IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG)
e-ISSN: 2321–0990, p-ISSN: 2321–0982.Volume 12, Issue 6 Ver. I. (Nov.-Dec. 2024), PP 49-59
www.iosrjournals.org

Two - Dimensional Magnetotelluric Data Modeling To Investigate Geothermal Anomaly in the Eastern Side of Olkaria Domes, Kenya

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Abstract
Olkaria is the most explored volcano along the Kenyan Rift Valley and it is in the advanced stages of development. Despite Olkaria's success as an energy provider, there is continued research into methods to improve the development of the fields. The area, east of the domes only has a single well OW-922 unfortunately, it did not sustain discharge during testing. A combination of 1D Magnetotelluric (MT) and Transient Electromagnetics (TEM) methods were utilized to understand the area resistivity structures. However, there were limitations in mapping the deep-seated structures. A geoscientific study has to be done to gain a deeper understanding of the resistivity structures of the subsurface. Geothermal investigation was carried out using the MT method to identify potential areas and subsurface structural information in the eastern side of Olkaria domes, Kenya. Dimensionality analysis using phase tensor was conducted to determine the presence and dimensions of the underlying structures using 50 MT soundings. MT data analysis was done to derive a dataset suitable for defining the resistivity model of the Earth from the observed MT data. Dimensionality analyses demonstrated that the MT data can be interpreted using two-dimensional approaches, but some localized 3D effects are observed. The inversion of data into resistivity models was performed using Occam 2D. The resultant 2D resistivity models were interpreted to identify the components of the eastern side of the Olkaria domes geothermal system. The two profiles obtained revealed a similar structure which can be construed as a potential pathway of low resistivity used by geothermal fluid to migrate and manifest on the earth's surface.
***Keywords;* East of domes, Magnetotelluric, Dimensionality analysis, 2D modeling.**

Date of Submission: 05-11-2024 Date of Acceptance: 25-11-2024

I. INTRODUCTION

Geothermal energy plays an important role as a cost-effective alternative to expensive fossil fuel power in the major economies of those countries endowed with this resource. Moreover, it is a green energy source that produces no greenhouse gas emissions. Kenya is well endowed with high-temperature geothermal resources that are largely untapped. These resources are located within the Kenyan rift which forms part of the eastern branch of the East African Rift system (EARS). The EARS is divided into the Eastern and Western branches. The Kenyan rift lies in the Eastern branch where more intense tectono-volcanic activities are observed compared to the Western branch. Intense volcanism in this section led to the eruption of large shield volcanoes along the axis of the rift during the Quaternary. The Quaternary volcanoes in the central segment of the Kenyan rift include Barrier, Emuruangogolak, Silali, Paka, and Korosi while those in the southern segment are Menengai, Eburru, Olkaria, Longonot, and Suswa (Figure 1). Most of these volcanoes have been explored for geothermal energy and are at different stages of exploration and development. The Olkaria volcanic complex is the most explored among these and is in the advanced stages of development (Ofwona *et al.,* 2006).

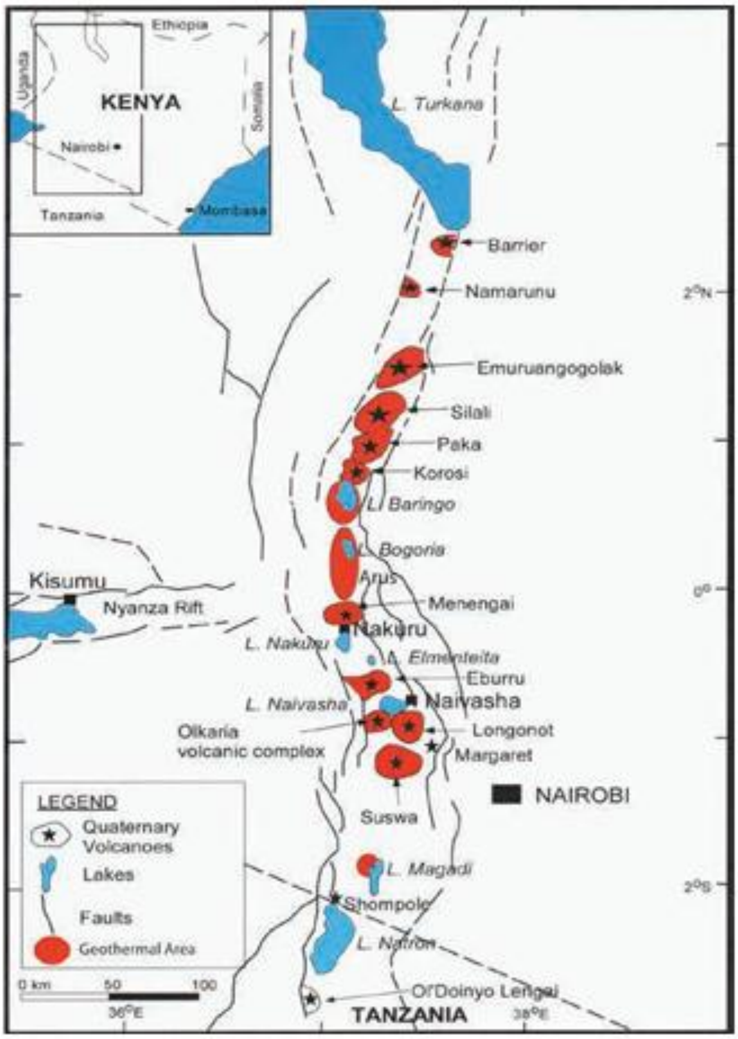

Figure 1: Map of the Kenyan rift system showing the location of potential geothermal prospects (Ofwona *et al.*, 2006).

For purposes of proper planning and development, the Olkaria geothermal field has been divided into seven sub-fields, namely Olkaria East, Olkaria Northeast, Olkaria Central, Olkaria Northwest, Olkaria Southeast, Olkaria Southwest, and Olkaria Domes, as outlined in Figure 2 with Olkaria Hill as reference point of the fields. Olkaria Domes geothermal field is one of the several sections of the Olkaria geothermal field. It is located in the southeast of the Olkaria geothermal field and it's the most productive sector within the Olkaria fields; hence the focus is on the Easten side of Olkaria Domes in this study.

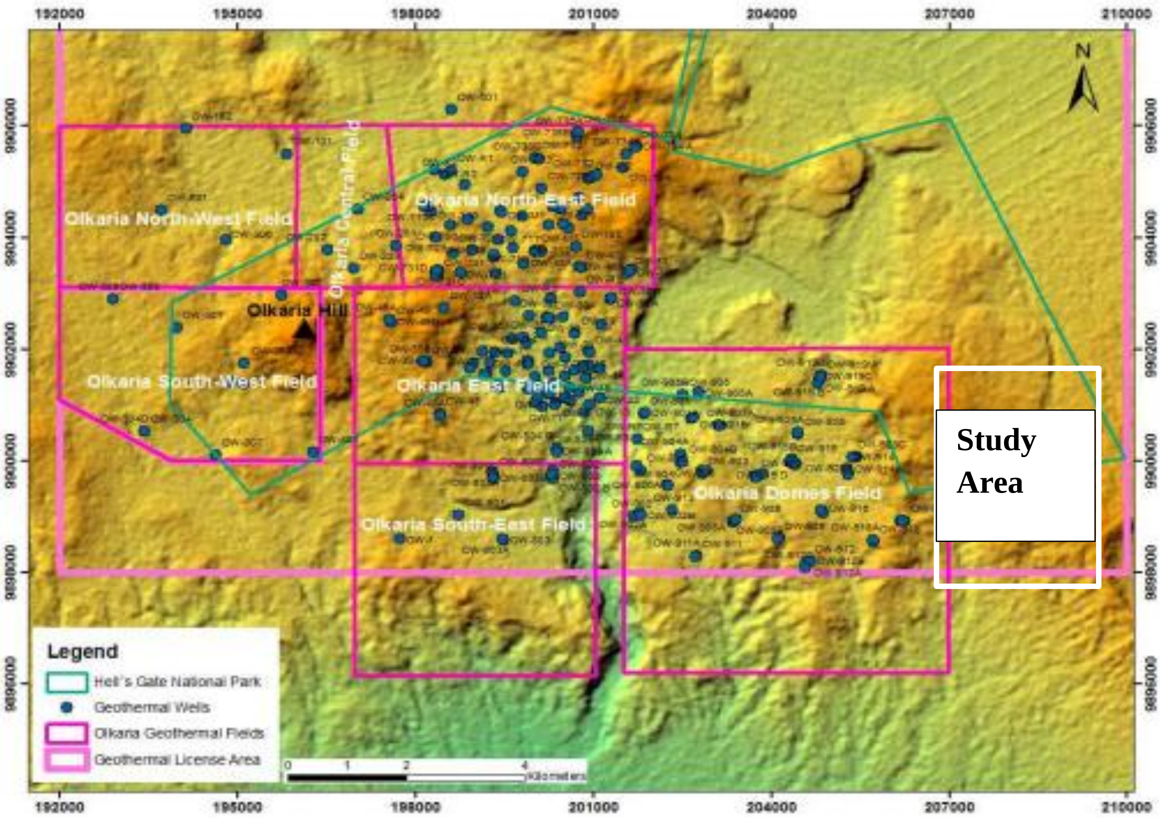

Figure 2: The sub-fields of Olkaria geothermal field (Otieno and Kubai, 2013)

Geophysical methods provide comprehensive subsurface information without drilling, and they have been employed in investigating geothermal potential (Telford *et al.,* 1990; Parasnis, 1997). Geophysical techniques like the Magnetotelluric method (MT), currently used in the exploration of natural resources, including geothermal resources, can identify zones of relatively low resistivity linked to geothermal reservoirs. It is one of the commonly used geophysical methods in the Olkaria geothermal area to map subsurface resistivity structures to depths of kilometers. Before the advent of the MT data acquisition and interpretation method in Olkaria, the DC resistivity method was applied in data acquisition to analyze and interpret subsurface structures. The MT technique probes deeper than the DC resistivity method, giving more detailed information on deeper formations. The joint 1D inversion method has been the primary data analysis and interpretation technique applied in the Olkaria field by Lichoro (2010) and Mwangi (2018). They mapped anomalously low and high resistivity bodies in the study area. However, in the previous work of the applied MT method, the lateral resolution of geological structures was limited; therefore, there was need to address these adequately using 2D inversion methods.

II. REGIONAL GEOLOGICAL SETTING

The field is characterized by comendite lava flows and pyroclastics on the surface and basalts, trachytes, and tuffs in the subsurface (Figure 3) (Marshall *et al.,* 2008). The main tectonic structures are aligned N-S and NW-SE, WNW-ESE, and NE-SW (Omenda, 2000). The second type of tectonic structure is the ring structure. They are most notable in the south and southeast, but less clear in other areas.

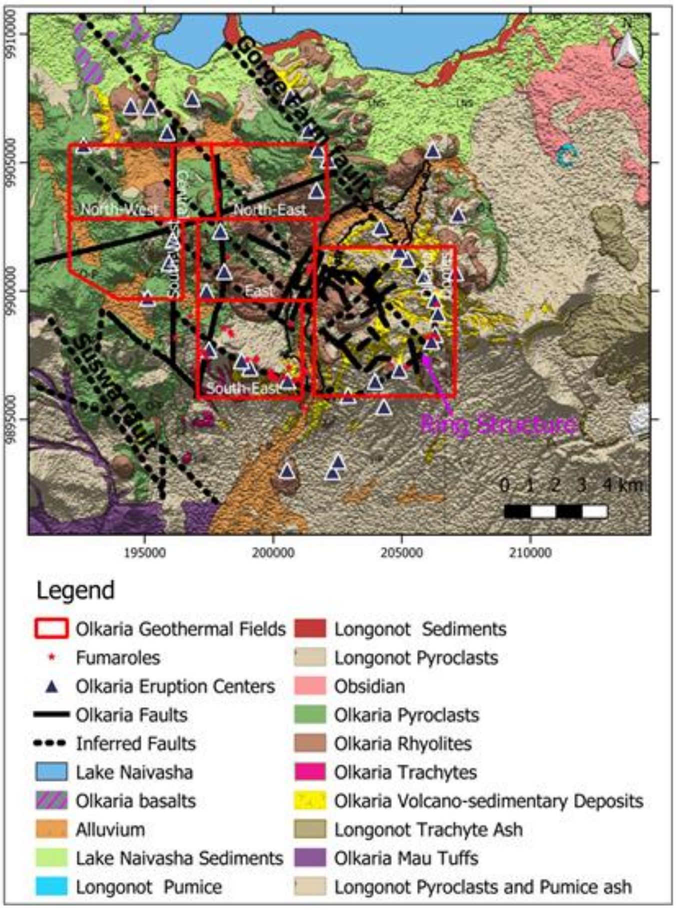

Figure 3: Structural and Surface geological map of Olkaria geothermal field (modified by Omollo *et al.*, 2022).

III. MAGNETOTELLURIC METHOD

The MT method is an electromagnetic (EM) sounding technique that uses surface measurements of the natural electric (E) and magnetic (B) fields to infer the subsurface electrical resistivity distribution. This method relies on the detection of small potential differences generated by electromagnetic waves propagated from the ionosphere (Ward and Wannamaker, 1983). The natural source of MT fields originates from lightning discharges and magnetospheric current systems set up by solar activity. These sources create a spectrum of EM fields in the frequency band 10^{-4} Hz to 10^{4} Hz that provide information used to delineate structures at depth, from a few tens of meters to the upper mantle (a few tens of kilometers). MT data at various frequencies provide a means to distinguish spatial variations in resistivity vertically and laterally. Higher frequencies map the near-surface resistivity distribution. Lower frequencies that penetrate deeper provide information on deeper structures (Christiansen *et al.*, 2006). The depth of investigation in MT is a function of subsurface resistivity and frequency (or the inverse of the period) of the electromagnetic signals. The penetration depth can be roughly related to the period by the use of the skin depth. The skin depth δ (m) at which the electromagnetic field amplitude is reduced to e^{-1} of its original value at the surface is given as:

$$\delta = \sqrt{\frac{2}{\omega\mu_0\sigma}} \approx 0.5\sqrt{\rho_a T} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 1$$

where ω is the angular frequency of the signal, $\mu_0 = 4\pi \times 10^{-7}\ H/M$ is the magnetic permeability of free space, ρ_a is the apparent resistivity of the earth and T is the periodic time.

IV. MT DATA ACQUISITION AND PROCESSING

The MT data used in this study was acquired in the year 2023 by Kenya Electricity Generating Company (KenGen) staff using Phoenix MTU-5 instruments. A total of 50 data points with spacing from one station to another varying from 300- 500m based on the terrain, in locations free from cultural and magnetic noise (power lines, metallic steam pipes, well casings, etc.), were integrated and used for the analysis of 2D. A remote reference station was deployed in the field about 10 km from the furthest station, in a cultural noise-free environment far away from human activities, to correct and improve the data quality in the noisy survey sites. The electric field in the x-direction (Ex) was measured in the north-south direction, and the magnetic field in the y-direction (Ey) was recorded in the east-west direction. The spacing between the electrodes was approximately 60 m. At each station, the recording time for the total variation of electric and magnetic fields was about 18 hours to acquire data for long periods. Time-series data from the MT unit were downloaded using the SSMT2000 program and processed using the MT Editor provided by Phoenix Geophysics-Canada.

V. MT DATA ANALYSIS

5.1 Static Shift Correction

The MT static shift effect is a galvanic distortion effect that locally shifts apparent resistivity-sounding curves by a scaling factor that is independent of the frequency, keeping the phases unchanged. Without the proper removal of static shift effects from the data, both results of the resistivity and depth estimates of the Earth structure will be erroneously interpreted (Samrock *et al.*, 2018). A spatial median filter method of 3km diameter was applied to each station to address the static shift problem in 2D inversion, where it showed a significant split in the apparent resistivity curves at high frequency as shown in Figure 4.

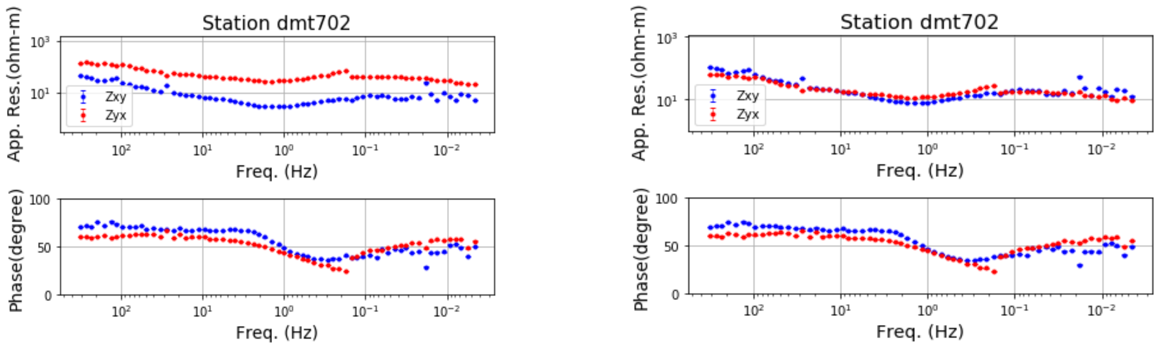

Figure 4: MT data curves before and after static shift and distortion removal.

5.2 Phase Tensor in Dimensionality Analysis

Before performing MT modeling, dimensionality analysis is conducted to assess the nature of the geo-electrical structures present in the subsurface. This analysis helps determine whether the computed responses, based on observed data at a specific frequency, represent 1D, 2D, or 3D structures. Through dimensionality analysis, any distortions present can be identified and quantified, and it aids in recovering the strike of the subsurface structures. Essentially, this process allows for a better understanding of the underlying geological features and helps refine the MT modeling approach accordingly (Marti *et al.*, 2010). For this study, the phase tensor (φ), which is a component of the decomposed impedance tensor having a ratio of the real (X) and imaginary part (Y) thus, expressed as $X^{-1}Y$ was applied. The analysis method by Phase Tensor was applied in characterizing the dimensionality of local and regional subsurface structures because it is insusceptible to galvanic distortion. The dimensionality analysis of the eastern side of Olkaria domes using phase tensors at different periods was conducted as shown in Figures 5 - 8. Analyzing the dimensionality of the data at different periods, the shortest periods (10^{-2}–1 s), i.e. shallower penetration correspond to the mostly 1D and 2D character of the near-surface. Additionally, the effect of very local structures is denoted by a yellow color and a low skew angle pronounced in the shallow formations (Figure 5- 7). Some stations show complex aspects at longer periods, which do not support the presence of a 2-D resistivity structure as shown in blue and red colors, see Figure 8.

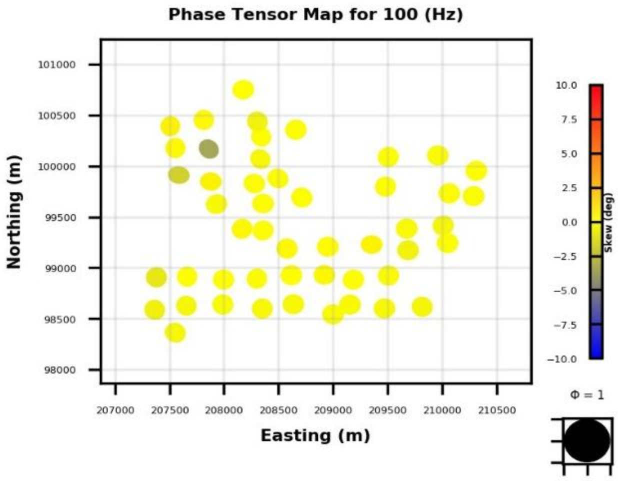

Figure 5: Phase Tensor maps at 100 Hz.

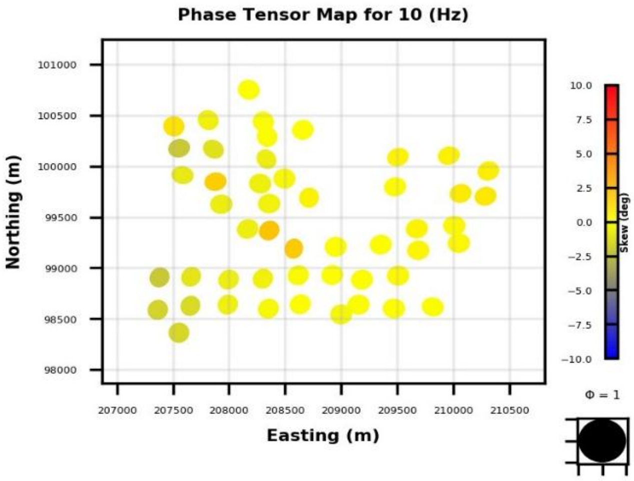

Figure 6: Phase Tensor maps at 10 Hz.

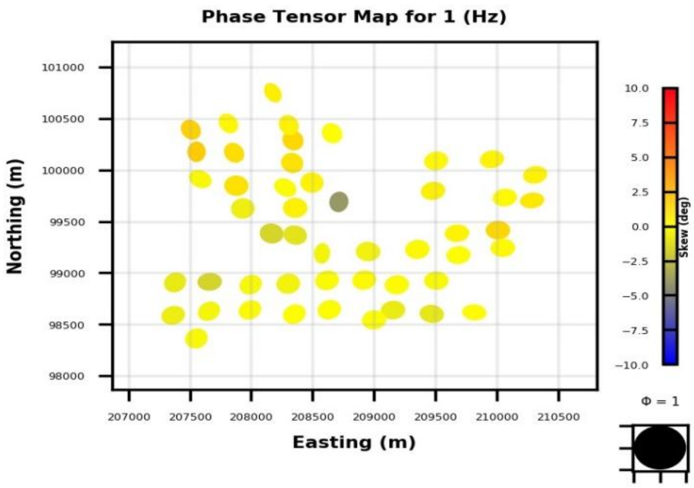

Figure 7: Phase Tensor maps at 1 Hz.

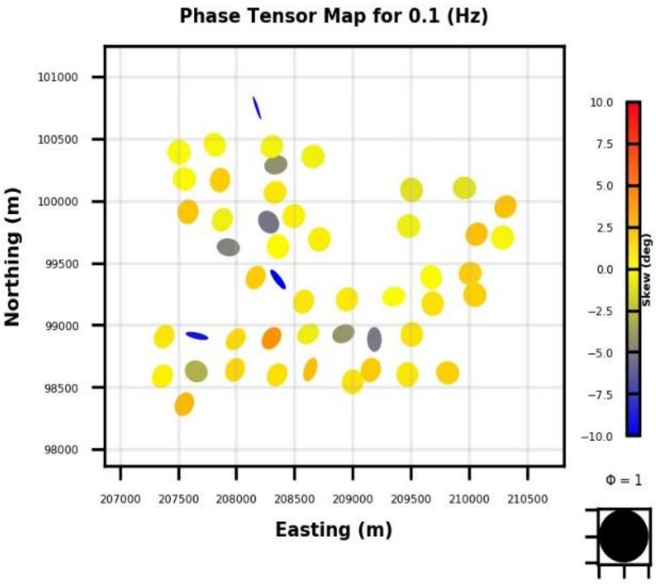

Figure 8: Phase Tensor maps at 0.1 Hz.

The geo-electric strike direction was determined using the rose diagram strike estimation method. The strike estimation of 45 degrees is fairly consistent with the major NE-SW local fault system in the Eastern side of Olkaria domes and was taken as the regional strike direction (Figure 9). The impedance components were, therefore, rotated N45°E at a period of 1- 10 s before the 2-D inversion. This strike conforms to the regional structure of Olkaria field.

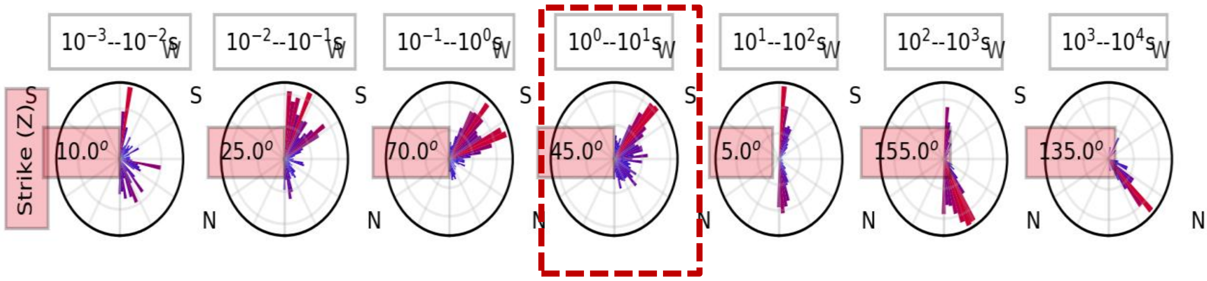

Figure 9: Geo-electric strike rose diagrams of 45^0 at periods $10^0 – 10^1$ s.

VI. MT DATA INVERSION

6.1 2D Inversion

2D inversion assumes that the resistivity varies with depth and in one lateral direction and that the resistivity is constant in the other horizontal direction (electrical strike). The two selected profiles investigated were inverted with a rectangular 50m width mesh of 70 layers starting with an initial layer thickness of 20m, increasing logarithmically with depth. All inversions were subjected to an initial model of 50 Ωm homogenous half-space. A maximum of 100 iterations and target root mean square (r.m.s) of 0.5 with a side padding increment factor of 2 for the three blocks added to both sides of the mesh were applied and subjected to a maximum of 65 frequencies ranging from 0.011 – 320 Hz to achieve the model inversion. The Occam 2D inversion code version 3.0 developed by Degroot-Hedlin and Constable (1990) was used. The two models had a minimum r.m.s misfit of 0.97 and 1.47 for profiles 1 and 2 respectively. A strike estimation of 45^0 was taken as the regional strike direction.

6.2 Transverse Electric (TE) and Transverse Magnetic (TM) Mode

In 2D earth, the off-diagonal terms of impedance tensors are decoupled into TE and TM modes. In TE mode, the electric field E is parallel to the strike, while in TM mode, the magnetic field H is perpendicular to this strike direction (Vozoff, 1990). As TE mode data is more sensitive to localized heterogeneities than TM mode data, more priority is given to TM mode to avoid these inherent effects which cause poor data fit in TE mode (Wannamaker *et al.,* 1997).

The TM and TE modes have varying sensitivities to both near-surface and deeper structures, and they provide different levels of accuracy when using the 2-D approximation of real 3-D bodies (Wannamaker *et al.*, 1997). Two parallel profiles, intersecting the geological structures, were chosen for the 2-D inversion. A joint 2-D inversion, incorporating both TE and TM modes, was conducted along all the profiles. Joint inversion of the TE and TM mode data was carried out to obtain a comprehensive view of the subsurface conductivity structure on the Eastern side of the Olkaria domes, to explain simultaneously the data from both polarizations. For the 2-D models, pseudosection plots of the observed and predicted responses were generated. In Profile 1, the pseudosection plots for both TE and TM modes, are shown in Figure. 10, demonstrate a good fit between the observed and predicted data. The TM mode exhibits a better fit than the TE modes, as it results in a smaller residual for Profile 1.

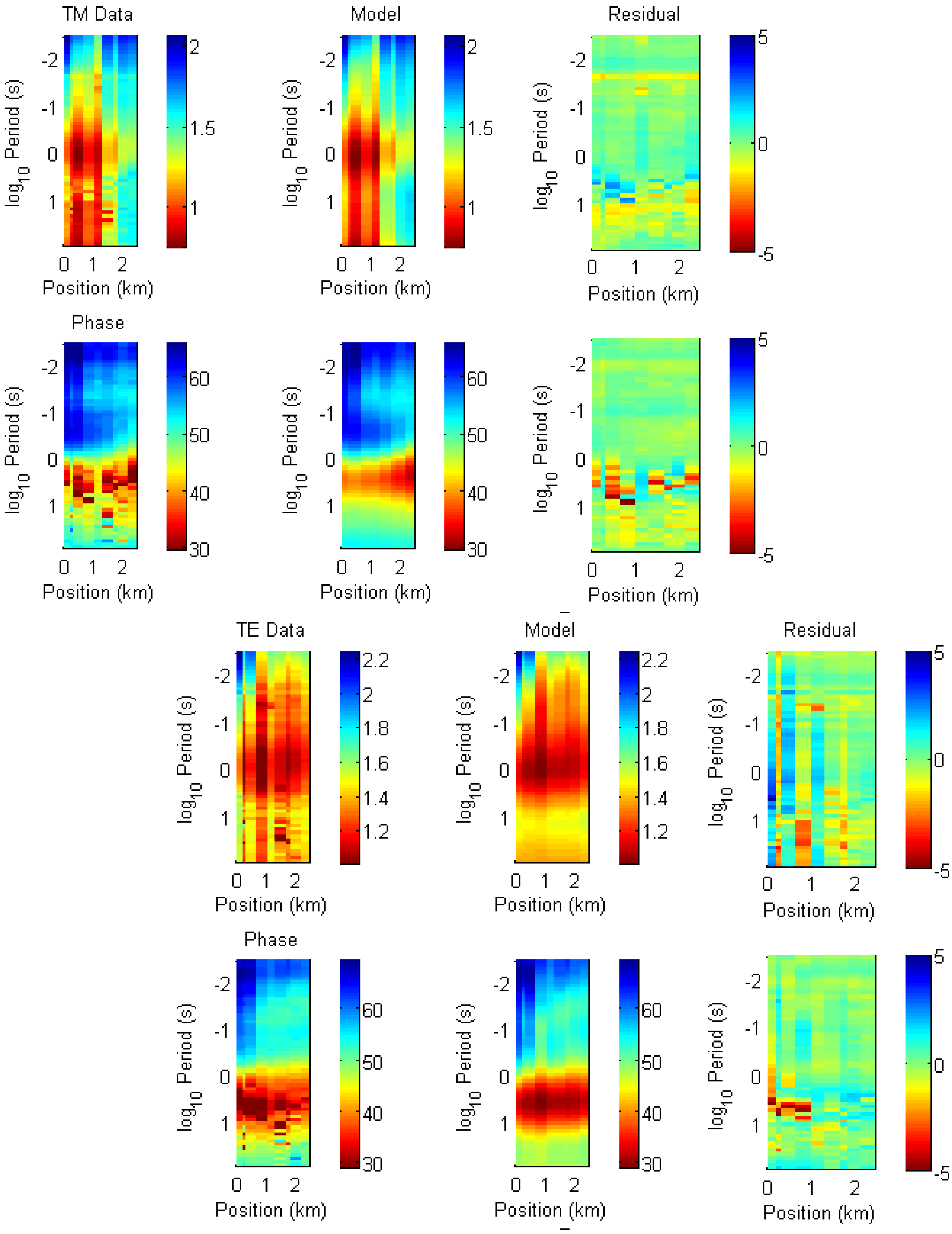

Figure 10: Pseudosections of observed and calculated apparent resistivity and phase for TM (above) and TE mode (below) for Profile 1. The residual map shows the differences between the observed and predicted responses of the two modes.

6.3 2D Inversion Results and Discussion

The resistivity models derived from the 2-D inversion schemes of the two resistivity profiles in Figure. 11 are shown in Figures. 12 and 13.

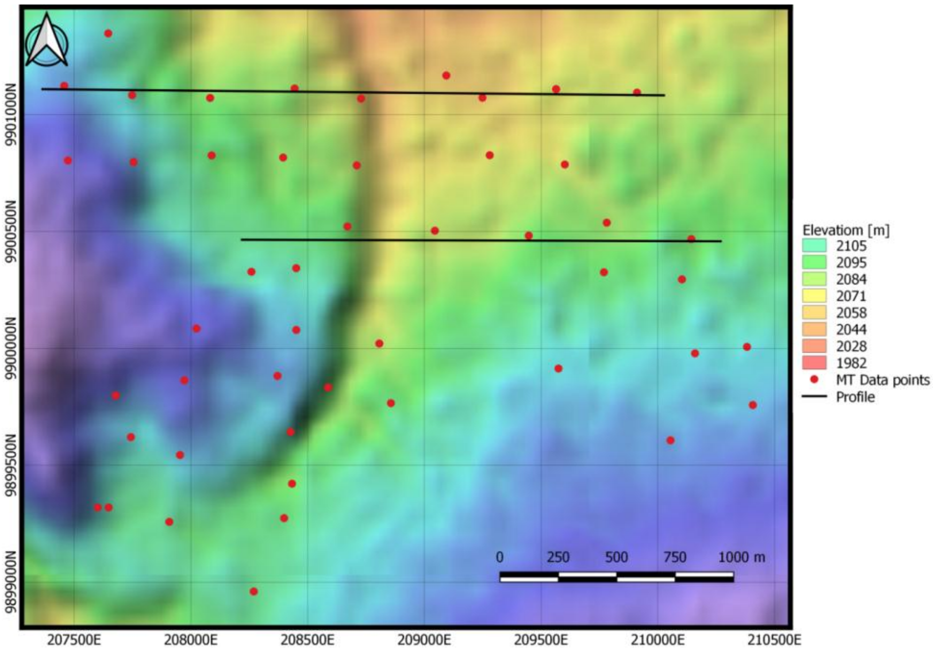

Figure 11: Topographical map showing MT profiles for 2-D inversion on the Eastern side of Olkaria domes

The resistivity models obtained from the two profiles are shown in Figures 12 and 13. The results revealed a distinct conductive channel and resistive anomalies. Figure 12 shows the 2-D Occam model along the profile resulting from 2D Occam inversion.

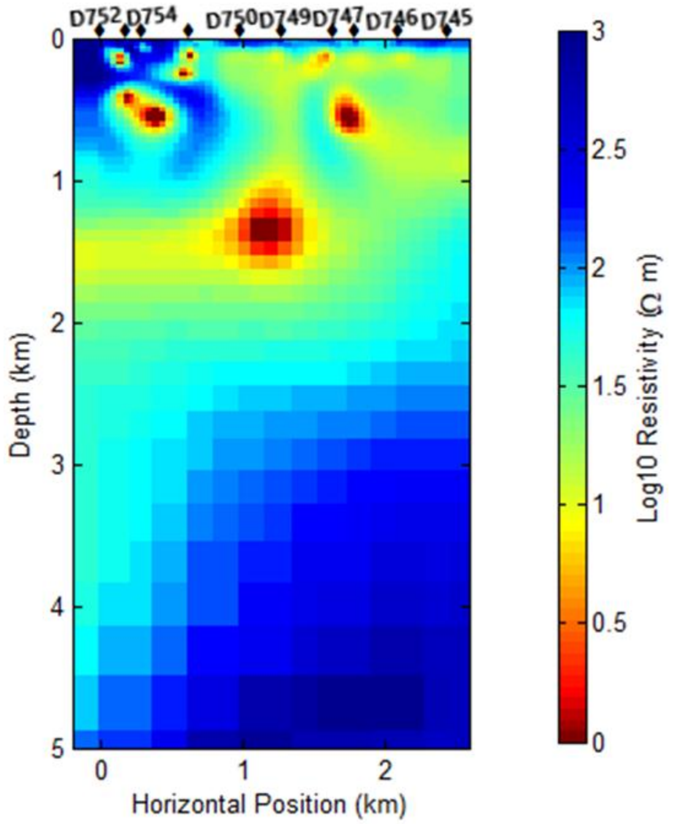

Figure 12: 2D resistivity models for Profile 1

This profile consists of 10 MT-sounding with a lateral length of 2.5 km and a depth range of 5 km. The result shows a highly resistive surface layer (>100 Ωm), covering the lateral distance along the profile with a layer thickness of about 0.5 km. This may be correlated with unaltered formation near the surface. Resistivity decreases with depth up to about (<10 Ωm). This may be interpreted as alteration zones caused by hydrothermally altered clay caps. Below the conductive channel, a relatively high resistive region (>10-60 Ωm) is observed trending from east to southwest at a depth of 3.5 km. This can be interpreted as reservoir extension or impermeable intrusive resistive formation zones. Figure 13 shows a 2D model along profile 2 which lies below profile 1. The results show a conductive channel (<10 Ωm) connecting the main channel almost having similar signatures as those in profile 1 imaged at a depth of 2 km with two resistive structures, mapped at either side, forming a conductive barrier separating the resistive structures. The anomalous resistive body (>100 Ωm) was observed at a depth of 4 km. The resistive structure indicates an extension of features imaged in profile 1 suggesting a possible inflow of a cold formation to the system. Generally, in geothermal areas, the clay cap layer possesses a low resistivity value of less than or equal to 10 Ωm (Pellerin *et.al*, 1996). In contrast, the reservoir typically exhibits a higher resistivity value of about 10-60 Ωm.

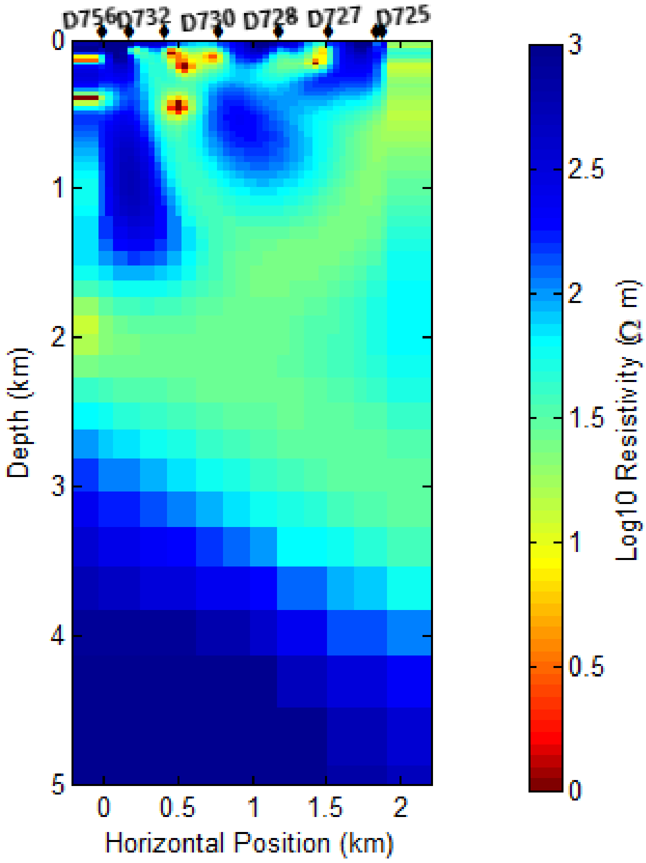

Figure 13: 2D resistivity models for profile 2

VII. Conclusion

Before 2-D inversion, it is necessary to identify a preferred geoelectrical strike. This is achieved by performing dimensionality analysis on the data or based on known local or regional geology. Dimensionality analyses showed that the MT data are generally one-dimensional and two-dimensional at short periods and therefore the need to carry out 2-D inversion. The two profiles analyzed revealed a structure that can be interpreted as a potential pathway of low resistivity used by geothermal fluid to migrate to the surface.

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