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Estimation of Heat Flow from Spectral Analysis of High Resolution Airborne Magnetic Data in Ilesha and its Environs, Southwest Nigeria

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Abstract

This study presents an analysis of High-Resolution Airborne Magnetic Data (HRAMD) over Ilesha and its environs situated on geographic latitude 7°30'N to 8°00'N and geographic longitude 4°30'E to 5°00'E. The work presents the structural and quantitative interpretation of airborne magnetic data (Sheet No.243), which was acquired from the archive of Nigerian Geological Survey Agency (NGSA). The study is aimed at determination of Curie Isotherm region in Ilesha south-west Nigeria using filtering of source spreading of magnetic sources and spectral analysis (matched filtering) of aeromagnetic data. The magnetic data were subjected to Fast Fourier Transform which transforms HRAMD from its space domain to wave number domain. The HRAMD were divided into 25 equal overlap blocks. The finding outcome reveals that the depth to the bottom of magnetic anomaly sources (DBMS) varies between 16.48 km and 41.47 km. Subsequently, the variation of geothermal gradient ranged between 13.98°C/km and 35.20°C/km, while estimated values of the resulting heat flow in the study area vary between 34.96 W/m and 87.99 W/m. However, this study is crucial for structural thoughtful of the geo-processes and rheological parameters in delineating geothermal regime within the under study because the thermal structure of the earth's crust is one of the leading parameters scheming geodynamic methods.

***Keywords**: Aeromagnetic; Airborne, Geothermal; Magnetics; Regional and Spectral.*

1. Introduction

High-Resolution Airborne Magnetic (HRAM) survey is the collection of magnetic data over a large expanse of the area by small aircraft and interpreting the data using several interpretational techniques [1]. HRAM surveys have a resolution in the nanotesla scale such that in addition to adequately mapping magnetic rocks which can be adopted to map intra-sedimentary faults segment with elevated magnetic minerals deposit concentration that generates small variation in the anomalies [2-3]. The magnetometer measured logged tiny variations in the intensity of the ambient magnetic field due to the effect of temporal constantly varying solar and spatial variations in the earth's magnetic field as the aircraft flies. This is due to both the regional magnetic field, and the local effect of magnetic minerals in the earth crust. The correction done by subtracting the solar and regional effects, the resulting airborne magnetic map shows the spatial circulation and comparative great quantity of magnetic minerals in the upper levels of the crust. Airborne magnetic surveys offer a nippy means of geological mapping. The magnetic data give information about geological patterns at depth about the metamorphic basement on which younger sedimentary rock lies, and channel light on the presence of major structures which could have influenced its development. Surveys of the spatial changes in the strength of the magnetic field over the surface of the earth have been used as a method for geophysical exploration for many decades [4]. The magnetic method has come into use for identifying and locating masses of igneous rocks that have a relatively high concentration of magnetic minerals (magnetite). Magnetite is the most common ferromagnetic mineral, and in most cases, the magnetic permeability is determined by the amounts of magnetite and related minerals available in the rock.

Subsequently, adequate information of the earth's interior thermal configuration is significant in geodynamic and geothermal inquiries [5-6]. Direct crustal temperature measurements are not substantial for regional studies; hence the depth to Curie-temperature avails for estimating the temperature at depth [6-8] which match up to the temperature at which magnetic minerals lose their ferromagnetic properties, and for regional-scale studies which it occurs can be inferred as the Curie Isotherm depth. Several researchers [6, 9-27] have presented the Depth to the Bottom of Magnetic Sources (DBMS), which could also considered as the Curie-point depth (CPD) and can be probable estimated from the analysis of regional magnetic data where various rocks loose its ferromagnetic natures (properties) due to an increase in temperature variation in the crust which will aid the heat flow [8,19].

The DBMS is an imperative factor in understanding the temperature distribution in the crust and the rheology of the Earth's lithosphere [25]. The main objective of heat flow measurements is to estimate the amount of heat energy being lost by natural process. The loss of high heat anomalies usually coincides with the trend of the structural geological features or extents with high thermal manifestations regime [3].

An assessment of DBMS in gridded blocks in the area would meaningfully compliment the available geophysical information and also add value to the thoughtful of the geothermal regime, crustal depiction, and geodynamic evaluation processes in Ilesha and its environs. The main objective of heat flow measurements is to estimate the amount of heat energy being lost by natural process. High heat loss anomalies usually coincide with the geological structural trend or areas with high thermal manifestations [3].

The present study is an attempt towards analyzing High-Resolution Airborne of Ilesha to estimates Depths to the Bottom of Magnetic Sources (DBMS) and ensuing geothermal parameters in order to inferred geothermal regime within different blocks.

2. Description and geology of the study area

Ilesha and its environ is situated in Osun State, Southwestern Nigeria. Ilesha is bounded in North by Kwara, in the south by Ondo, in the east by Ekiti and west by partly Oyo state. The area is located within geographic latitude 7°30'N to 8°00'N and geographic longitude 4°30'E to 5°00'E covering an area of about 3025 km^2. Ilesha lies within the tropical climate marked by wet and dry seasons with an average elevation of 391m above sea level. The average daily temperature varies between about 20°C for a very cold day to about 35°C for a very hot day [28].

Ilesha is situated within the Nigeria Basement Complex of south-western Nigeria. The Ilesha and its surroundings lie in the Basement Complex of the Southwest Nigerian [29]. The formation is a pre-drift sequence of continental sands, grits, and silts (Figure 1). In 1953 and 1957, [30-31] proposed that the Nigerian Basement Complex rock is Polycyclic. In 1970 Hurley confirmed the rock ages using radiometric approach. The main rock associate Ilesha and its environ made up of a fragment of the Proterozoic schist straps in Nigeria. The geological formation of Ilesha and its environs comprise of Precambrian rocks that are typical for the basement complex of Nigeria [32]. Regarding the structural geological features, lithology, and mineralization, the schist belts of Nigeria display considerable resemblances to the Achaean Green Stone Belts [32-33].

3. Methodology

3.1. Data acquisition

In August 2009, a nationwide regional High-Resolution Airborne Magnetic (HRAM) data were acquired in Nigeria by Fugro Airborne Survey Limited United State of America for the Geological Survey Agency of Nigeria. This acquisition, processing, and compilation of the new data sets were jointly sponsored by the Federal Government of Nigeria and the World Bank as part of the Sustainable Management for Mineral Resources Project (SMMRP). The airborne magnetic surveys, using 3x Scintrex CS3 cesium vapour magnetometers (resolution of 0.1 nT) with a data recording interval of 0.1 seconds, were done by means of Fixed-wing aircrafts flown at mean terrain clearance of 80m with 500 m line spacing and nominal tie-line spacing of 5000 m along series of NE-SW. The flight line and tie-line trends were 135 and 45 degrees respectively.

The average magnetic inclination, magnetic declination, and magnetic field strength across the survey were 14.02^0, 3.83^0 and 32,446.006 *nT* respectively. Map of the study area under consideration is published on a scale of 1:10000 (that is 1 cm = 1 km on the ground). The topographical detail of the map was based on 1: 100000 topographical series of Federal Surveys of Nigeria.

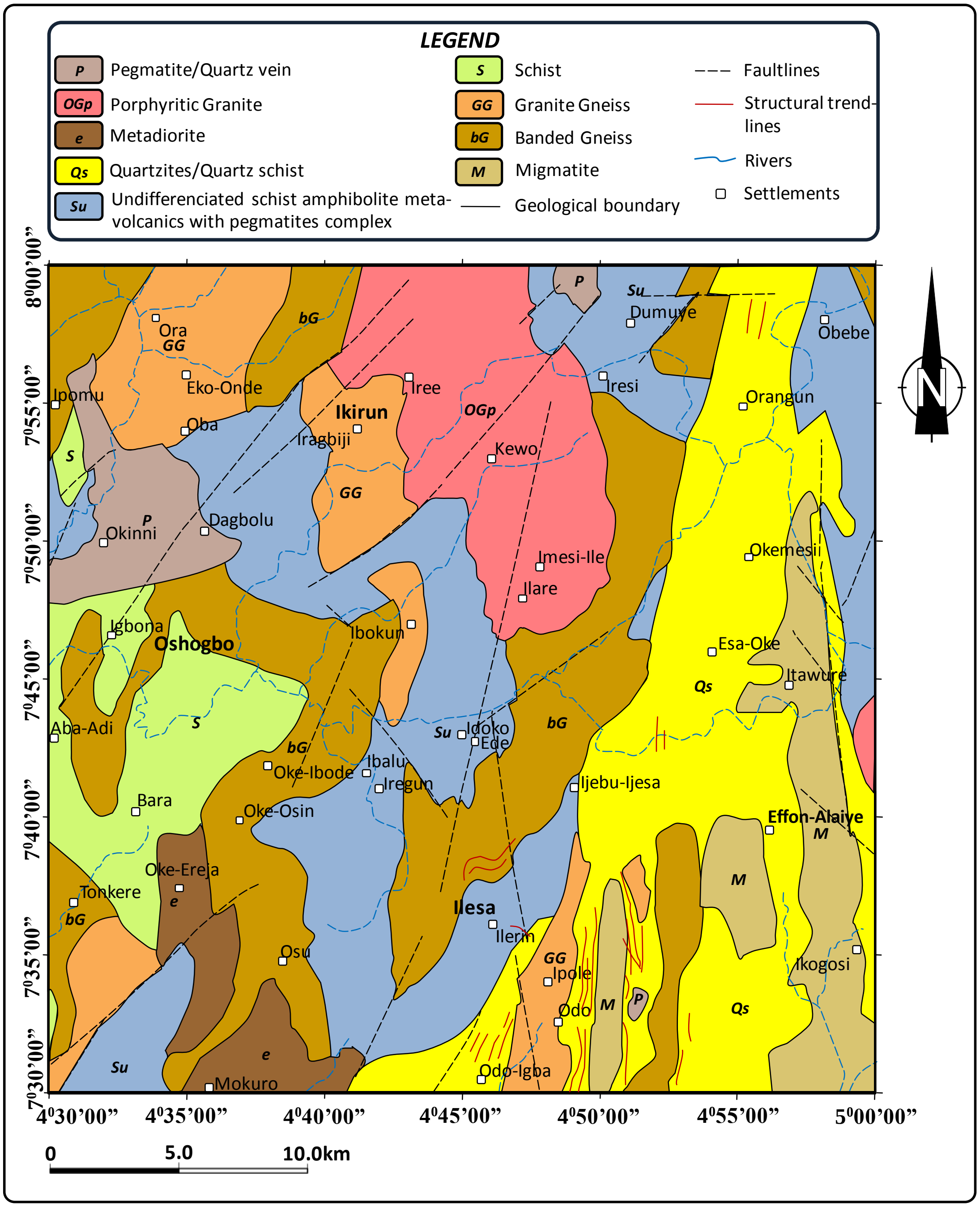

Figure 1. Geological Map of Ilesha and its Environs (Adapted from NGSA 2009)

3.2. Estimation of depth to the bottom of magnetic sources (DBMS)

Power Spectrum analysis of potential field data has been in used over the years to estimate the depth of definite geological features, such as magnetic basement [9,15,34-37]. Two-dimensional (2-D) spectral analyses of the potential field data have been used extremely over the past Four (4) decades to estimate the depth of target sources of anomaly [9,33]. Spectral depth analysis is based on the principle that a magnetic field measured at the surface can be considered as the integral of magnetic signatures from all depths [38]. The power spectrum of the apparent field can also be used to evaluate the average depth of anomalies source ensembles.

Several robust approaches have been employed in the estimation of DBMS [8-9,11,16,18,21,25]. The modified centroid method recently developed by [8] was adopted in this presented study. The adoption of conservative centroid method to evaluate DBMS is built on the spectral analysis of the target anomalies of the magnetic field [14,19]. Application of spectral analysis technique to infer magnetic anomalies have been expansively described by [9-11,37]. They validated that contributions from the source parameters; depth, width and thickness of a magnetic source ensemble could disturb the shape of the power spectrum. The principal term, which pedals the spectral shape, is known as the depth factor. The power spectral density (P(k)) and DTMS (Zt) are related by the expression proposed by [9,19].

The Discrete Fourier Transform is the mathematical tool for spectral analysis and applied to regularly spaced data such as the aeromagnetic data is given by Equation 1.

$$g(x) = h_0 + \sum_{n=1}^{\infty}\left(h_n \cos\frac{n\pi x}{J} + i_n \sin\frac{n\pi x}{J}\right) \qquad (1)$$

In 1995, Blakely [16] introduced the power density spectra of the total field anomaly $\Phi_{\Delta\mathrm{T}}$.

$$\Phi_{\Delta\mathrm{T}}(K_x, K_y) = \Phi_{\mathrm{M}}(K_x, K_y) F(K_x, K_y) \qquad (2)$$

$$F(K_x, K_y) = 4\pi^2 C_m^2 |\Theta_{\mathrm{T}}|^2 |\Theta_{\mathrm{G}}|^2 \mathrm{e}^{-2|\mathrm{k}|\mathrm{Z_t}}(1-\mathrm{e}^{-|\mathrm{k}|(\mathrm{Z_b}-\mathrm{Z_t})})^2 \qquad (3)$$

where Φ_{M} is the spectra power density of the magnetization, C_m is a proportionality constant, and Θ_{T} and Θ_{G} are factors of the direction of the magnetization and geomagnetic field direction, respectively.

Equation 3 can be simplified noting all terms, except $|\Theta_{\mathrm{T}}|^2|$ and $|\Theta_{\mathrm{G}}|^2$,which are radially symmetric. Moreover, the radial averages Θ_{T} and Θ_{G} are constant. If M(x, y) is downright random and uncorrelated, $\Phi_{\mathrm{M}}(K_x, K_y)$ is a fixed constant. Hence, the radial average of $\Phi_{\Delta\mathrm{T}}$ is given by equation 4,

$$\Phi_{\Delta\mathrm{T}}(|k|) = Ae^{-2|k|Z_t}(1-\mathrm{e}^{-|\mathrm{k}|(\mathrm{Z_b}-\mathrm{Z_t})})^2 \qquad (4)$$

where A is constant.

In the case where wavelength less than about twice the thickness of the layer, Eq. (4) becomes:

$$\ln\left[\Phi_{\Delta T}(|k|)^{\frac{1}{2}}\right] = \ln \mathrm{B} - |\mathrm{k}|\mathrm{Z_t} \qquad (5)$$

where B is a constant.

The top bound of a target magnetic source could be evaluated from the slope of the power spectrum of the total field anomaly graph plotted against the wavenumber. Thus, Equation 5 can be written as:

$$\Phi_{\Delta\mathrm{T}}(|k|)^{1/2} = Ce^{-|k|Z_0}\left(\mathrm{e}^{-|\mathrm{k}|(\mathrm{Z_t}-\mathrm{Z_0})} - \mathrm{e}^{-|\mathrm{k}|(\mathrm{Z_b}-\mathrm{Z_0})}\right) \qquad (6)$$

where C is a constant. At long wavelengths, Eq. (6) is:

$$\Phi_{\Delta\mathrm{T}}(|k|)^{1/2} = Ce^{-|k|Z_0}\left(\mathrm{e}^{-|\mathrm{k}|(-\mathrm{d})} - \mathrm{e}^{-|\mathrm{k}|(\mathrm{d})}\right)$$
$$\approx Ce^{-|k|Z_0}2|k|d, \qquad (7)$$

where 2d is the wideness of the magnetic anomaly source. From Eq. (7)

$$\ln\{[\Phi_{\Delta\mathrm{T}}(|k|)^{1/2}]/|k|\} = \ln D - |k|Z_0 \qquad (8)$$

where D is a constant, the top bound as well as the centroid of the magnetic source could be evaluated by fit a straight line through the high wavenumber and low wavenumber portions of the averaged radially spectrum of $\ln\left[\Phi_{\Delta T}(|k|)^{\frac{1}{2}}\right]$ and $\ln\{[\Phi_{\Delta\mathrm{T}}(|k|)^{1/2}]/|k|\}$ from Equation 5 and 8 respectively.

A plot of the power spectrum versus wavenumber usually shows straight-line segment which related to decreasing in gradient with increasing wavenumber, and the gradient of the sections provide give estimates of the depths to the magnetic sources causing the magnetic anomaly is calculated using equation 9

$$Z_t = \frac{\ln \Phi_{\Delta T}(k_{i+1}) - \ln \Phi_{\Delta T}(k_i)}{2(k_{i+1}-k_i)} \quad (9)$$

Relationships from the outspread wavenumber curves, where $\Phi_{\Delta T}$ is the magnitude of pthe ower spectrum of the filtered magnetic data (RTP), k is the angular frequency and Z is the depth of the anomaly target sources.

Then, Curie point depth (Z_b) of the target magnetic sources in the area under consideration evaluated using equation 10 proposed by [11,14] and the graphs of the Logarithms of the Power spectral density for blocks using potential field package [39] as presented in Table 1.

$$Z_b = 2Z_0 - Z_t \quad (10)$$

Table 1. Estimate of Curie point depth and succeeding geothermal parameters

Block	D1(Residual)	D2 (Regional)	Zb(m)	q(Heat Flow)	dT/dZ
1	1.164863	1.329567	1.329567	1090.58	436.2322
2	1.166454	1.300923	1.300923	1114.593	445.8373
3	1.000955	1.902451	1.902451	762.1748	304.8699
4	0.905474	1.421069	1.421069	1020.358	408.1433
5	1.000955	1.7831	1.7831	813.1905	325.2762
6	1.028008	1.591343	1.591343	911.18	364.472
7	0.936505	1.591343	1.591343	911.18	364.472
8	0.926	1.421069	1.421069	1020.358	408.1433
9	0.926957	1.421069	1.265913	1145.418	458.1672
10	1.089274	1.459262	1.459262	993.6532	397.4613
11	1.097231	1.578612	1.578612	918.5282	367.4113
12	0.506525	2.248568	2.248568	644.8549	257.942
13	0.826703	1.46324	1.46324	990.9516	396.3806
14	0.932527	1.989179	1.989179	728.944	291.5776
15	1.144971	1.674093	1.674093	866.1407	346.4563
16	1.10837	1.344685	1.344685	1078.32	431.3278
17	0.821133	1.275461	1.275461	1136.843	454.7374
18	0.795672	1.530076	1.530076	947.6651	379.066
19	0.971515	1.736155	1.736155	835.1787	334.0715
20	0.760582	1.764799	1.764799	821.6231	328.6492
21	0.663033	1.193507	1.193507	1214.907	485.9627
22	0.82909	1.637492	1.637492	885.5005	354.2002
23	0.783259	1.856302	1.856302	781.123	312.4492
24	0.962763	2.188097	2.188097	662.6764	265.0705
25	1.363781	1063.221	1.363781	425.2882	142.8101

3.3. Calculation of the geothermal gradient and heat flow

In order to obtain geothermal gradient and heat flows, simple relation for conductive heat transport (Fourier's law) [6,19-42] was adopted. In the case of 1-dimensional using the assumptions that the variation in temperature direction is vertical and the gradient temperature is constant, the law takes the form as presented in Equation 11

$$q = -K\frac{dT}{dZ} \quad (11)$$

where k and q is the coefficient of thermal conductivity and heat flux magnitude respectively

According to Tanaka *et al.* [19], the Curie temperature (T_c) can be obtained from the Curie point depth Z_b, and the thermal gradient is given as Equation 12,

$$T_c = \frac{dT}{dZ} Z_b \qquad (12)$$

Substituting Equation 12 into Equation 11, it gives equation 13,

$$Z_b = -K\frac{T_c}{q} \qquad (13)$$

In 1999, Tanaka *et al.* [19] revealed that the thermal isotherm is inversely proportional to heat flow, where q is the heat flow at any certain depth. Equation 11 indicates regions of high heat flow are associated with shallower isotherms; however regions of lower heat flow are associated with deeper isotherms [6]. Mean shallow heat flow value will compute using Equation 11 and will be based on possible Curie point temperature of 580°C using a thermal conductivity of 2.978 $Wm^{-1}°C^{-1}$, given by [43] and adopted as the [19,40-41] average for igneous rocks.

The results of the plot of the logarithm of the Power spectrum against wavenumber. Evaluating the slopes of the graphs, the average depths to the magnetic basement for each of the 25 blocks were calculated using Equation 9, and the results are presented in Table 1.

4. Result and discussion

The quantitative interpretation was adopted for the interpretation of airborne magnetic in Ilesha, and its environ with the aim of estimating Depths to the Bottom of Magnetic Sources (DBMS) and ensuing geothermal parameters in order to inferred geothermal regime within the different block. Generally, the variations in the earth's magnetic field intensity magnitude are presented in Figure 2.

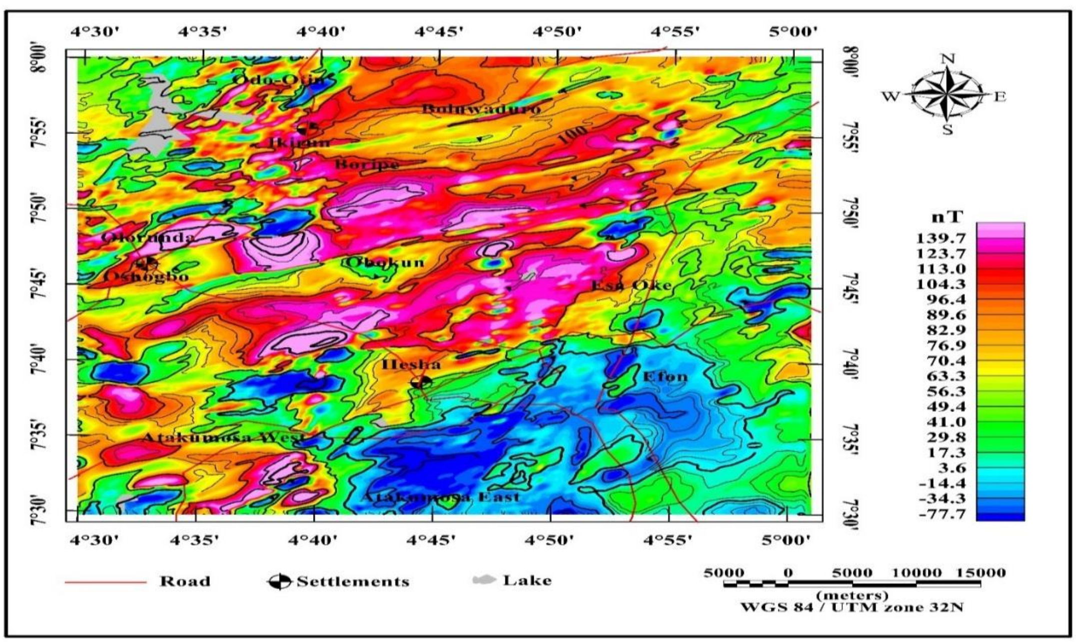

Figure 2. Total magnetic intensity map of the study area

The magnetic intensity value of the field ranged from -77.7 to 139.7 nT. Total magnetic field intensities map indicates high magnitude magnetic intensity values in the north, east, parts of the west and the central mapped area. Regions of magnetic lows (low amplitude magnetic anomaly) and highs (high amplitude anomaly) are apparent on the magnetic map. The defined magnetic highs and lows as visible on the map are in real sense relative. The north-eastern part of the study area is characterized by high intensity which related to lithological variation in the basement. The sharp contrast is enhanced due to sharp magnetic intensity contrast between the crystalline and the sedimentary rocks magnetic susceptibilities. Spectral energy peaks which were clearly noticeable in graphs of the logarithms of the spectral energies against wavenumbers were plotted for each block, and the connotation of this is the indication of the fact that Curie temperature isotherm depths are demonstrable as it defines the target source bottoms., from which Curie point depths (Isotherm depth) were evaluated, and the depth to the Centroid (Z_0) ranges from 9.77 km to 22.51 km.

On the other hand, the values of depth to the top (Z_t) of magnetic sources ranged from 2.51km to 4.72km as presented in Table 1. The corresponding curie depth ranges from 16.47 km to 41.47 km, these values were in agreement with earlier work by [41]. The calculated values of Curie point depth (CPD) obtained reveal the mean local curie depth point values below each block. The estimated Curie point depths values for the blocks were used to create Curie isotherm in the Ilesha (Figure 3). The CPD reveals the innumerable depths to curie points which define the thermal nature of the Earth crust. Previous studies by [41,44-48] presented that the geological context of an area is linked to the Curie point depth.

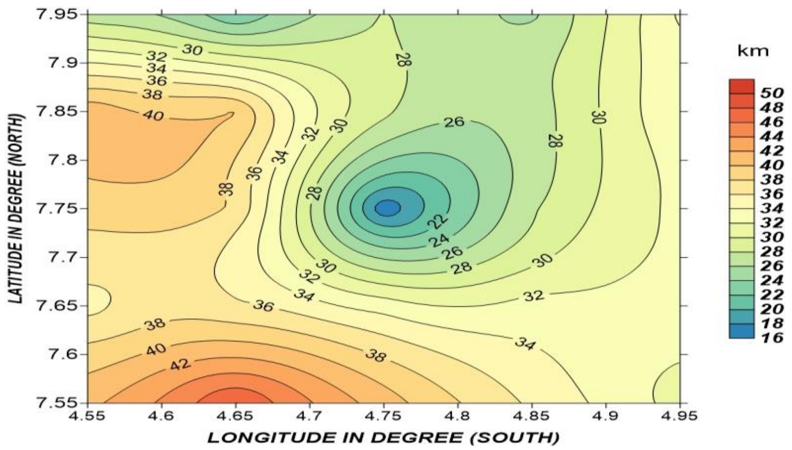

Figure 3. Curie point Depth (Curie Isotherm) map of the Ilesha and its environs

Using a standard value of Curie temperature of Igneous rock (magnetite, 580°C) and the estimated depth to bottom (Curie point depths), variation in a geothermal gradient within Ilesha and its environs were evaluated from where the geothermal gradient map was generated as shown in Figure 4. This is linked to the heat flow map (Figure 5), meaning that most areas of high heat flow relate to high geothermal gradient as shown in Figure 4

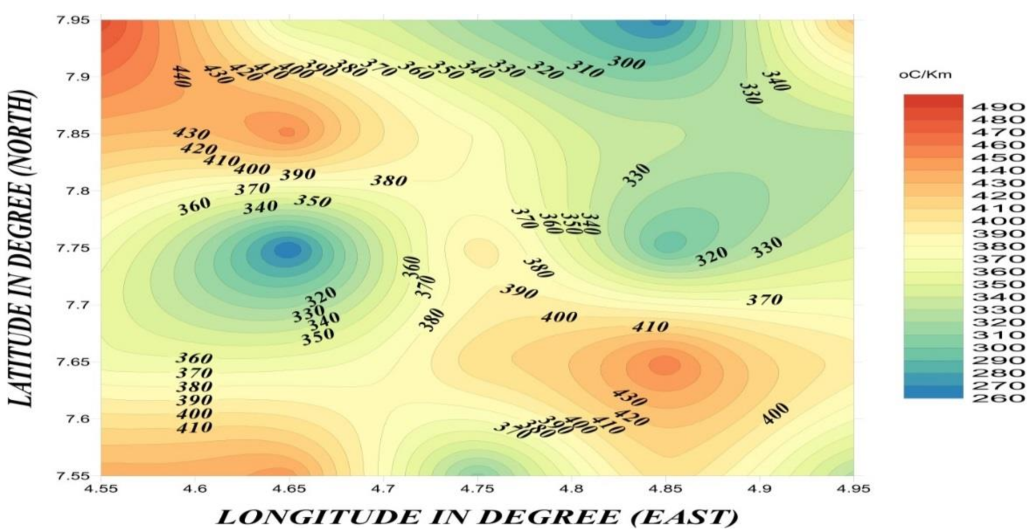

Figure 4. Geothermal gradient map of Ilesha and its environs

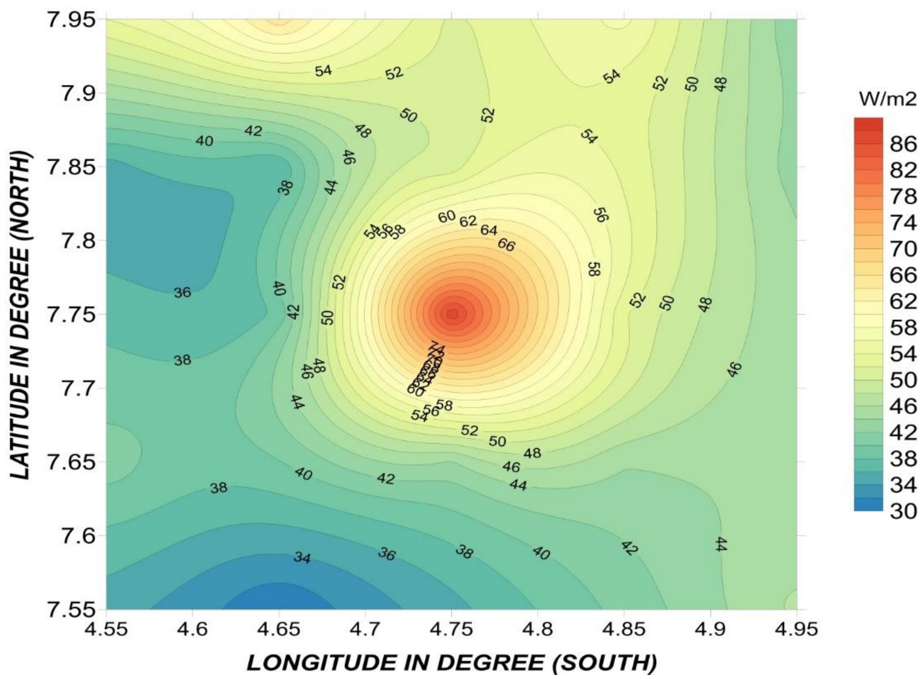

Figure 5. Heat flow map of Ilesha and its environs

Analysis of the potential field data in conjunction with heat flow values using Power spectral has shown a virtually inverse linear correlation between heat flow and Curie depths. The relationship was used to construct the Curie isotherm regime from the current data. It was noticed from the heat flow map of Ilesha were found to be less than 60 mWm^{-1}. This suggests that the heat flows in Ilesha are not uniform, which conceivably designate that the magma tubes were indiscriminately distributed.

The mean heat flow values using Curie point depth were derived from Equation (11) with the average thermal conductivity k.

The mean heat flow obtained for Ilesha and its environs is 46.008 Wm^{-1} which may possibly be painstaking as distinguishing of continental crust. Most of the recent literature state that the heat flow and Curie point depth is greatly reliant on upon geological situation. In geothermal exploration heat flow is the primary observable parameter in geothermal exploration. Generally, the units that comprise of high heat flow values correspond to metamorphic regions since the rock unit has high heat conductivity [48]. Therefore the finding makes the study area to have geothermal regime potentials.

5. Conclusion

High resolution airborne geophysical approach was used to delineate the subsurface structure of the studied area (Ilesha and its environs) in order to determine geothermal regime using power spectral analysis of magnetic data. The result of the finding using power spectrum display clearly the variant along the blocks in the magnetic basement across the study area. The source depth of the deeper (regional) sources ranges from1.19 km- 2.25 km and is assumed to relate to the apparent of the magnetic basement in the Ilesha and its environs. The shallower depth of anomaly, ranging from 0.45km to 1.165km might denote main magnetic components, to improved basement apparent magnetic structures. The CPD for Ilesha and its environment estimated using HRAD via filtering technique (Power Spectrum). The end result divulges that the CPD be at variance contrariwise with heat flow. The inference drawn from the output results show that CPD acquired in all blocks ranges from 16.479 km to 41.47 km which stemmed from the emergence of the asthenosphere. The obtained results compared favorably in agreement with earlier work done (Nur *et al.* [49]). The mean heat flow value acquired is 46.008 Wm^{-1} which can be utilized for exploration of substitute source of geothermal energy. The analysis of HRAD investigate the extent to Curie Point Isotherm (CPI) and heat flow anomaly over Ilesha and its environs, added greatly to the improved understanding of geothermal anomaly regime in this study which indications a prospect for geothermal possibilities to reconnoiter for new and more energy locations in Nigeria.

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