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Spectral Analysis of Ground Magnetic Data Using Fast Fourier Transform In Eburru, Southern Rift, Kenya.

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Abstract: *Eburru area lies in the Kenya's rift valley which has several geothermal heat sources. Spectral analysis of ground magnetic data was done to determine the curie point isotherm depth for Eburru study area. Magnetic data in Eburru study area was collected by proton precession magnetometer. Diurnal correction and geomagnetic correction were applied to the raw magnetic data to obtain residual magnetic data. Residual magnetic data was transferred to Oasis montaj software for spectral analysis and interpretation.Oasis Montaj MAGMAP was used to generate radially averaged energy spectrum. Fast Fourier Transform (FFT) was used to convert the space domain grid data to the Fourier wavenumber domain where filters were applied. Results from spectral analysis revealed a curie point isotherm depth of approximately 2150m.This is a shallow isotherm depth indicating high heat flux within the subsurface of Eburru area. There is high potential for geothermal resource in this study area because at curie point isotherm depth ofapproximately* $2150m$*, the temperatures must be above* 130℃*. Oxidation of iron titanium oxides usually causes an increase in curie temperature. In this study area, the curie temperature at isotherm depth varies between* 130℃ *and* 680℃ *depending on oxidation of titanomagnetite mineral which is common in this study area.*

Key words: *Fast Fourier Transform, Geothermal, Heat source, Curie isotherm depth, Curie temperature, Magnetisation, Energy spectrum.*

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I. Introduction

Eburru area lies in Kenya's rift valley, 123 km west of Nairobi. It is 8 kms northwest of Lake Naivasha. It is among the volcanoeswithin the Kenya's rift valley which have shown high potential of geothermal resource occurrence Figure 1. Akira plains separate Olkaria volcano where geothermal energy has been generated to the south and Eburru volcano to the North. Eburru area has east west trending ridge covering a region of approximately $470\ \text{km}^2$ and a highest point at2850 m above the sea level(Kiende & Kandie, 2015).There are hot springs, fumaroles and steam jets along the recent faults hence spectral analysis of ground magnetic data was done to estimate geothermal curie point isotherm depthwhich can be used to ascertain the potentiality of a geothermal heat source in the area.

Spectral analysis of ground magnetic data can be used to map the geothermal isotherm depth. Geothermal isotherm depth is a point with the curie temperature where magnetic materials ceases to exhibit magnetism. Temperature increases with depth within the Earth's interior at a normal gradient of 30℃per kilometer but varies to a higher gradient in regions having high heat flux. Increase in temperature causes a reduction in magnetism of the material and if the temperature is continuously increased, it will reach a temperature point where the material loses its magnetism completely. This temperature is called the curie temperature and the depth within the Earth's subsurface where the curie temperature is achieved is called the isotherm depth.Geothermal energy is the natural heat from the Earth's interior in form of magma which can be used as a source of renewable energy. Because of temperature gradient, there is a continuous heat flow from the Earth's interior which is hot towards the crust which is cooler.Geothermal resource occurs along major fracture lines and inactive volcanic craters where meteorite water seeps down to be in contact with the hot magma(Nyakundi, Githiri, & Ambusso, 2017).

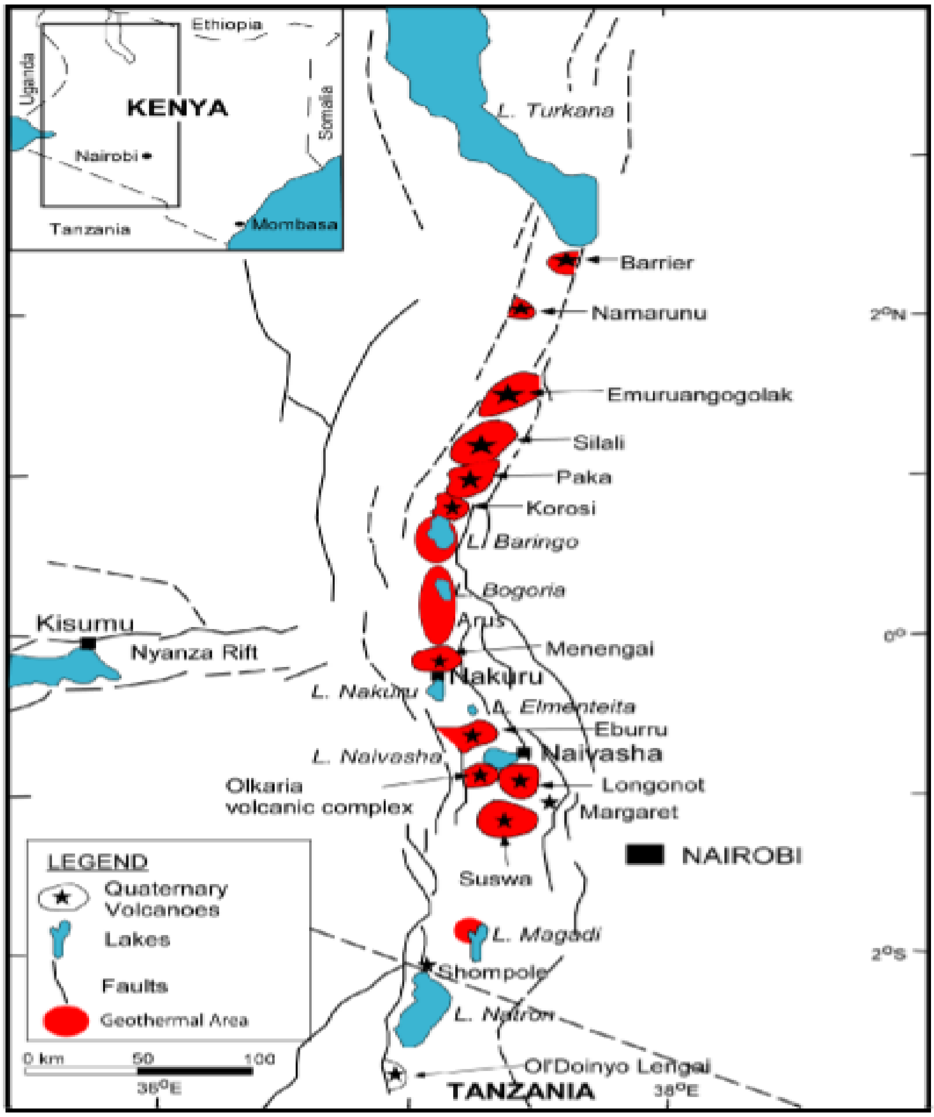

Figure 1: Map showing geothermal prospect areas in Kenya.(Mwawongo, 2013).

Magnetic method

In magnetic survey, the Earth's subsurface geology is examined on the basis of anomalies in the Earth's magnetic field resulting from the magnetic properties of the underlying rocks(Parasnis, 1986). The basic principle of magnetic method is the underlying mass of a higher magnetisation, for instance magnetite that perturbs the Earth's geomagnetic field resulting into magnetic anomalies.

The magnetic anomaly is due to underlying causative body beneath the surface of the Earth that either has more or less magnetic susceptibility than the surrounding host rocks. Magnetic high anomaly indicates a body with higher magnetic susceptibility than the surrounding host rocks while magnetic low anomaly indicates a body with low magnetic susceptibility. Geothermal heat source occur in magnetic low zone due to demagnetization by higher temperatures(Georgsson, 2009).

The purpose of a magnetic survey is to examine the Earth's subsurface geology on the foundations of the changes in the Earth's magnetic field due to the magnetic properties of the underlying masses (Telford, Geldart, & Sheriff, 1990). The magnetic susceptibility of rocks within the subsurface varies depending on the magnetic types of masses present and the Earth's underground activities such as hydrothermal demagnetization. Dykes, faults, basic intrusions, metamorphic basement, magnetic ores and lava flow causes an increase in magnetic susceptibility hence magnetic high. In a geothermal environment, increased temperatures reduce magnetic susceptibility. For example, in Iceland, hydrothermal demagnetization results to negative magnetic anomalies (Mariita, 2011). Therefore, Magnetic surveys can locate demagnetized masses because of thermal variations and it can provide complementary structural information of the surveyed region. The magnetic content of a mass within the Earth's subsurface and the temperature at which it gets removed depends upon the magnetic composition of the mass such as magnetite and hematite (Rivas, 2013). Spectral analysis of magnetic data shows the variation of radially averaged energy spectrum against wavenumber. This was analyzed to determine the depth at which magnetism of rocks disappears. This depth is the curie isotherm depth and can be used to estimate the curie temperature and characterize most activities associated with a geothermal resource.

Methodology

Magnetic data forEburru study area was collected by proton precession magnetometer. International Geomagnetic Reference Field (IGRF) was calculated because of secular variations. IGRF gave field value of the Earth's magnetic field at any location of the Earth.Diurnal correction and geomagnetic correction were applied to the raw magnetic data to obtain residual magnetic data. Residual magnetic data was transferred to Oasis montaj software for spectral analysis and interpretation.

Residual magnetic anomaly

MAGMAP in Oasis Montaj was used to remove the effect of regional trend and shallow features which are not of interest. Effect on the Earth's geomagnetic field by shallow features to the depth of 500m and deep structures beyond 5000m was removed. The residual magnetic anomaly map displays the effect on the Earth's geomagnetic field by themagnetic variation of rockspresent between 500m and 5000m depth. This is the depth which can be accessed by meteorite water that can enable development of a geothermal resource(Mariita, 2011).In MAGMAP, Fast Fourier Transform (FFT) was used to convert the space domain grid magnetic data to the Fourier domain which was used to enhance information of interest.

Oasis Montaj MAGMAP filtering was done that involved pre-processing and post-processing steps. Pre-processing step involved preparing the original space domain grid for filtering, after which filters were applied. Filters were multiplied by the transform of the grid on an element by element basis. Post-processing step involved returning the filtered data to the same size and shape as the original grid and replacement of a regional trend. Fast Fourier Transform (FFT) was used to remove geologic and cultural noise. Fast Fourier Transform (FFT) also performed regional and residual separations for interpretation purposes. It also enabled the evaluation and interpretation of frequency dependent relationships in the transformed data via power spectra.

Residual magnetic map images the effect on the Earth's geomagnetic field by the distribution of magnetism of rocks present between the bandpass depth indicated. This reveals magnetic alteration due to geothermal activity. The alternating magnetic high and low indicates magnetic demagnetization at magnetic low zones due to high temperatures and flowage of geothermal fluid.

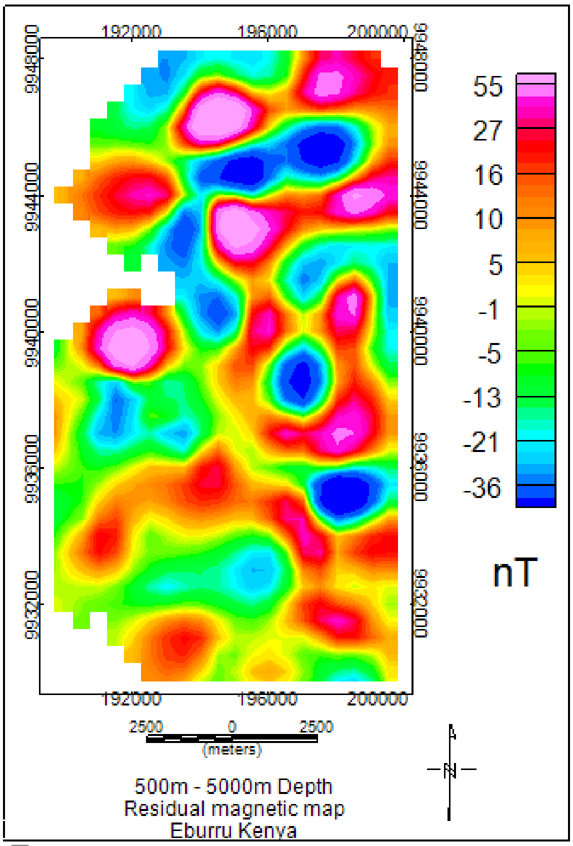

Figure 2: Residual magnetic anomaly map forEburrustudy area, Kenya.

The residual magnetic map in Figure 2displays distribution of residual magnetic field values between 500m and 5000m bandpass depth. This depth range was used as most geothermal resource developed occurs within 500m and 5000m depth(World Energy Council, 2013). Figure2 clearly images the effect on the Earth's geomagnetic field due to the presence of magnetic rocks within the band pass indicated.There is alternating high and low magnetic field values indicating regions with rocks of high magnetism and others with low magnetism. The possible cause of magnetic low in the region could be hydrothermal demagnetization of rocks due to high geothermal temperatures. Movement of geothermal fluids beneath the surface of the Earth can easily demagnetize rocks hence generating a magnetic low. Magnetic high could be a collection of high magnetic content materials due to hydrothermal movement. Also, could be due to intruding basic igneous dyke and sill from the interior of the Earth with high magnetic content. Alternating highs and lows could also be caused by a single causative body beneath the Earth surface that has a positive pole at magnetic high and negative pole at magnetic low.Demagnetized rocks suggest the presence of a hot mass within the Earth' s crust while high susceptibility suggest presence of dykes, faults, basic igneous intrusions, magnetic ore bodies and lava flows. Also, hydrothermal fluids circulation results into destruction of magnetic content in an underground mass thus causing decreased magnetic susceptibility (Ochieng, 2013).

Spectral analysis

Oasis Montaj MAGMAP was used to generate radially averaged energy spectrum. Fast Fourier Transform (FFT) was used to convert the space domain grid data to the Fourier wavenumber domain. Magmap applies filters in the Fourier wavenumber domain. Mathematically, the Fourier transform of space domain function $f(x, y)$ is defined as

$$\bar{f}(\mu, v) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f\,(x, y).\, e^{-i(\mu x + vy)}\, dxdy$$

The reciprocal expression is;

$$f\,(x, y) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \bar{f}(\mu, v).\, e^{i(\mu x + vy)}\, dxdy$$

Where µ and v are wavenumbers in the x and y directions measured in cycles per metre.

A given potential field function in the space domain has a single and unique wavenumber domain function and vice versa. The 2D function of energy against wavenumber and direction is called the energy spectrum. Spectra explains the variation of energy as a function of wavenumber. The power spectrum$\left|\bar{f}(\mu, v)\right|^2$ and its total energy E_T are related by:

$$E_T = \frac{1}{2\pi} \int_{-\infty}^{\infty} \left|\bar{f}(\mu, v)\right|^2 d\mu dv$$

Where μ and v are wavenumbers in x and y directions. Geophysical potential data iscollected with defined boundaries of study area unlike the infinite area assumedin mathematical equations.

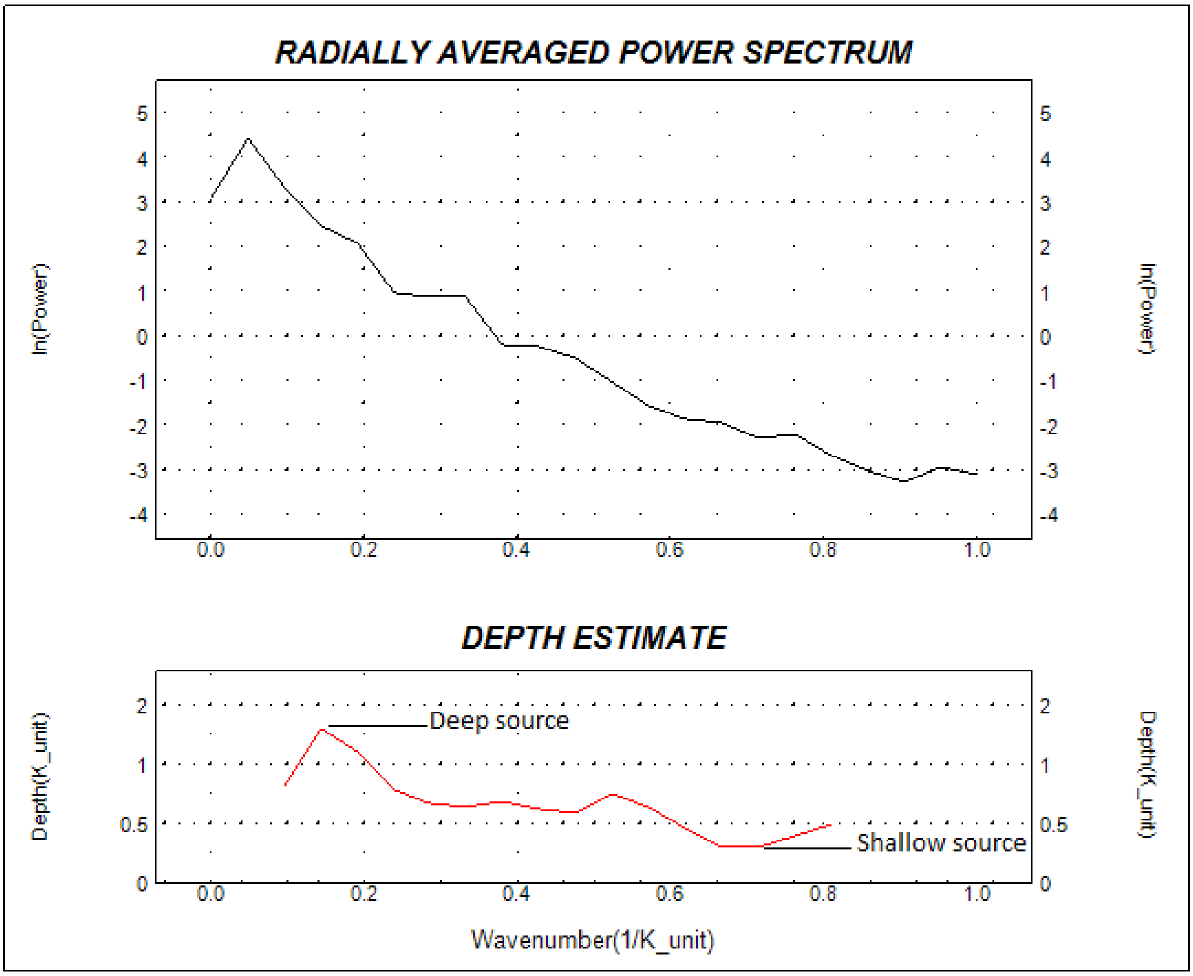

Figure3: Spectral graph showing the signal power distribution as a function of spatial frequencies.

This area of study was taken as one block and radially averaged energy spectrum produced because isotherm depth involves imaging deeper structures. The radially averaged energy spectrum is a function of wavenumber only. It is determined by averaging the energy for all directions for the same wavenumber. Wavenumber k is the spatial frequency of a wave measured in cycles per unit distance. The Nyquist wavenumber N is the largest wavenumber that has been sampled by the grid which is the highest frequency that it is possible to measure given a fixed sample interval.

$$N = \frac{1}{2d}$$

$$N = \frac{1}{2 \times 0.5} = 1$$

Where d is the sample interval.

FromFigure 3, wavenumber k ranges between 0 and 1, the Nyquist frequency. Depth axis is in multiples of grid cell size, which is 0.5 km for this study.

The depth to a statistical ensemble of sources is determined by:

$$h = -\frac{s}{4\pi}$$

Where h is depth and s is the five-point average of the slope of the energy spectrum (Spector & Grant, 1970).

There is a spectral peak between wavenumbers of 0 $cycles/metre$ and 0.0002 $cycles/metre$. This is due to contribution from deep seated sources at a depth of approximately 1600 m from depth estimate graph. The spectral peak between wavenumbers 0.0006 $cycles/metre$ and 0.0008 $cycles/metre$ is due to shallow near surface sources contribution at a depth of approximately 250 m.

From Figure 3,

Mean deep source depth = $1.61km$

Mean shallow source depth = $0.25km$

The basal depth z_b which was assumed to be the curie point depth (Okubo, Graf, Hansen, Ogawa, & Tsu, 1985) was calculated from this equation.

$$z_b = 2z_0 - z_t$$

Where,
z_0 is mean depth to the deep source body
z_t is mean depth to the shallow source body
z_b is the curie point depth.

$$z_b = (1.6 \times 2) - 0.25$$
$$= 2.4 - 0.25$$
$$= 2.15\ km = 2150m$$

The curie point isotherm depth for the study area was determined to be approximately $2150\ m$. This implies a shallow geothermal heat source. Curie point isotherm depth is the depth where magnetism of materials disappears due to high temperatures. The temperature at which magnetism of materials disappears is called curie temperature. Minerals exhibit variation in curie temperatures and this results to rocks having different curie point temperature due to different minerals present in their composition. In this study area, there is high potential for geothermal heat source because if the curie point isotherm depth is approximately $2150m$, then the temperatures at this depth must be above 130℃. For example,the curie temperature for titanomagnetite varies from 463℃ to 580℃ in an area mostly occupied by granite rhyolite rocks(Reynolds, 1998). For an area mostly occupied by ilmenite hematite rock, the curie temperature varies from 130℃ to 220℃.

Oxidation of iron titanium oxides usually causes an increase in curie temperature(Reynolds, 1998). The intensity of magnetisation reduces when oxidation takes place at lower temperatures for example temperatures less than 300℃. Titanomagnetite converts to titanmaghemite then finally to magnetite with curie temperature of550℃ − 580℃ because of oxidation and decrease in intensity of magnetisation(Reynolds, 1998). In this study area, the temperature at curie point isotherm depth of approximately $2150m$could be in the range of 550℃ − 580℃ if complete oxidation took place to change titanomagnetite mineral to magnetite mineral. If oxidation did not take place, then the temperatures at curie point isotherm depthwould be less than 550℃.Minerals are made up of atoms and if these atoms are chemically stable, oxidation cannot occur.

Hematite has very high curie temperature which ranges from 650℃ to 680℃ and lowest intensity of magnetisation. In this study area, there is low magnetisation intensity which could be due to alteration of high magnetic intensity minerals to hematite with lowest intensity of magnetisation because of oxidation and hydrothermal alteration. These are areas with high temperature hence a geothermal heat source.

II. Discussion and Conclusion

Spectral analysis of ground magnetic data of Eburru area indicates curie point isotherm depth at approximately 2150m. This implies the magnetism of rocks present beneath the Earth's surface at Eburru area disappears averagely at this depth. The temperature at curie point isotherm depth is called the curie temperature. The curie temperature varies depending on the type of rocks present in the Earth's crust at this depth. Rocks are classified as diamagnetic, paramagnetic or ferromagnetic depending on their magnetism(Telford et al., 1990). Above the curie temperature, rocks cease to exhibit magnetic behaviour.

The circular movement of electrons around the nucleus and their spin causes magnetic moments in atoms(Parasnis, 1986). From quantum theory, two electrons spinning in opposite directions can be in the same electron state andsuch two electrons are called paired electrons.The paired electrons generate zero magnetic moment because individual magnetic moment contributions cancel out. When there is an external applied magnetic field such as the Earth's geomagnetic field, the spin magnetic moments of neighbouring atoms are aligned uniformly thus generating overall magnetisation.

There are no unpaired electrons in diamagnetic minerals such as halite hence all the electron shells are complete(Kearey, Brooks, & Hill, 2002). Magnetisation is induced when an external magnetic field is introduced for example, the Earth's geomagnetic field.Negative magnetic susceptibility arises because electrons revolve in a manner which produces a magnetic field that resist the applied field.

There are unpaired electrons in paramagnetic minerals for example fayerite, amphiboles, pyroxenes, olivines, garnets and biotite(Reynolds, 1998). This results into incomplete electron shells that generate unbalanced spin magnetic moments among atoms of paramagnetic minerals. When an external magnetic field such as the Earth's geomagnetic field is introduced, the magnetic moments organise themselves in line with the direction of an applied magnetic field. These produces a weak positive anomaly which reduces as the temperature of the materials increases. This is in agreement with the curie-weiss law(Reynolds, 1998). During spectral analysis of magnetic data paramagnetic materials generate a bigger anomaly than diamagnetic rocks.

The temperature and the strength of the applied magnetic field affects the magnetic susceptibility of ferromagnetic minerals.Interaction among the neighbouring atoms and overlap of electron shells causes the spin moments of unpaired electrons to join together magnetically. These results to magnetic moments being aligned parallel or antiparallel. The magnetic coupling can be in a such way that the magnetic moments are aligned either parallel or antiparallel.

Genuine ferromagnetic minerals such as cobalt, nickel and iron(Reynolds, 1998)do not occur commonly but can be found in some areas. These ferromagnetic minerals have parallel arrangement of magnetic moments. When the temperature of a ferromagnetic mineral rises above the curie temperature T_C, the dipoles are disorganised and the mineral ceases to exhibit ferromagnetic propertiesthus showing Paramagnetic behaviour.

The magnetic moments of antiferromagnetic minerals are antiparallel to one another for example hematite(Telford et al., 1990).The overall magnetic moment of antiferromagnetic mineral is zero because the magnetism of dipoles in opposite directions cancel each other.The dipoles in ferrimagnetic minerals are antiparallel and unequal which generates a resultant magnetisation. Common examples of ferrimagnetic minerals include magnetite, titanomagnetite and Ilmenite(Parasnis, 1986).Ferrimagnetic minerals are characterised by spontaneous magnetisation and large magnetic susceptibilities for example pyrrhotite. Above the curie temperature ferrimagnetic minerals ceases to possess magnetic behaviour. Common magnetic rocks occurring within the Earth's crustare either ferrimagnetic or antiferromagnetic.

Therefore, in this study area, the curie temperature varies depending on the type of rocks present within the Earth's subsurface and their oxidation process. Ageothermal isotherm depth of $2150m$ is a shallow depth with curie temperaturerange of between$130℃$and $680℃$which can be classified as an accessible geothermal heat source.Eburruis a volcanic area commonly occupied by granite rhyolite rocks. This implies the curie temperature at this curie point isotherm depth could range between $463℃$ and $580℃$ depending on oxidation process of titanomagnetite mineral. If titanomagnetite is oxidized to titanmaghemite and finally to magnetite, then the curie temperature at this depth varies from $540℃$to $580℃$. The average depth of geothermal wells range from 1500m to 3000m (World Energy Council, 2013). The isotherm depth in this study area which is approximately 2150m is within the range and can be easily accessed by meteorite water hence a geothermal resource can be developed. Residual map in Figure 2 reveals massive basic igneous intrusions in form of dykes and sills within the Earth's subsurface which could be heat sources. Figure 2 also images underground conduits that dictate fluid movement beneath the Earth's surface that is paramount in characterizing a geothermal resource.This enables surface and underground water to reach heat sources. The availability of these conduits within the study area also reveals a lot of underground convectional movement of hot fluids.

III. Recommendation

This study recommends shallow heat flow measurements to determine heat flux for the area. Heat flux can be used to estimate the temperature at curie isotherm depth and characterize the type of rocks at this depth.

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