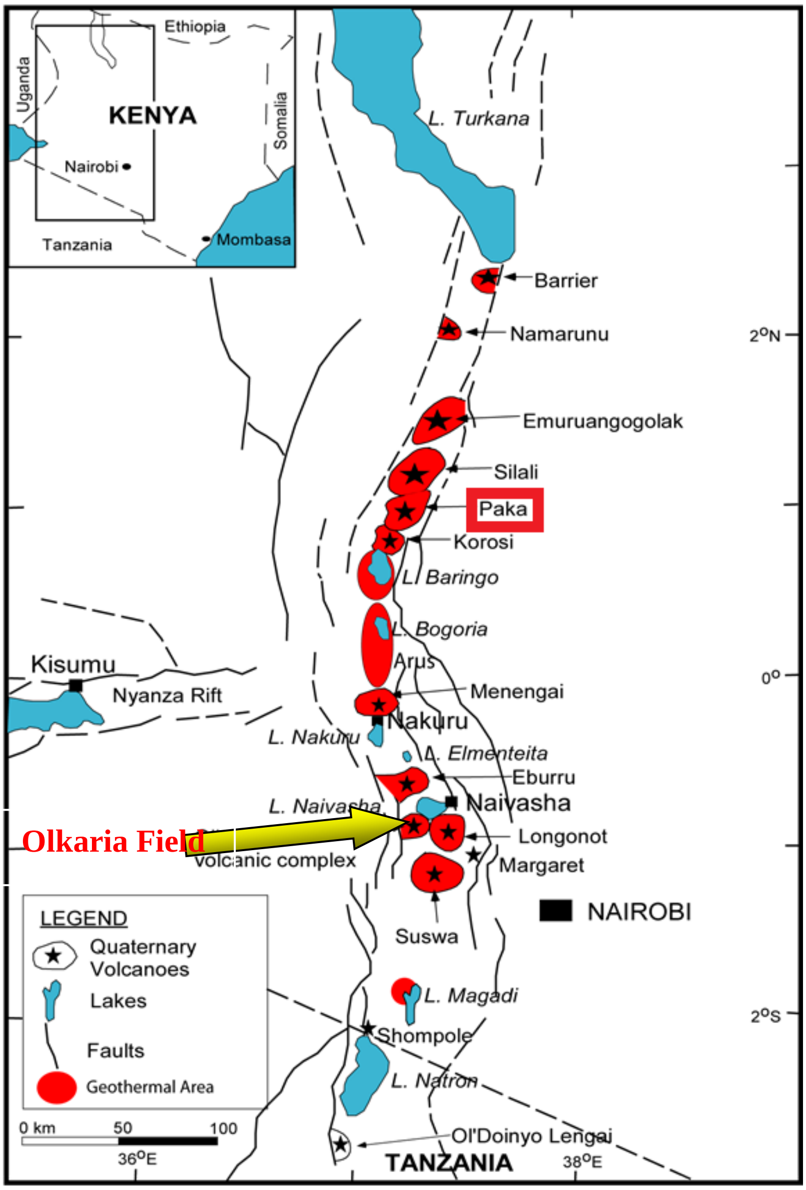

FIGURE 1: Map showing location of Olkaria field along the Kenyan rift valley

With increased emphasis on geothermal development, new exploration methods are needed in order to improve general understanding of geothermal reservoirs, characterize their extent and assess the potential for sustainable utilization and site high producer wells. Surface investigations geological, geochemical, and geophysical and reservoir studies indicate that the potential is over 7000 Mwe if fully exploited. The geothermal activity is attributed to Neogene volcanic activity which has resulted to the presence of near surface heat generating sources. Geothermal fields of the Kenya rift occur in two types of environments. The main geothermal fields are associated with Quaternary volcanoes while the second type is associated with fissures that are related to active fault zones. In either case, these fields are dissected by numerous rift faults that give rise to a number of geothermal springs and fumaroles. Olkaria geothermal field is an intensely faulted field and these structures play a big role in the presence of the geothermal system (Figure 2).

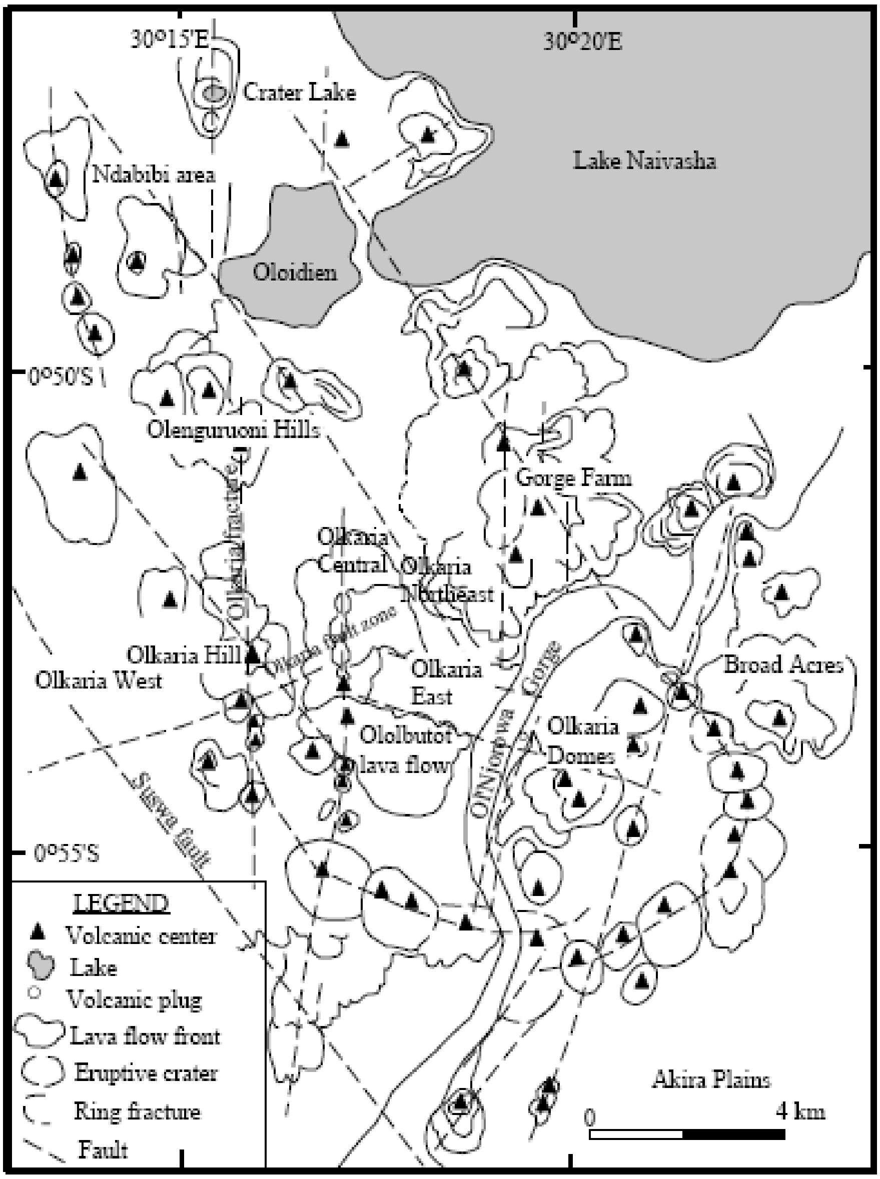

FIGURE 2: Map showing structural features and volcanic centers in Olkaria Geothermal field

2. GEOPHYSICAL EXPLORATION METHODS USED IN OLKARIA

Exploration for geothermal energy resources can involve several geophysical methodologies that result in determination of the earth's physical properties, with the aim of delineating geothermal prospects, locating reservoirs, site boreholes and provide information on which economical exploitation of the resource can be based. During these measurements, emphasis is put on parameters that are sensitive to rock temperature, permeability, porosity and salinity of the fluids that are contained in the formations.

Geophysical techniques that are commonly employed in prospecting for geothermal energy include gravity, magnetics, magnetotellurics (MT), transient-electromagnetics (TEM) and micro-seismology. The gravity survey is envisaged to detect and map out geological formation bearing different densities. It also can help in mapping various structures such as faults, intrusives, magma chambers that can act as heat sources. Gravity method is usually interpreted along with magnetics measured from the same area, both being potential fields. MT and TEM are the commonest resistivity (conductivity) methods applied during prospecting for geothermal energy. These methods are used to measure electrical resistivity with depth. Low resitivities are generally associated with geothermal reservoirs and are due to the presence of hot rocks and saline hot waters.

Seismic methods use the propagation of elastic waves to image heat sources and structures within the earth. Earthquake location and fault plane solution give information about active faults and permeable zones in a geothermal system. In geothermal industry, monitoring of seismic activity has been used to study the geothermal reservoir and its processes. These processes can be ground noise (microseisms) generated by the geothermal system (e.g. boiling and/or convective flow), micro earthquakes and earthquakes on active faults planes, hydraulic fracturing and tensile cracking of cooling intrusions (Hersir and Bjornsson, 1991). Earthquakes are an essential part of geothermal systems for they break up the bedrock by faulting and fissuring and provide paths for water to percolate down into the thermal areas creating permeability thus the geothermal areas are constantly changing (Bolt, 2004).

In Olkaria, several geophysical survey methods have been used to map and understand the geothermal field with various levels of success achieved. Magnetic and Gravity methods have been used in to identify heat sources and geological structures while seismology has been used to locate depth to heat sources and also the geological structures. However, resistivity surveys (MT and TEM) have been used extensively in the field to map. However, this does not mean that resistivity methods are superior to other methods.

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 (ts-tp<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. 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 4500°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.

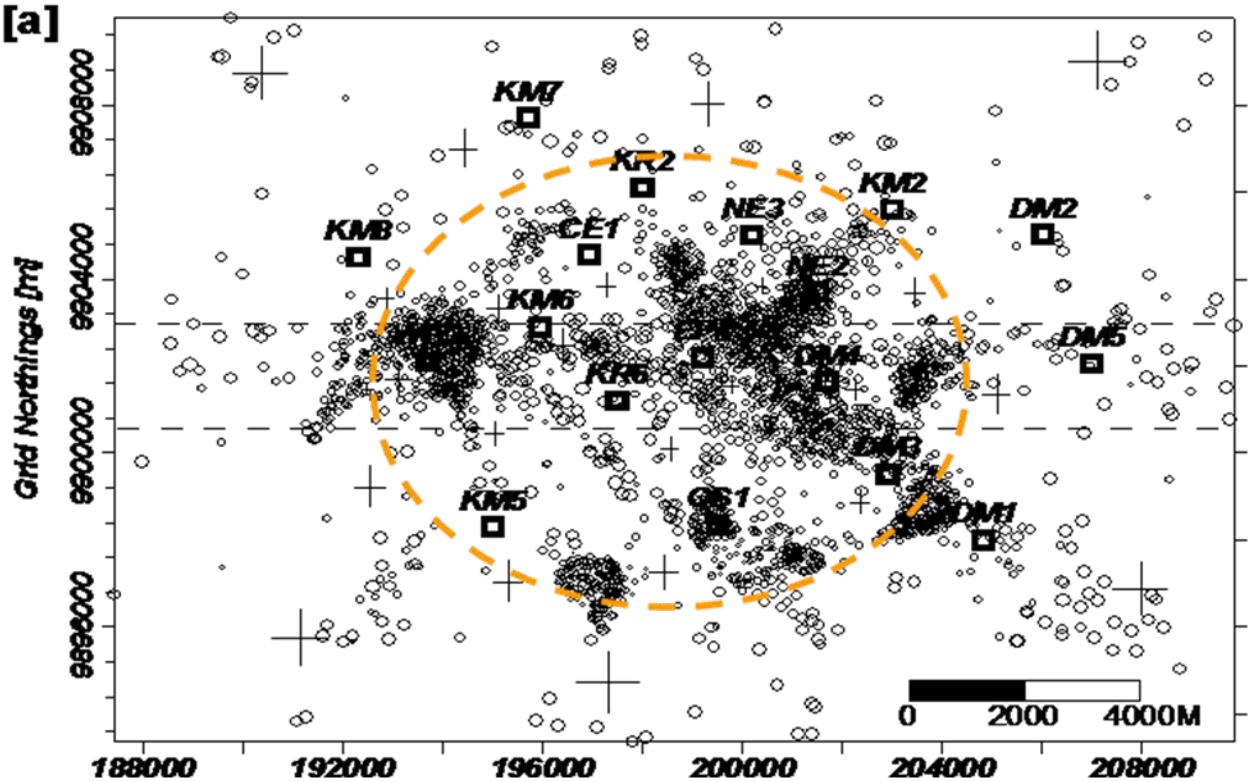

FIGURE 3: Micro earth quake event location around olkaria as presented by the KRISP project. Thick square boxes represent the location of seismic receivers.

2.2 Gravity and magnetics

Gravity and Magnetic methods are potential methods that have been applied in Olkaria. Gravity survey of the shallow crust beneath Olkaria indicated a volcanic zone of three layers that appears downfaulted 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. Figure 4 shows gravity structure in Olkaria. 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).

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, localized basaltic lavas or plugs. 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 (575^0C) 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 demagnetized 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 microseismicity

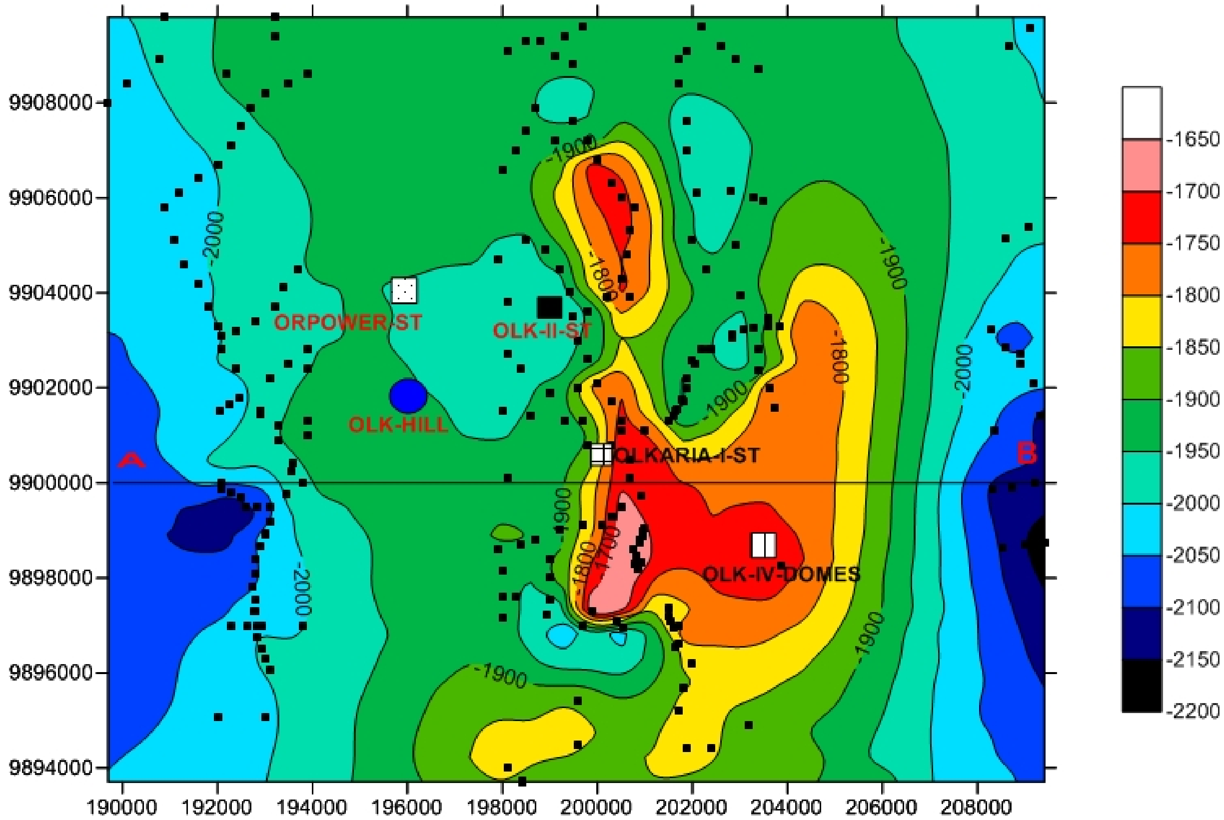

FIGURE 4: Gravity map of Olkaria geothermal field

2.3 Resistivity methods

Earlier resistivity methods used in Olkaria geothermal fields are DC methods with various configurations such as Schlumberger, Wenner, dipole and head on resistivity. The methods were successful since the data collected was used for siting the first wells in Olkaria. As technology advanced, Magnetotelluric (MT) and Transient Electromagnetic (TEM) were adapted and have become quite common.

2.3.1 Resistivity structure of a high temperature geothermal field

Geothermal water reacts with rocks to form secondary alteration minerals and cause high concentration of dissolved ions in the fluid. This lowers the resistivity of the host rock. The type of secondary minerals formed depends on the type of the host rock, the temperature, and the salinity of the fluid. The distribution of alteration minerals provides information on the temperature of the geothermal system, the flow path of the geothermal water and the physicochemical characteristics of the geothermal water. The alteration intensity is normally very low for temperatures below 50-100°C. Pore fluid conduction exists in this zone. At temperatures from 100 °C to 220°C, low-temperature zeolites and the clay mineral smectite are formed (Árnason et al., 2000). Smectite has hydrated and loosely bound cations between the silica plates, making the mineral conductive and with a high cation exchange capacity. The range where low-temperature zeolites and smectite are abundant is called the smectite-zeolite zone. In the temperature range from 220 °C to about 250°C, the low-temperature zeolites disappear and smectite is transformed into chlorite in a transition zone, the mixed-layer clay zone, where smectite and chlorite coexist in a mixture. Mineral conduction is dominant in this zone due to loosely bound cations. At about 250°C the smectite has disappeared and chlorite is the dominant mineral, marking the beginning of the chlorite zone. At higher temperatures, about 260-270°C, epidote becomes abundant in the chlorite-epidote zone. This zoning applies for fresh water basaltic systems. In brine systems, the zoning is similar but the mixed-layer clay zone extends over a wider temperature range, or up to temperatures near 300°C (Árnason et al., 2000). The conductive smectite layer may be quite deep over the system up flow and much closer to the surface in cooler outflow areas.

Normally one would expect the resistivity of a geothermal system to decrease with increasing temperature. However, in high-temperature volcanic areas the resistivity in the chlorite and chlorite-epidote alteration zone increases due to an extremely low concentration of mobile cations and the high temperature alteration minerals are bound in a crystal lattice. The conduction mechanism in this zone is surface and pore fluid conduction. Figure 5 demonstrates the relationships between resistivity, alteration and temperature both for saline and fresh water systems. At depths, where the resistivity increases below a low-resistivity zone, a chlorite alteration zone is expected, indicating a temperature of 250°C or higher, provided the alteration is in equilibrium with the temperature. If the geothermal system has cooled down, then the alteration remains the same and hence the resistivity structure is the same. In such a case, the interpretation of the resistivity structure can be misleading since it reflects alteration minerals that were formed in the past but not necessarily the present day temperature. It has also occurred that alteration minerals have indicated lower temperature than measured in the wells. This has been interpreted as being due to a young system being heated up and the alteration is lagging behind, still not in equilibrium with the temperature (Hersir and Árnason, 2009).

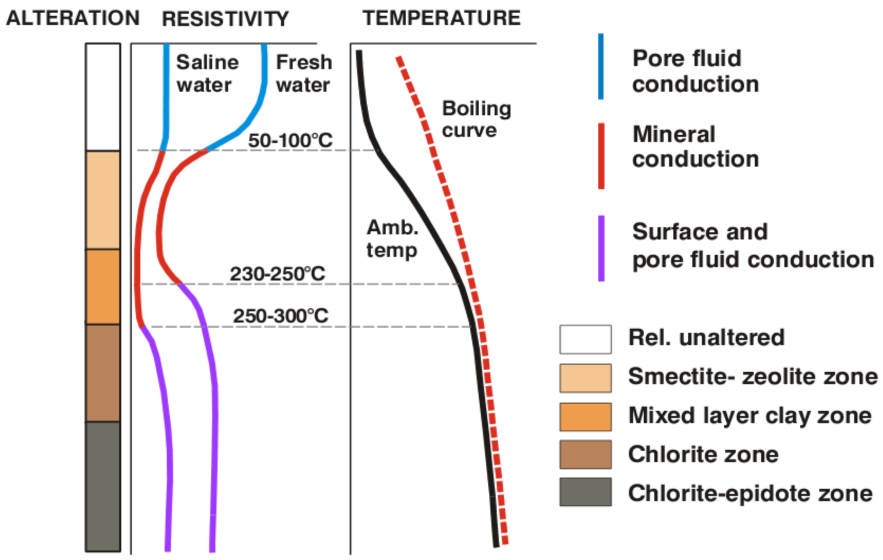

FIGURE 5**:** General resistivity structure of a high-temperature geothermal system showing resistivity variation with alteration and temperature (modified from Árnason et al., 2000)

Outside geothermal systems, formation resistivities are quite variable. Values of 200 to 500 ohm-m are commonly encountered in dry and partially-saturated surface volcanic rocks, and 50 to 200 ohm-m are typical of deeper cold parts of a prospect area. Sediments, especially of a marine origin, can have resistivities of less than 5 ohm-m.

2.3.2 Transient Electromagnetic Method (TEM)

The common TEM configuration used in Olkaria is central loop. In Central Loop Transient Electromagnetic method, a steady current is transmitted in a transmitter wire loop, laid on the ground at the area to be examined. Measurements are carried out by ejecting a current in the loop i.e. the TX-loop. The current is turned off abruptly and the related change in the primary magnetic field induces an electromotive force in the conducting surroundings. In the ground, this electrical field will result in a current which again will result in a magnetic field, the secondary field. Just after the transmitter is switched off, the secondary magnetic field from the current in the ground will be equivalent to the primary magnetic field which is no longer there. As time passes by, the resistance in the ground will still weaken the current, i.e., it is converted to heat, and the current density maximum will eventually move outwards and downwards, leaving the current density still weaker.

The decaying secondary magnetic field is vertical in the middle of the Tx-loop (at least if the ground consists of plane and parallel layers). Hereby an electromotive force is induced in the Rx-coil. This signal is measured as a function of time. Just after the current in the Tx-loop is turned off, the current in the ground will be close to the surface, and the measured signal reflects primarily the resistivity of the top layers. At later decay-times the current has diffused deeper into the ground, and the measured signal then contains information about the resistivity of the deeper layers. Measuring the current in the Rx coil will therefore give information about the resistivity as a function of depth.

160 TEM soundings have been carried out within the prospect area up to date since exploration started. The equipments used for this survey are TerraTEM (from Monex Geoscope) and Zonge TEM. Some TEM stations have a spacing of 200m x 200m while others have 100m x 100m. Since TEM data does not suffer from static shift problem, the data has been analysed together with MT data to correct for the static shift problem in MT. Effort is always made to ensure that and TEM sounding are done at the same station.

2.3.3 Magnetotelluric (MT)

Magnetotelluric method is a natural-source electromagnetic geophysical method of imaging the earth's subsurface based on measuring electric currents (known as telluric currents) induced in the ground by natural variations in the earth's magnetic field. The measured frequency ranges between 10-4Hz to 10 kHz. The time varying magnetic field and the electric field generated in the surface are measured in orthogonal directions giving two impedance tensors and their phase which are used to derive the resistivity structure of the subsurface. Low frequencies come from ionospheric and magnetospheric currents while the high frequencies come from thunderstorm activities in the equatorial. Some of the thunderstorm energy is converted to electromagnetic fields, which are propagated in the ionosphere-earth interspace. The depth of penetration of electromagnetic fields within the earth depends on the period and the earth’s conductivity structure. Propagation of EM fields is described by a set of relations, called the Maxwell equation which hold true for all frequencies.

MT method has the greatest depth of exploration of the available EM methods (some tens or even hundreds of kilometres) and is practically the only method for studying deep resistivity structures. It has, however, limited resolution at shallow depths (in the uppermost 1 km) since it suffers static shift problem, which is commonly resolved by analysing its data alongside that of the central-loop TEM method to generate the resistivity structure in the uppermost kilometre. 220 MT soundings have been collected in Olkaria geothermal field so far. Figure 6 and 7 shows results obtained after joint inversion of MT and TEM data.

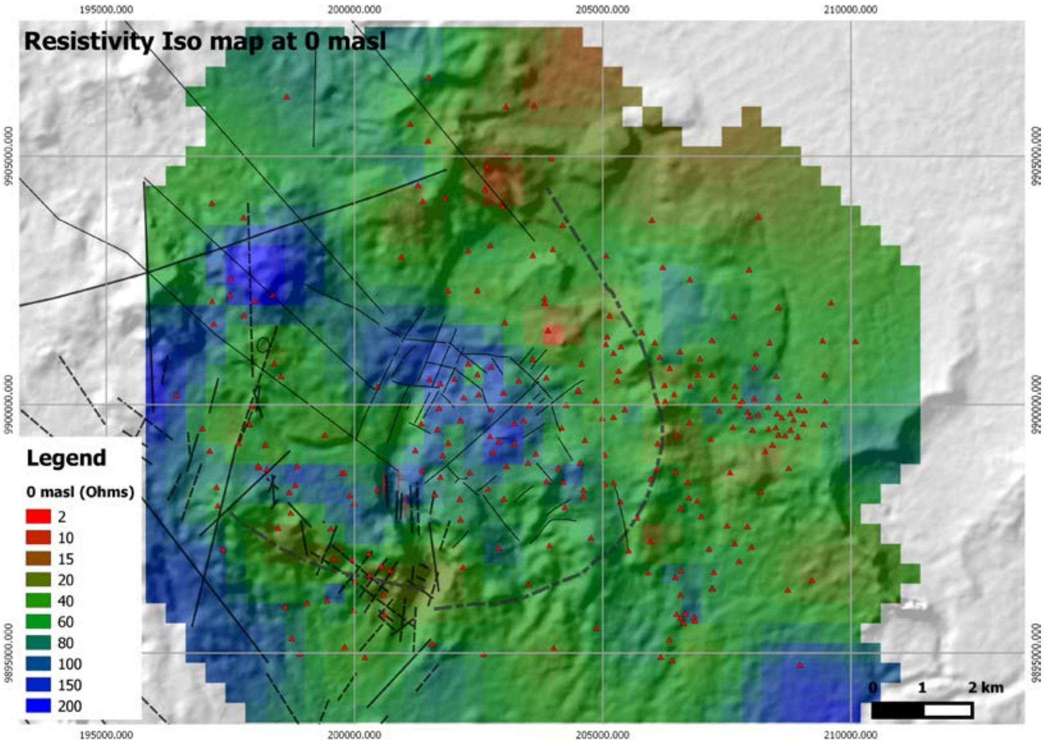

FIGURE 6: Resistivity map at sea level (approximately 2 km below the ground level. The map is produced by performing 1D inversion of TEM and MT data. The red triangles show the MT stations

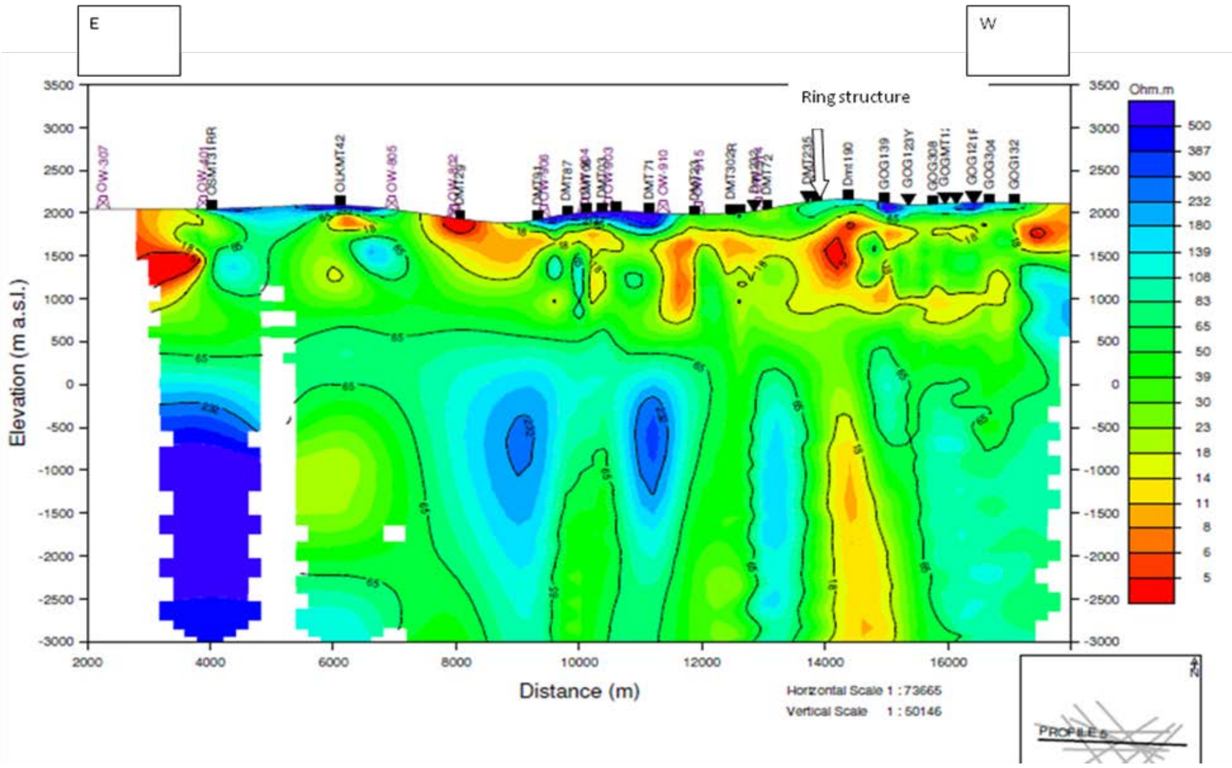

FIGURE 7: East West Cross section along Profile 5 in Olkaria Geothermal Field
cutting across the ring structure

3. DISCUSSIONS

Resistivity structure in most high-temperature geothermal systems is characterized by a low resistivity cap at the outer margins of the reservoir, underlain by a more resistive core towards the inner part. This structure has been found in both freshwater systems as well as brine systems, with the later having lower resistivities values. Comparison of this resistivity structure with data from wells has been carried in high temperature geothermal fields in Iceland and in the East African rift. The results have shown a good correlation with alteration mineralogy. This observation is of great importance, because the temperature dependence of the alteration mineralogy makes it possible to interpret the resistivity layering in terms of temperature, provided that the temperature is in equilibrium with the dominant alteration minerals.

Magnetotelluric (MT) method targets deep hot rocks that act as the heat source for a geothermal system under survey. From the results of the joint inversion of MT and TEM data of the Olkaria Geothermal Field, a fairly good correlation with the available geological information is noted and the following resistivity structure can be deduced as seen on cross-sections and iso-resistivity maps. Generally, the area is characterised by a thin shallow layer of high resistivity on the surface especially on higher grounds. This is interpreted as being caused by unaltered rock formations on the surface possibly due to the thick pyroclastic cover from the adjacent Longonot volcano. Underlying this layer is a low resistivity (<15 Ωm) layer that extend to approximately 1000 m a.s.l. This layer is presumed to be dominated by low temperature alteration minerals such as smectite and zeolite and defines the clay cap. A deep high resistivity (resistivity core) layer with values greater than 100 Ωm is observed underlying the clay cap. This is a zone where high temperature hydrothermal alteration minerals such as epidote, chlorite and actinolite are observed and is interpreted as the reservoir zone.

The existence of a high resistivity core indicates reservoir temperatures exceeding 250°C, which has been confirmed by the drilled wells and this zone is probably dominated by pore fluid conduction. Comparison of well data with the resistivity structure shows a good correlation between the resistivity and alteration mineralogy.

It is worth noting that the field is intensely faulted and structurally complex with most faults concealed by volcanics. A notable structure is the ring structure that seems to control the resistivity and shows low resistivity from the surface to depth. This structure, which is about 1km wide, indicates an area that is intensely faulted and weathering and alteration is at an advanced stage. The ring structure forms the contact between low and high resistivity anomaly and controls resistivity structure of the area. Prominent also is the presence of vertical high resistivity anomalies that are deep seated and structurally controlled. These are interpreted as intrusives and dykes that act as heat sources fuelling the Olkaria geothermal system. Figure 8 shows Olkaria conceptual model.

In conclusion, Olkaria definitely hosts a large geothermal system. The area is fuelled by heat sources in form of intrusive and dykes that are structurally controlled. The orientation of the resistivity anomalies, as indicated by MT results, is in line with the tectonic features in the study area as mapped on the surface. The major fracture directions are NW-SE, N-S and NE-SW. The temperature in the high resistivity core is expected to be more than 250°C as evidenced from the well data. It is also evident that the Olkaria geothermal system extends Southwards and Eastwards from Olkaria Domes.

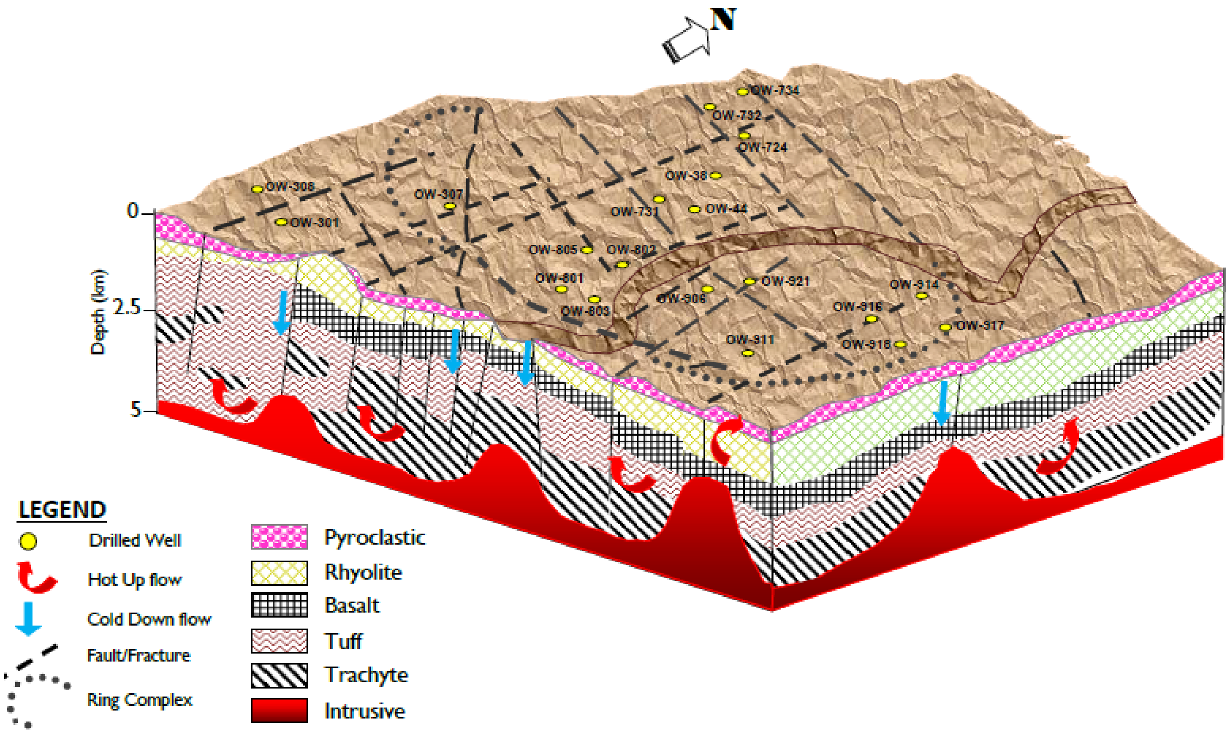

FIGURE 8: Olkaria Conceptual model showing geological structures, stratigraphy and heat sources present in the field

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