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Application of MT and TM Resistivity Techniques in a High Temperature Geothermal System: A case of Olkaria Geothermal System, Kenya

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Abstract
The most important aspect in geothermal energy exploration is the ability to predict the location and extent of the subsurface resource. This has been achieved by application of geophysical methods due to its ability to image subsurface structures. The electrical resistivity of the earth's subsurface is affected by geothermal processes as a result of fracturing that increases fluids and rock interaction leading to the formation of alteration minerals that create subsurface resistivity contrast as a function of depth and temperature. A combined TEM and MT soundings was carried out in Olkaria domes geothermal field to map subsurface resistivity distribution. The MT static shift was corrected by TEM data through a joint inversion of 120 MT and 79 TEM soundings. From the resistivity contours at selected depths, three main resistivity regions were inferred; one low resistivity to the Northwest, the second low resistivity was observed to the Eastern side of the field. The two low resistive regions are separated by a NE-SW trending high resistive region. Resistivity decreases with depth up to a depth of 500masl then it increases with depth. From the cross sections, the results reveal three main resistivity zones. The first zone was characterized by a narrow layer of higher resistivity near the surface and was depicted to represent unaltered region. This was followed by another broader layer of high conductivity that was interpreted to be due to high conductive hydrothermally altered mineralogy such as zeolites. A relatively higher-resistivity zone follows at which resistivity is controlled by the formation of high temperature mineralogy at depth such as epidote. It is recommended that directional production wells can be drilled in the western and eastern regions where resistivity is low, and believed to represent permeable zones. The wells should bend towards the centre at depth where resistivity is high representing high temperature core.
Key words: MT, TEM, Resistivity, Geothermal Field, Olkaria Domes

1.0 Introduction

The greater Olkaria geothermal area is situated in the southern part of the Kenyan rift, nearly 127 km from Nairobi (0° 53'S; 36° 18'E) as shown in Figure 1. The Kenyan rift forms part of the structure of the East African rift that extends to Mozambique region in the south from Ethiopia (Kandie *et al.*, 2016). It forms a section of the eastern arm that extends to Lake Natron from Lake Turkana, (Omenda *et al.*, 2016).

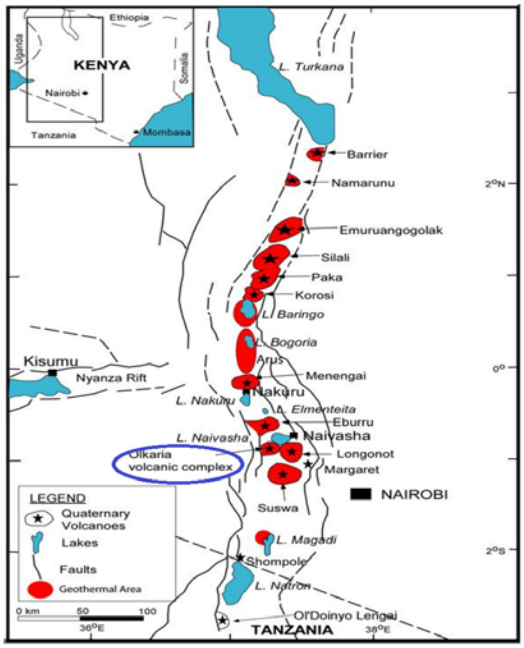


Figure 1: Location of Olkaria Geothermal Field in the Kenyan Rift Valley (Wanjohi, 2014)

Geophysical method of resistivity is used to show the resistivity changes beneath the earth's surface. This method has found its application in the expedition of geothermal energy since good geothermal reservoir has been associated with low resistivity (Abdou, 2015). Electrical conductivity of rocks rely on rock permeability, porosity, fluid salinity, temperature and pressure (Harald, et al., 2020).

The MT and TEM geophysical methods have played a major role in the X-Raying and detailing the buried earth's interior by means of establishing structures that are deeply seated and are in charge of geothermal system control. These structures include heat sources and geothermal fluid flow conduits (Arthur, 2017). Geophysical methods of study have played an important aspect in understanding earth's interior as they are the only mechanisms of establishing subsurface structures at depth at a reduced cost as compared to direct drilling method (Wamriew, 2019). Determination of subsurface signatures from resistivity method is achieved by the ground being actuated by currents and the signal produced observed at the surface. This process measures apparent resistivity which needs to be transformed into specific resistivity that is material dependent. Rocks are regarded as poor conductors and their conductivity can only be achieved if their properties are transformed through alteration by earth processes. Therefore, porosity and fluid conductivity are the major reasons for rock conductivity near earth surfaces (Thanh, et al., 2019).

2.0 Field Setup and Data Acquisition

2.1 MT Data Acquisition

The MT data were collected by Kenya electricity generating company (KENGEN) between 2005 and 2017 by use of a 5-channel (MTU-5A) MT equipment. The equipment layout was as shown in figure 2. MT data from each site was acquired for about 20 hrs.

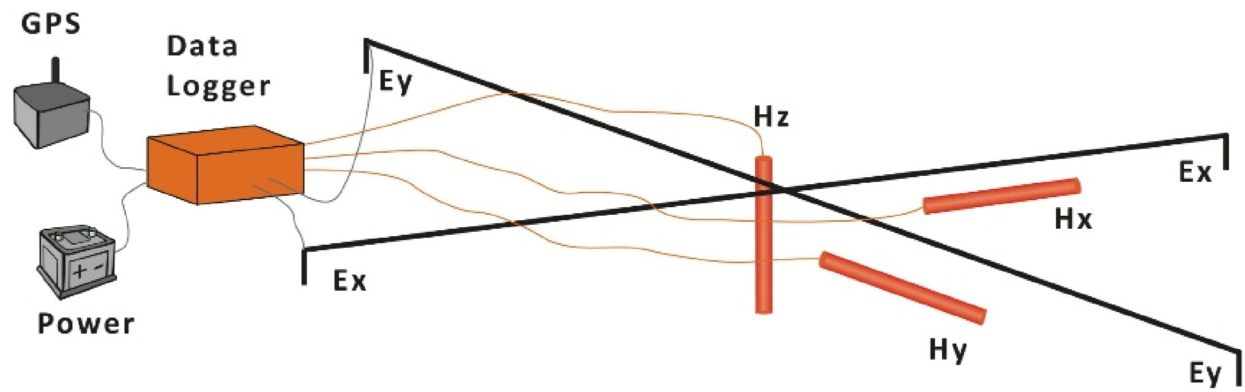


Figure 2: MT Equipment Setup (Flóvenz Et Al., 2012)

120 MT soundings were used for interpretation in the Domes prospect covering an area of about 45 km^2 as shown in figure 3.

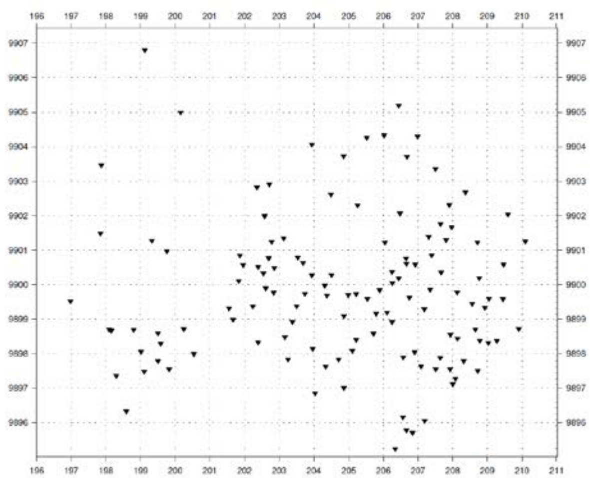


Figure 3: Magnetotelluric Soundings

2.2 Transient Electromagnetic (TEM) Method

The TEM equipment used in this survey is from Zonge. A 200 m × 200 m transmitter wire loop was used (Figure 4)

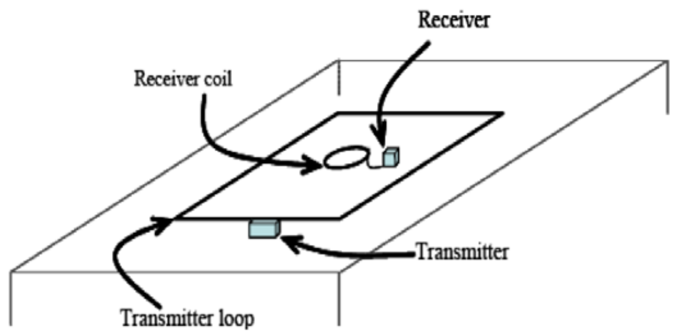


Figure 4: Transient Electromagnetic Equipment Setup [7]

A total of 79 Central Loop TEM soundings were carried out and were distributed as shown in figure 5.

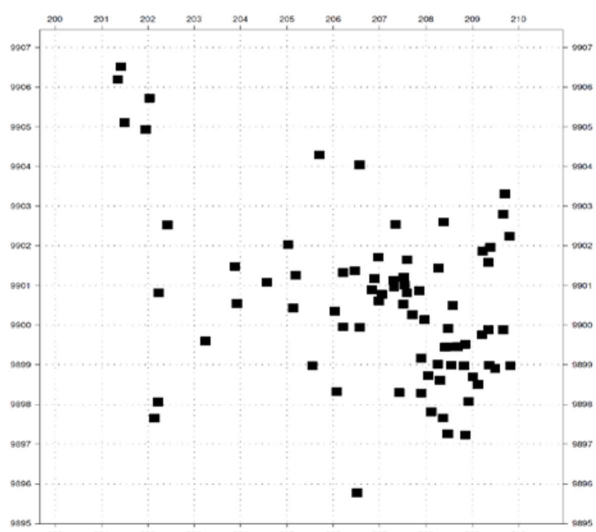


Figure 5: Transient Electromagnetic soundings

2.3 MT Data Processing

The SSMT2000 software was used to process the data in time-series form from the MT. through Fourier transformation, the data was changed to frequency spectrum. Noisy data points were eliminated by the MT editor. The resulting time-series data were Fourier transformed to the frequency domain. From the Fourier transform band, the robust processing method was used to compute average cross-powers and auto powers, which were then edited to get rid of noisy data by the MT editor program graphically. The data was then saved in Electronic Data Interchange (EDI) files and later used as TEMTD input for joint inversion with the TEM.

2.4 TEM Data Processing

The raw TEM data processed using the program TemxZ where the data collected at same were averaged and late time apparent resistivity computed as a function of time after current turn-off.

2.5 The MT Static Shift Analysis

The MT static shift corrected by TEM data through joint inversion as shown in figure 6

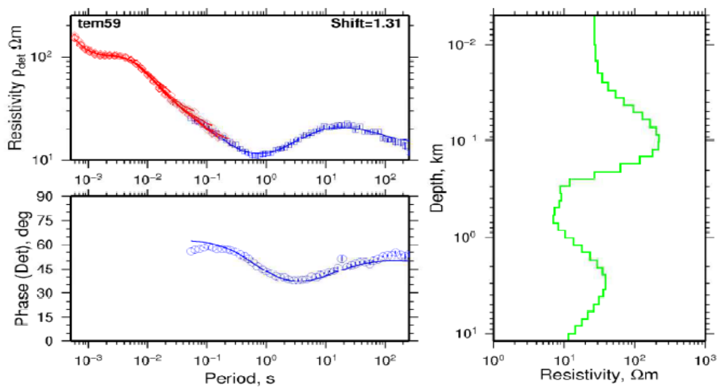


Figure 6: joint 1-D inversion of TEM and MT soundings for station DMT08A

3.0 Results

3.1 Resistivity Iso Maps

Contours maps at different elevations from 1900 m.a.s.l down to 2000 m.b.s.l were constructed by TEMRESD program.

3.1.1 Resistivity map at 1900 m.a.s.l contours

This is shown in figures 7 and covers a depth of 100 metres below the surface. The figures show a dominant high resistivity region with resistivity ranging from 16Ωm-1000Ωm.

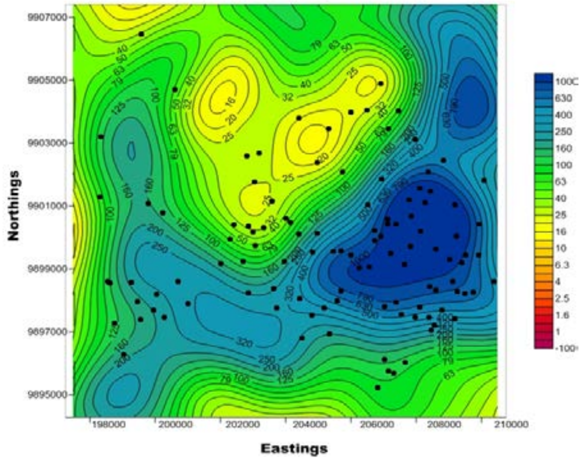


Figure 7: Resistivity Iso Map at 1900 masl

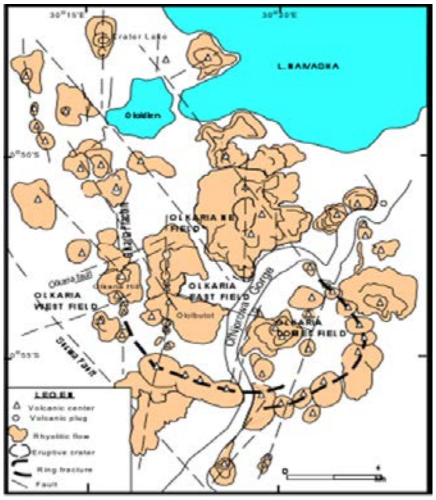
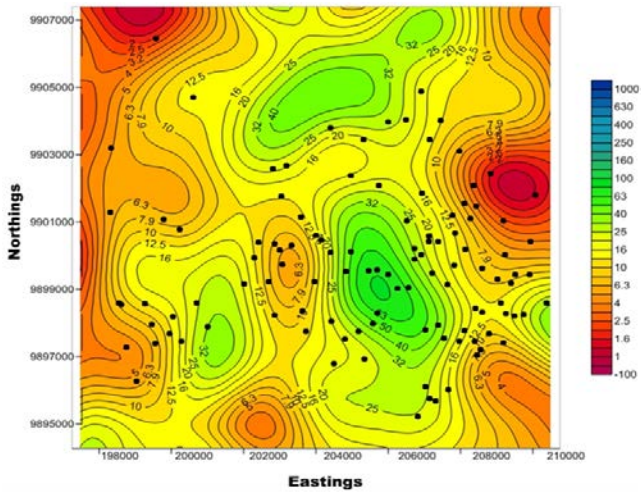


Figure 8: Geological Map (Mariita, 2009)

High resistivity in this region is an indication of un-altered subsurface formations near the earth's surface. The eastern region of the field exhibits the highest resistivity trending northwards and in the SW direction. This outlines the ring structure as indicated in the geological map (figure 8). This could be as a result of resistive rhyolite rocks that cover the top parts of the structure. The central part shows lower resistivity that shifts towards the west and northwest parts as we move down the surface. The general resistivity within the field gradually reduces with depth as shown in figure 9.

3.1.2 Resistivity maps at 1500- 1000 m.a.s.l contours

This is shown in figures 9 and 10 and covers a depth of 500 to 1700 metres below the surface. The figures show a region of enhanced conductivity ranging from 1Ω-80Ω across the area especially in the western and eastern regions.



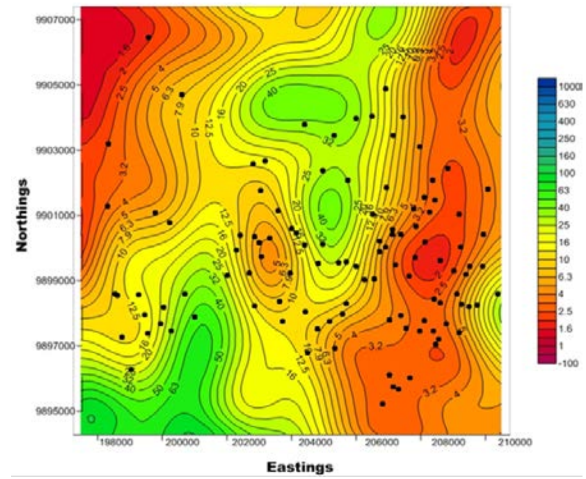


Figure 10: Resistivity Iso Map at 1000 masl

Figure 9: Resistivity Iso Map at 1500 masl

Relatively high resistive anomaly patches appears to emerge at the centre of the study area aligning in the NE - SW direction. This indicates a structural control that coincides with the geological fault structure in figure 8. This high resistivity anomaly could be as a result of un-altered or presence of clay cap fills in the fault line. High resistivity is observed in the SW region. This indicates patches of un-altered grounds at this depth. The western and eastern flanks have low resistivity also aligning in the NE - SW direction. This is as a result of high permeability as shown in temperature recovery profiles (Figure 11) and low resistivity hydrothermal alteration minerals such as zeolites and smectites with their cations loosely bound are formed making the rocks conductive hence an indication of high hydrothermal fluid circulation exists at depth. The trend of resistivity decreasing with depth continues.

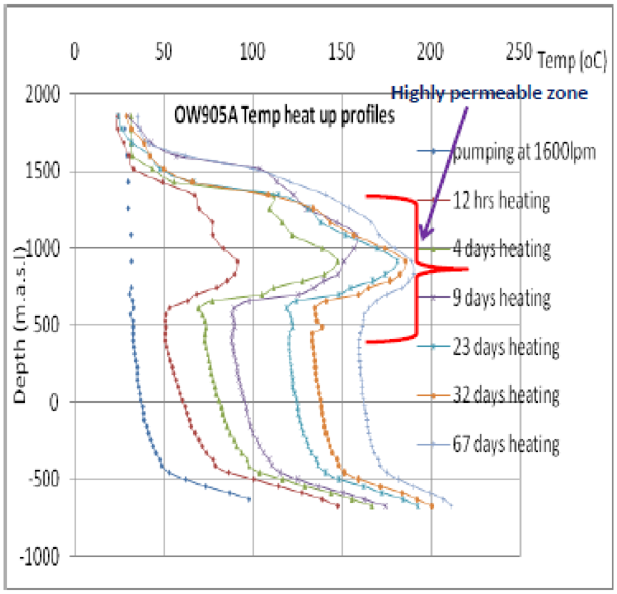


Figure 11: Temperature Warm Up Profile of Well OW905A

3.1.3 Resistivity maps at 0- 2000 m.b.s.l contours

This is the region that covers 2200-4000 metres below the earth's surface. In this region, resistivity starts to increase with depth as shown in figures 12 and 13. However western and eastern regions still show low resistivity as compared to other areas. The southern region is the most resistive.

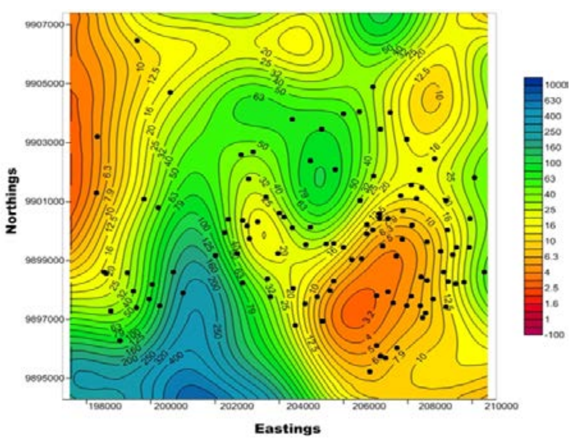


Figure 12: Resistivity Iso Map at 0 masl

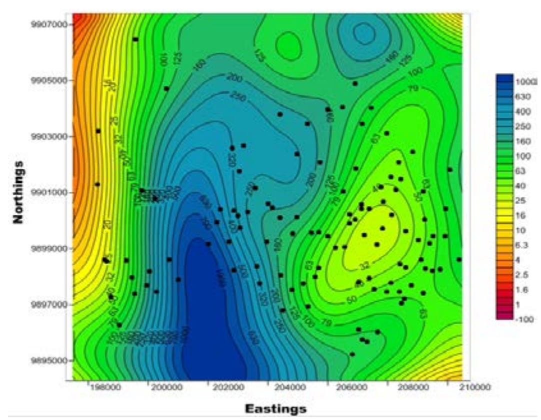


Figure 13: Resistivity Iso Map at 2000 basl

The increase in resistivity with depth indicates that we are high temperature core that has resulted into the formation of high temperature alteration minerals. This is because according to

(Árnason et al., 2010), epidote and chlorite minerals with bounded ions in the crystal lattice dominate at higher temperatures exceeding 250°C making the system more resistive.

3.2 Resistivity Cross-Sections

Two cross-sections were generated by TEMCROSS program, the NW-SE and the SW-NE Cross-Sections as shown in figure 14

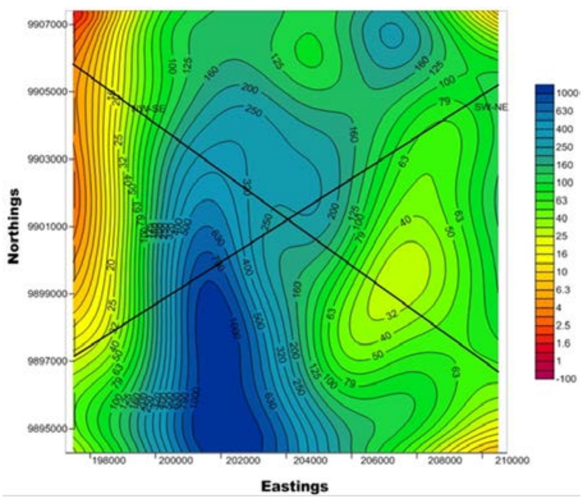


Figure 14: cross-section map.

3.2.1 NW-SE Resistivity Cross-Section

The NW-SE Resistivity Cross-Section depicts a non-uniform resistivity structures. This could be as a result of and localized rock distribution in the area. At the surface, a narrow layer of high resistivity was realized. This could be as a result of unaltered rock formations. A high resistive structure R1 on the surface indicates non uniform distribution of unaltered rhyolitic rocks lava flows and other eruptive materials such as other ashy minerals. This is an indication of poor water saturation at R1.

Another broader layer of low-resistivity elevated at the centre of the study area was observed. This was due to the presence of low resistivity hydrothermal alteration minerals such as zeolites and smectites with their cations loosely bound are formed making the rocks conductive hence an indication of high hydrothermal fluid circulation exists at depth. Conductivity zones C1 and C2 indicate elevated permeability in these regions and therefore there is a high hydrothermal fluid circulation. The resistivity discontinuity between C1 and C2 reflects a SW-NE trending fault line as shown in geological map of figure 8 that could be as a result of un-altered or presence of clay cap fills in the fault line.

The third layer of resistivity structure dominated by relatively higher resistivity followed at depth. The high resistivity was attributed to the dominance of high temperature alteration minerals such as epidote and chlorite minerals with bounded ions in the crystal lattice. West and East sides of the reservoir are dominated by low resistive regions at depth indicating high permeability in these regions. Surface elevation indicates doming at the centre of the study area.

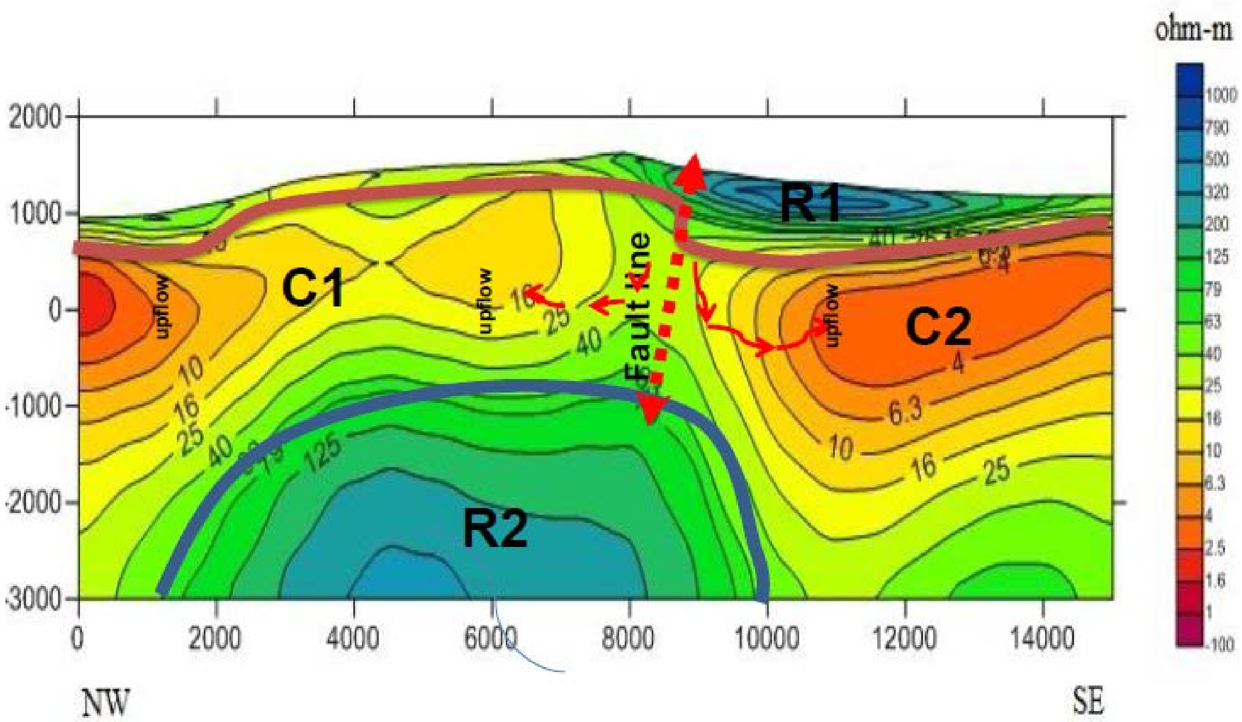


Figure 15: NW-SE Resistivity Cross-Section

3.2.2 SW-NE Resistivity Cross-Section

Similarly, NW-SE Resistivity Cross-Section of Olkaria dome in figure 16 revealed similar features as in figure 15 with a non-uniform resistivity structures at depth and a narrow layer of high resistivity at the surface as a result of unaltered rock formations. It was also followed by another broader layer of low-resistivity layer with three main patches (west, central and east). Low resistivity within this region was attributed to the presence of low resistivity hydrothermal alteration minerals such as zeolites and smectites with their cations loosely bound are formed making the rocks conductive. A relatively higher-resistivity zone followed due to dominance of high temperature alteration minerals such as epidote and chlorite. West and East sides were dominated by low resistive at depth. High resistive body at the centre from the depth of 1250 masl downwards which is believed to be the heat source was observed.

In figure 16, conductivity regions C1, C2 and C3 indicate elevated permeability in these regions and therefore there is a high hydrothermal fluid circulation. Resistivity discontinuity between C1 and C2 is an indication of a possible fault.

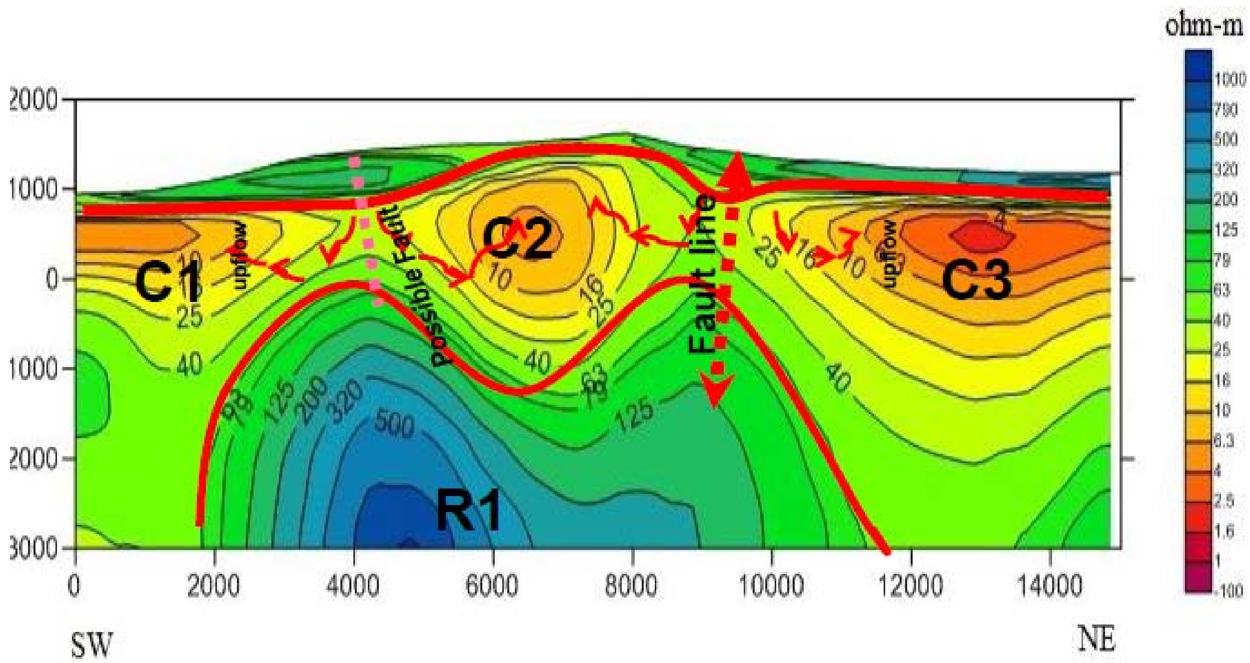


Figure 16: SW-NE Resistivity Cross-Section

4.0 Conclusions and Recommendations

From the resistivity iso-maps at selected depths, three main resistivity regions were inferred; one low resistivity to the Northwest, the second low resistivity was observed to the Eastern side of the field. The two low resistive regions are separated by a NE-SW trending high resistive region. Resistivity decreases with depth up to a depth of 500masl then it increases with depth. From the cross sections, the results reveal three main resistivity zones. The first zone was characterized by a narrow layer of higher resistivity near the surface and was depicted to represent unaltered region. This was followed by another broader layer of high conductivity that was interpreted to be due to high conductive hydrothermally altered mineralogy such as zeolites. A relatively higher-resistivity zone follows at which resistivity is controlled by the formation of high temperature mineralogy at depth such as epidote. It is recommended that directional production wells can be drilled in the western and eastern regions where resistivity is low, and believed to represent permeable zones. The wells should bend towards the centre at depth where resistivity is high representing high temperature core.

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