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Spectral Analysis Of The Magnetic Data To Assess The Geothermal Potential Of The Olkaria Domes Area.

Answari Wesonga Otanga, Justus Maithya And James Munyithya
Department Of Physics, Jomo Kenyatta University Of Agriculture And Technology, P.O Box 62000 (00200) Nairobi, Kenya

Abstract
In geothermal exploration, key parameters such as the geothermal gradient and heat flow are essential for evaluating the geothermal potential of a region. In the Olkaria geothermal field, these parameters are usually obtained directly from drilled wells at shallow depths. However, the magnetic method offers an indirect approach to determine the geothermal gradient and heat flow by determining the depth to the base of magnetic sources (DBMS), making the assumption that DBMS is influenced by temperatures at Curie point depth (CPD) and by lateral variations in lithology with differing magnetic properties. The CPD is the depth at which magnetic minerals lose their magnetism due to high temperatures. Spectral analysis techniques such the centroid methods have been quantitatively widely applied on the magnetic data to assess the depth and extent of the magnetic sources. This study applied spectral analysis technique (centroid method) to the ground magnetic data to estimate the DBMS/CPD, geothermal gradient and heat flow, to assess the geothermal of potential of the Olkaria domes area. The results showed that the Olkaria domes area exhibit a shallow CPD of 10.352 km, an elevated geothermal gradient of 56.0278 °C/km, and an increased heat flow of 140.0696 mW/m². These values suggest that the region possesses greater geothermal potential thus making the region promising for sustainable geothermal energy development.

Key Word: *Magnetic data, spectral analysis, Curie point depth, subsurface temperature.*

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I. Introduction

Geothermal energy is one of the cleanest forms of energy that is still being explored and developed in Kenya. In the geothermal exploration, key parameters such as geothermal gradient and heat flow are important in evaluating the geothermal potential of a region. The measurement of geothermal gradient and heat flow can be done both directly in drilled wells or can be inferred indirectly using the geophysical methods such as the magnetic method. The geothermal gradient and heat flow revel directly the condition of the subsurface temperatures. At Olkaria geothermal field, the direct measurement of geothermal gradient and heat flow in drilled are normally done at shallow depths not generally exceeding 1000m, and as a result this approach may lead to provision of insufficient information about the subsurface temperatures at deeper depths. In addition the surface temperature variations with time and subsurface ground water flow may impact the measured heat flow particularly (Ibrahim *et al*., 2022).

Magnetic method can be used to infer the subsurface temperatures indirectly by determining the depth to the base of magnetic sources (DBMS). In many cases DBMS advocates Curie point depth (CPD). Once the DBMS/CPD, has been established, it can be used to determine the geothermal gradient and heat flow of a region. The geothermal gradient and heat flow determined from the DBMS are based on assumption that the DBMS is been influenced by temperatures at Curie point depth, and by lateral variations in lithology with differing magnetic properties (Ross *et al*., 2006). However using the CPD to determine the geothermal gradient and heat flow is still problematic because CPD may reflect subsurface mineralogical variations rather than temperature. The CPD is the depth below the surface at which the magnetic minerals lose their magnetism properties due to high temperatures known as Curie temperature.

Temperatures in the Earths subsurface increases with depth at a normal gradient of 30 per kilometer. However, in regions of high heat flow/ flux, the gradient tend to be higher. High heat flow exceeding 100 mW/m² has been observed along the East African Rift System (EARS) (Didas *et al*., 2022). The Kenya Rift is a section of EARS along which the Olkaria domes area is located, southern region of L.Naivasha. Therefore it is expected that the region to exhibit high heat flow values. In addition, seismic velocity studies in the region have revealed higher heat flow at deeper depths (Simiyu, 1999). Furthermore, the region is a high-temperature geothermal system with the temperature of the geothermal reservoir exceeding 200 ^{0}C

The magnetic data can be analyzed and interpreted into two major ways, including qualitatively and quantitatively. Qualitative interpretation which is the initial step in magnetic interpretation, involves describing survey results and explaining major features in terms of likely geological formations and structures that cause anomalies using the potential field maps or grids. In contrast, quantitative interpretation focuses on making numerical estimates of the depth and dimensions of the sources of anomalies (Revees, 2005). The quantitative approach adopted in this study was spectral analysis.

The application of 2D spectral analysis techniques (power spectrum methods) on magnetic data to determine the depth and extent of magnetic anomaly sources is based on radially average power spectra analysis of a region of magnetic data developed by Spector and Grant 1970. When applying power spectrum methods, various techniques can be used to identify the depth to the top and bottom of a magnetic susceptibility source, such as the fractal methods, forward modeling, spectral peaks and centroid method (Kelemework *et al.,* 2021). These techniques are based on different magnetization distributions, including random sources for spectral peak and forward modeling approaches, statistical magnetization ensembles for the centroid method, and fractal sources for fractal techniques (Peredo *et al*., 2021). While all of these methods have been widely applied, Maus and Dimri (1996) have shown that their ability to provide accurate depth information is limited when not properly utilized. Nevertheless, the application of these methods are reliable when the estimated depths are constrained and validated by other geophysical and geological data (Ravat *et al*., 2007).

To apply the power spectrum methods on the anomaly data, the data must be processed due to dipolar nature of the magnetic data. This is achieved either by doing a reduction to the magnetic Equator (RTE) for the low latitude regions or a reduction to magnetic North pole (RTP), to correct the shape and location of magnetic anomalies above their causative sources. The shallow and deeper magnetic sources cause anomalies on the Earth's surface (Thébault *et al.,* 2010). The removal of shallow sources (short wavelength anomalies) enhance the estimation of CPD (Ibrahim *et al*., 2022) The removal of these shorter wavelength anomalies is influenced by several factors, including the geological setting of the region like the presence of exposed or shallow basement rocks and the amount of data noise. Applying low pass (LP) wavelength filtering facilitate the removal of shallow sources.

The current study applied the spectral analysis technique (centroid method) to the magnetic anomaly data to estimate DBMS/CPD, geothermal gradient and heat flow, to assess the geothermal potential of the Olkaria domes area.

Study area and the geology.

Olkaria domes area is one of the subfields of the larger Olkaria geothermal field, located in the southern region of L. Naivasha, Kenya along the Kenyan Rift (a section of EARS) as shown in Figure 1. Olkaria Domes area is bounded by an approximate latitudes of 1˚ 40´ S to 2˚ 10´ S and longitudes of 36˚ 00´ E to 36˚ 30´ E as shown in Figure 2. Surface investigations conducted in the Olkaria domes area during 1992 and 1993 contributed to the establishment of a preliminary working model for the site.

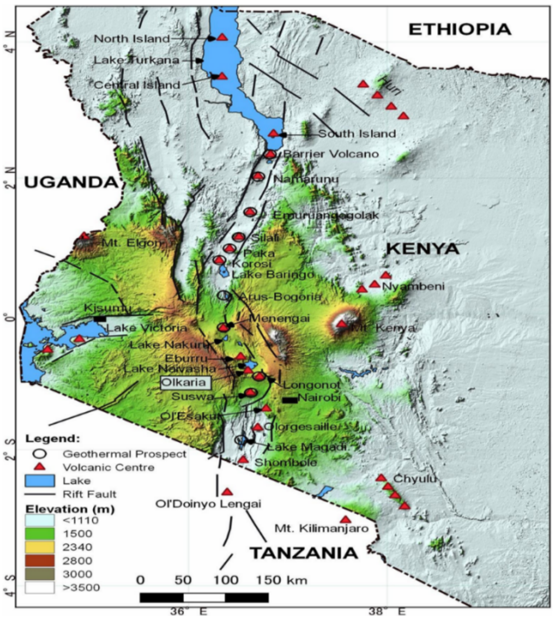

Figure 1. Location of the larger Olkaria geothermal field along the Kenyan Rift (Adopted from Omollo *et al.,* 2022)

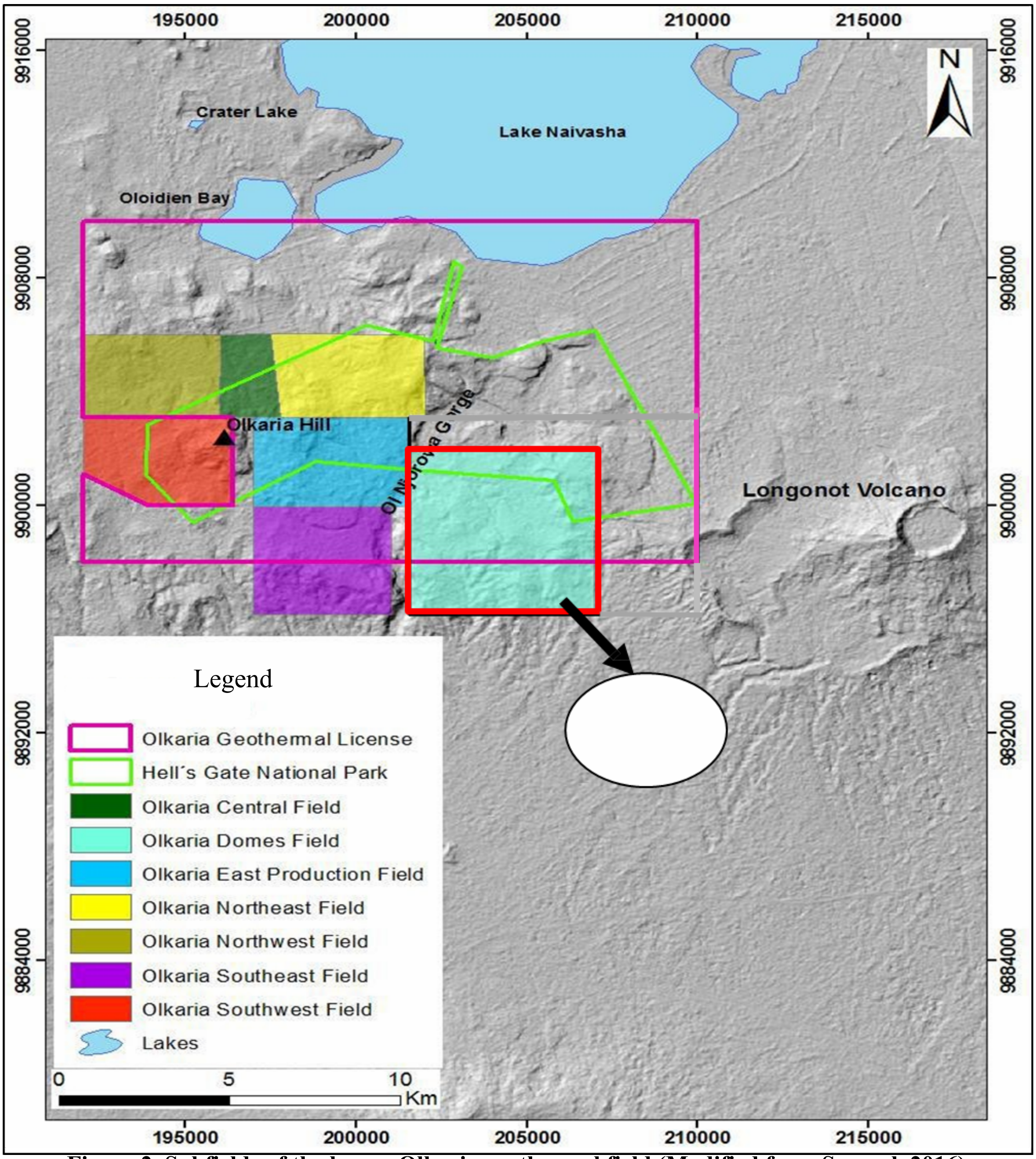

Figure 2. Subfields of the larger Olkaria geothermal field (Modified from Samuel, 2016)

The larger Olkaria geothermal field is situated within the Olkaria volcanic complex. The field is classified as a late Quaternary volcano located within the central Kenya Rift, which is part of the EARS (Chorowicz, 1990). The Olkaria field exhibits a complex structural system, with some structures trending E-W and NE-SW. These structures are significant for analyzing dynamic geological processes. Naylor (1972) proposed the existence of a ring structure, characterized by an alignment of rhyolite domes, which predates the N-S tectonic trend in the Rift Valley zone. He attributed this to the collapse of a large volcanic complex following a catastrophic explosive eruption.

The surface geology of the Olkaria geothermal field is overlain by Quaternary lava flows, pyroclastic deposits, and ash fall from Mount Longonot as shown in Figure 3 (Marshall *et al*., 1998). The most recent lava flow in Olkaria, the Ololbutot comenditic flow, is dated at approximately 180±50 years BP using radiocarbon methods (Clarke *et al*., 1990). Basaltic lava flows are observed on the southwestern side of the field. The dominant subsurface rock types include tuff, trachyte, comendite rhyolite, and basalts. Analysis of borehole data reveals that tuff and trachyte are the predominant reservoir rocks, with tuff being more common in the western reservoir zones and trachyte and basalt primarily found in the eastern reservoir (Omenda, 1998). Pyroclastic fall deposits partially cover a small outcrop of trachyte flow in the southern part of the area, with minor volcanic rock occurrences scattered throughout the geothermal field (Clarke *et al.,* 1990).

The structural features in the area include lineaments and faults trending N-NW-SE, NE-SW, and NW-SE (Otieno, 2016). West of the Olkaria hills lies a structure known as the Suswa lineament, which trends NW-SE into the western rift flank, plunging into the Suswa caldera and emerging SE of the volcano as a scarp. This lineament also intersects the southwestern end of the Ol Njorowa Gorge, which traverses the field in a NE-SW direction. The Gorge Farm fault (NW-SE) and Olkaria fault (E-NE-W-SW) are considered associated with rift formation and are among the oldest, while the N-S, NE- SW, and N-NE-SW faults are linked to more recent tectonic activities (Omenda, 1998) and the proposed caldera collapse.

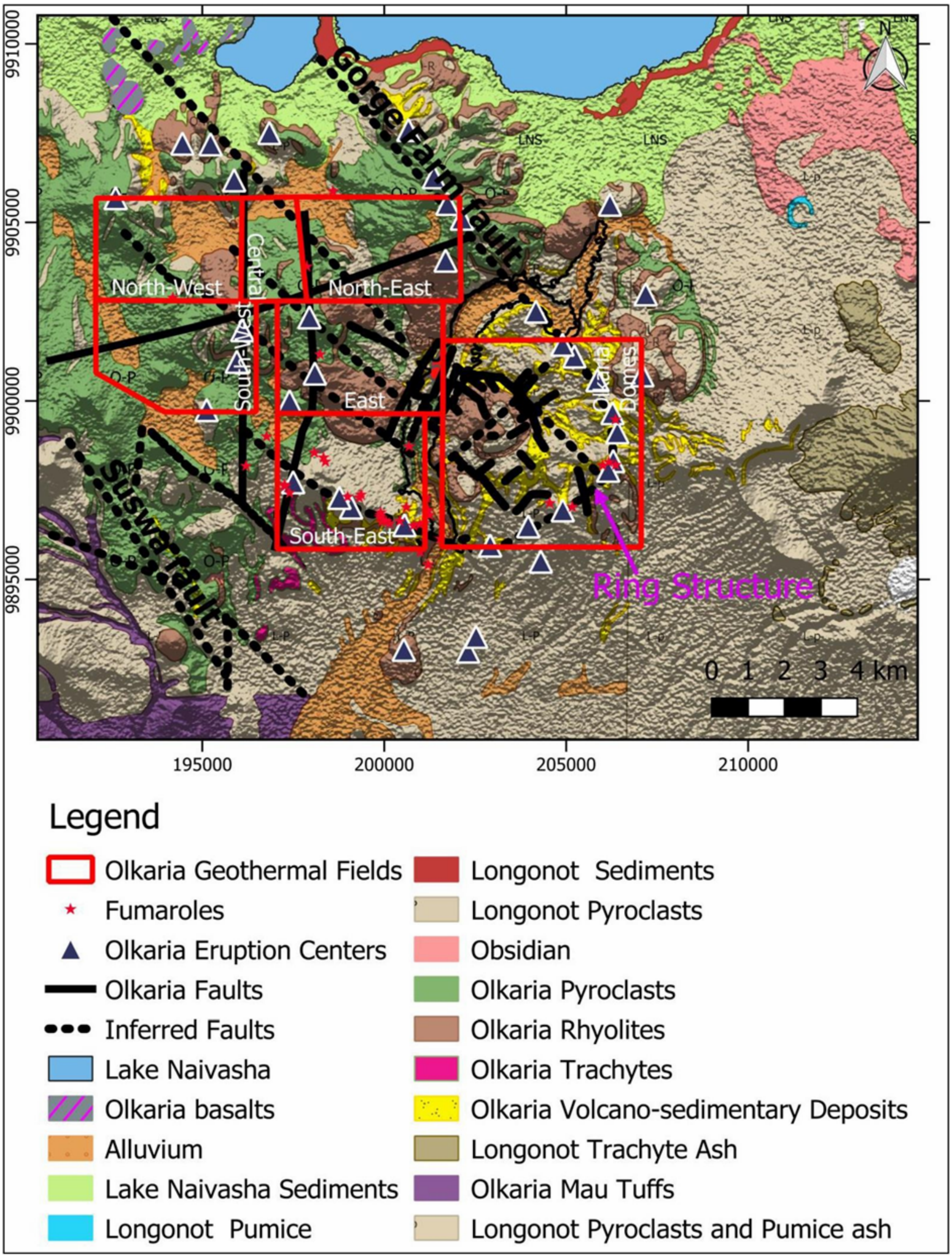

Figure 3. Surface geological and structural map of Olkaria geothermal field (Adopted from Omollo *et al.,* 2022)

II. Magnetic Method.

The fundamental principle of the magnetic method involves a mass with higher magnetization, such as magnetite (magnetic mineral), which disturbs the Earth's geomagnetic field and leads to the creation of magnetic anomalies. The magnetic susceptibility of rocks in the subsurface varies based on the types of magnetic mineral present and geological processes such as hydrothermal demagnetization.

The magnetic field of material is given as:

1

where is the magnetic permeability of vacuum, is the magnetic susceptibility of medium, and is the magnetizing field strength.

Magnetic anomalies arise from underlying causative bodies that possess either higher or lower magnetic susceptibility compared to the surrounding host rocks. A magnetic high anomaly indicates a body with greater magnetic susceptibility, while a magnetic low anomaly signifies a body with reduced magnetic susceptibility.

Geothermal heat sources may be found in a low magnetic zones due to demagnetization of the rocks by high temperatures (Georgsson, 2009). In geothermal environments, increased temperatures lead to a reduction in magnetic susceptibility. For instance, in Iceland, hydrothermal demagnetization resulted in negative magnetic anomalies (magnetic lows) (Mariita, 2011). Therefore, magnetic survey can effectively delineate demagnetized masses of high temperatures. And also, magnetic survey can provide complementary structural information about the surveyed area. The magnetic characteristics of a rock within the Earth's subsurface and the temperature at which it loses its magnetism depend on the magnetic composition of the rock, such as the presence of magnetite or hematite (Rivas, 2013).

III. Spectral Analysis

Spectral analysis of a magnetic data, entails converting the data from the spatial domain to the Fourier domain (frequency domain) through Fourier transformation. The 2D Fourier Transform (FT) of the magnetic field anomaly is expressed as:

2

where is the space domain, is the frequency domain, is the wavenumber.

Centroid method as a spectral analysis technique estimate the magnetic source depths from the slope of logarithmic power spectra (e.g. Didas *et al.,* 2022; Ibrahim et a*l.,* 2022).

Blakely (1995) stated that, the power spectrum of the magnetic field anomaly field is been expressed as:

3

where is an arbitrary constant, and are basal and top depths of the magnetic source.

For short wavelengths (high wavenumbers), equation (3) can be rewritten as:

4

where is an arbitrary constant.

The slope of best fit fitted through the region of intermediate to high wavenumber part of the power spectrum plot of equation 4 gives the depth to the top of the magnetic source.

Equation (4) can be rewritten as:

5

where is an arbitrary constant.

For long wavelengths (low wavenumbers), equation (5) can be rewritten as:

6

where is the thickness of the magnetic source, and are an arbitrary constants.

Equation (6) can be expressed as:

7

In similar way, the slope of best fit fitted through the region of lower wavenumber part of the power spectrum plot of equation 7 gives the centroid depth.

Okubo *et al.* (1985) and Tanaka *et al.* (1999) combined the top depth and centroid depth to yield the basal depth (DBMS) as:

8

DBMS is assumed to be CPD. Figure 4 illustrate an assumed relationship between the top depth, centroid depth and basal depth.

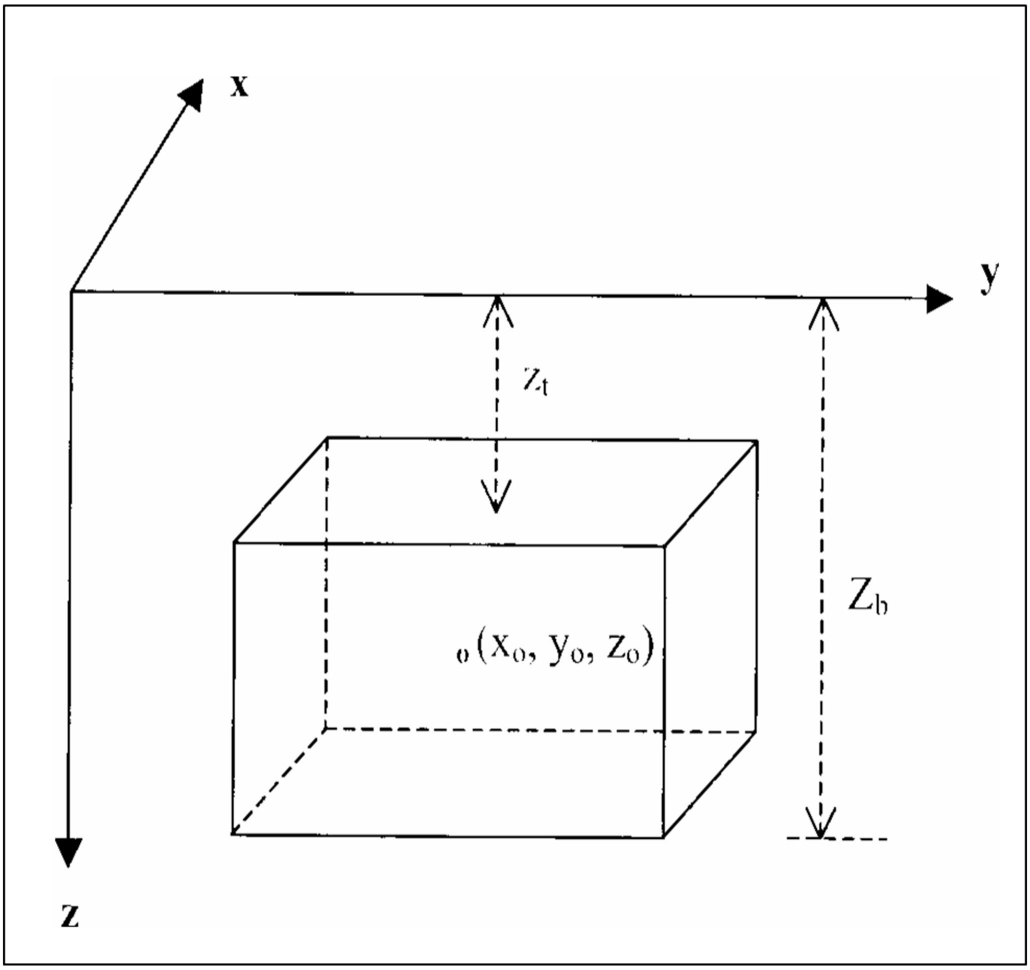

Figure 4. The assumed relationship between the top depth, centroid depth and basal depth.

IV. Geothermal Gradient And Heat Flow

Geothermal gradient (GG) and heat flow (HF) can be determined from DBMS/CPD (Tanaka *et al.*, 1999) as:

9

And

10

where T_c is the Curie temperature, and is the coefficient of thermal conductivity of the subsurface materials

V. Materials And Methods

The collection of the magnetic data can be either on land, at sea or in air. In this study, we used magnetic data collected on land. The diurnal corrected ground magnetic data used in this study was Kenya Electricity Generating Company (KenGen) Olkaria Plaza, Naivasha Kenya. In this study the effect of main field on the measured field was removed by carrying out IGRF correction. The removal of diurnal field variations and the main fields from the measured field result to magnetic field anomaly data, basically the anomaly field data or total magnetic intensity (TMI) data. The total magnetic intensity (TMI) data obtained, was subjected to gridding using krigging method in Surfer 13 software to generate the anomaly grid (TMI grid). But before proceeding to later procedure, we had to confirm whether the data provided was collected in the area of interest (Olkaria Domes) by validating the location of the TMI grid and data points on Earth's surface by overlying the coordinates on Google Earth Pro as shown in Figure 5 and 6. The validation of the locations confirmed that indeed the magnetic data used in this study was from the area of interest, proved by Olkaria IV and V power plants which are situated within the Olkaria domes field.

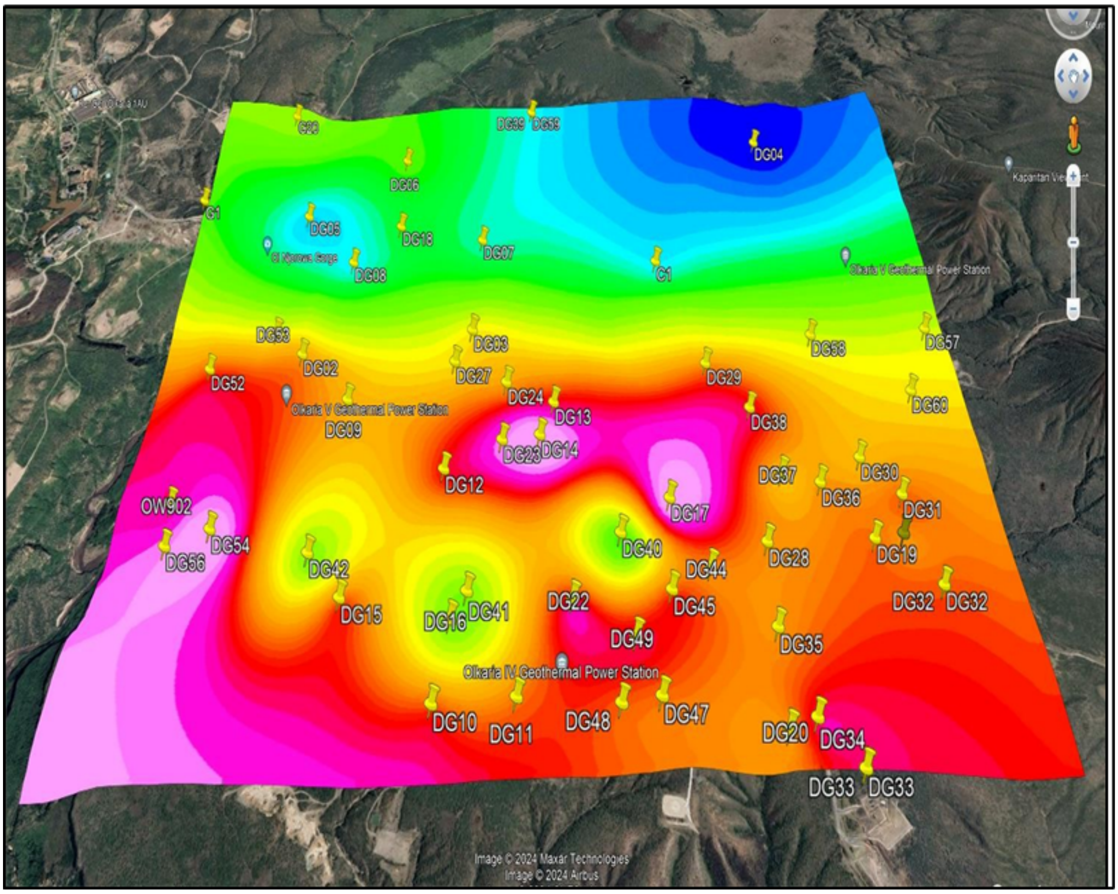

Figure 5. Location Of TMI Grid (Exported As A Map) On Earth's Surface.

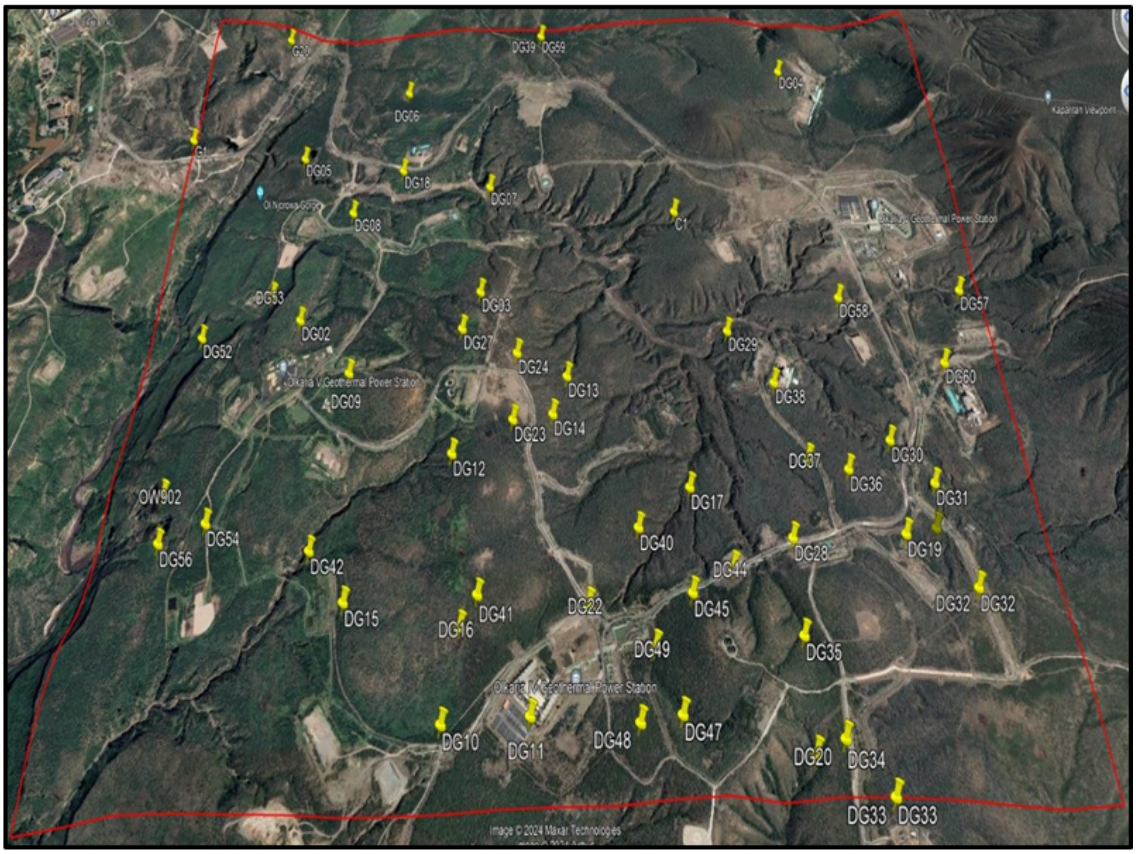

Figure 6. Location Of Data Points On Earth's Surface, Red Boundary Indicate Study Area Boundary

Before estimating the magnetic source depths in the subsurface by applying spectral analysis on the magnetic data (TMI grid), the TMI grid had to underwent some consecutive series of steps in order to obtain the final anomaly grid of interest for spectral analysis purpose. First, in order to adjust the peaks and gradients of anomalies to align directly above their sources in the subsurface, the reduction to the magnetic Equator (RTE) was applied on the anomaly grid to obtained RTE-TMI grid, the transformed grid. In the transformation process, the angles of declination and inclination used were 0.8 and -22.82 degrees respectively. Second, the transformed anomaly grid (RTE-TMI grid) underwent regional-residual grid separation to obtain the residual RTE-TMI grid.

Thirdly, to remove the effects of very shallow magnetic sources to a depth not exceeding 0.5 km, the residual RTE-TMI grid underwent low pass (LP) wavelength filtering with cut off frequency of 0.5 km. As a result the wavelength filtered residual RTE-TMI grid was obtained. This was the final anomaly grid of interest before undertaking the spectral analysis for depth estimation.

Depth estimation

Calculated 2D radially averaged power spectrum of the wavelength filtered residual RTE-TMI grid was generated using the MAGMAP load menu in Oasis Montaj software. The procedures for generating 2D radially power spectrum involved first preparing the grid, then First Fourier transformation (FFT) of the grid then lastly display spectrum. The spectrum was analysed in MS Excel software to generate power spectrum plots used to estimate the top depth and centroid depth as shown in Figure 7.

Following the plots of equations (4) and (7), respectively, the top depth was determined from the slope of the best-fit line fitted through the region of intermediate to high wavenumbers of plot (a) while the centroid depth of the magnetic source was determined from the slope of the best-fit line fitted through the region of lower wavenumbers of plot (b). Top and centroid depths together were used to calculate the basal depth of the magnetic source (DBMS) using Okubo *et al*. (1985) equation (8). This basal depth was assumed to the CPD.

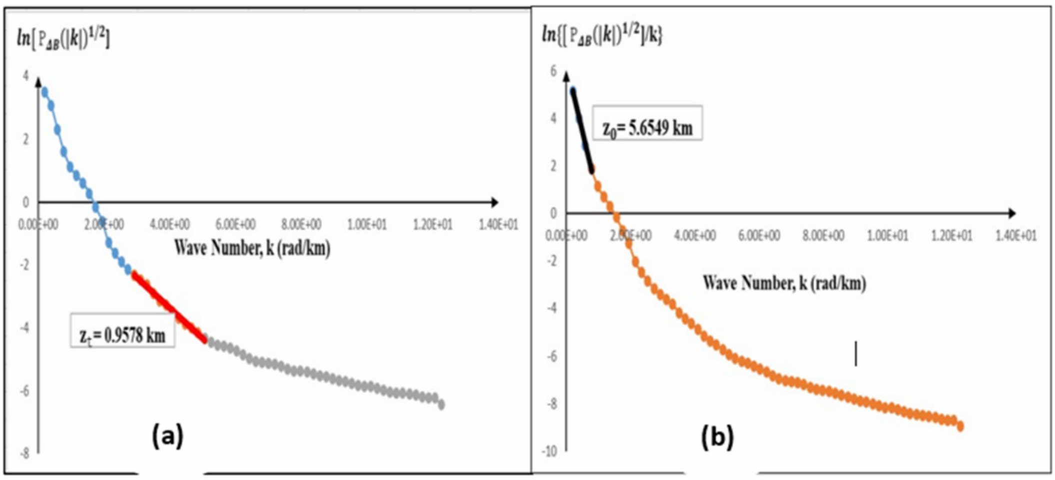

Figure 7. Power spectrum plots used to estimate top depth (a) and centroid depth (b)

Determination of geothermal gradient and heat flow

Geothermal gradient and heat flow was determined from the estimated DBMS/CPD using Tanaka *et al*. (1999) equations (9) and (10) respectively. In this study, Curie temperature was taken as 580 °C which is the Curie temperature for magnetite mineral, a very dominant magnetic mineral in the subsurface, while the coefficient of thermal conductivity was taken as 2.5 W/m °C, which is the average value for igneous rocks. This value was chosen due to the predominance of igneous-origin rocks in the subsurface geology of the Olkaria geothermal field. In addition, several authors have used this value to determine heat flow of a region just to mention a few (e.g. Didas et *al.,* 2022; Ibrahim *et al*., 2022)

VI. Results And Discussions

In a centroid method spectral analysis technique, the window size of the magnetic data (anomaly grid) used for spectral analysis is crucial thing to consider. Window sizes of few kilometers are considered unable to estimate the source depths (e.g. CPD) at deeper level. However, the optimum window size to be used in computing DBMS/CPD is still a matter of scientific discussion (e.g., Andr´es *et al*., 2018) and is in general unique for each area (Kumar *et al*., 2020). It is small over tectonically active areas with high heat flow and large in stable regions such as the cratonic areas (Kelemework *et al*., 2021). However, a common approach is to choose a window large enough to display a clear peak in the very low wavenumber band of the spectrum (e.g., Ravat *et al*., 2007). However, as small as possible window size is required to detect the expected shallow CPDs along the EARS (Didas *et al.,* 2022). In this study, anomaly grid (wavelength filtered residual RTE-TMI grid) used for spectral analysis had a window size of approx. 8 by 8 km. This window size is small enough to detect the expected shallow CPDs along the Kenyan Rift.

The estimated CPD in this study was 10.352 km which reflect the depth below the surface at which temperatures are high to cause magnetic minerals become nonmagnetic. In a geothermal region, such temperatures (Curie temperature) are normally associated with hot masses (magma). The Curie temperature varies depending on the type of magnetic mineral. Generally, it ranges from 440 to 580°C (Hunt *et al*., 1995). In most cases, due to the dominance of magnetite as a magnetic mineral, its Curie temperature of 580°C is considered the reference temperature for the CPD (Hunt *et al*., 1995).

The CPD can be used to ascertain the depth of potential geothermal heat source (Githiri *et al*., 2012). The depths to the potential geothermal heat sources at Olkaria geothermal field range between 5.0 and 8.0 km (Omollo *et al*. 2022) ;Rop *et al*. 2018). This imply that extreme temperatures are been expected at depths beyond 8 km.

The geothermal gradient and heat flow can be determined by determining DBMS/CPD. However, using DBMS/CPD to determine geothermal gradient and heat flow can be challenging because DBMS may be influenced by factors rather than the temperature. In addition, the computation of DBMS/CPD can be affected by the window size of the data used for calculating the power spectrum (Ravat *et al*., 2007). Therefore, it is often necessary to gather additional independent geothermal, geological, and geophysical data to verify the relationship between DBMS and CPD (Okubo *et al*., 1985), like the heat source depth of the survey region. As heat source signify the depth below the surface at which temperatures are abnormal.

In this study, the DBMS/CPD of 10. 352 km resulted to geothermal gradient of 56.0278 °C/km, and heat flow of 140.0696 mW/m^2. In regions where heat flow data is insufficient, CPD can serve as an indirect indicator of temperature variations at depth (Ross *et al.,* 2006). According to Tanaka *et al.* (1999), CPDs tend to be less than 10 km in volcanic and geothermal regions, range between 15 and 25 km in island arcs and ridges, exceed 20 km in plateaus, and extend beyond 30 km in trench environments. Therefore, the CPD of the Olkaria domes area of 10.352 km is in the band of "tends to be less than 10 km" suggesting that the area is volcanic/geothermal region.

The normal average geothermal gradient of Earth's continent is around 30-35 ^{0}C/km, while the normal average heat flow value for "thermally" regions is around 60 mW/m^2. The excess values suggest the anomalous geothermal conditions in the subsurface (Jessop *et al.*, 1976). The shallow CPD of 10.352 km observed in this study resulted to excess values for geothermal gradient of 56.0278 °C/km and heat flow of 140.0696 mW/m^2, suggesting greater heat dissipation from the subsurface to the surface.

The CPD, geothermal gradient, and heat flow all together are the essential parameters in geothermal exploration. A shallow CPD may indicate the presence of upwelling magma, while a deeper CPD could suggest isostatic compensation. A shallow CPD implies that the Earth's crust in that region heats up more rapidly with depth, indicating the proximity of hot rocks or magma that could serve as a potential geothermal heat source. This makes areas with shallow CPD particularly promising for geothermal development, as they are more likely to have the necessary conditions for sustainable geothermal reservoirs, including high temperatures at accessible depths. In regions with high heat flow, the geothermal gradient typically increases. Areas with high temperatures and relatively shallow CPDs often exhibit elevated heat flow, potentially signaling the presence of a hot magmatic intrusion. Therefore, a potential geothermal region possess shallow CPD, high geothermal gradient and increased heat flow.

VII. Conclusion

Depth to the bottom of the magnetic sources (DBMS) can be used to advocate Curie point depth (CPD), the depth at which magnetic minerals in the Earth's crust lose their magnetism due to high temperatures, known as the Curie temperature. The Curie temperature varies depending on the type of magnetic mineral. In most cases, due to the dominance of magnetite as a magnetic mineral, its Curie temperature of 580°C is considered the reference temperature for the CPD. At Olkaria high temperatures exceeding 580°C are expected at depths beyond 8 km.

The CPD tends to be less than 10 km in volcanic or geothermal regions, implying that a geothermal/volcanic regions CPDs are expected to be shallow as possible. The CPD of 10.352 km of Olkaria domes area suggest that the area is volcanic/geothermal, which is true because in Kenya, the geothermal prospects are located within the volcanoes along the Kenyan rift. Shallow CPDs result to elevated geothermal gradient and increased heat flow.

Regions with a shallow CPDs, a high geothermal gradients, and increased heat flow are mostly likely to possess significant geothermal potential. The Olkaria domes area (study area), for example in this study, exhibits a shallow CPD of 10.352 km, an elevated geothermal gradient of 56.0278°C/km, and an increased heat flow of 140.0696 mW/m². These conditions suggest that the area likely has significant geothermal potential.

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