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Radially Average Power Spectrum and Curie Isotherm from High Resolution Aeromagnetic Data, Over Upper Benue Trough, Northeastern Nigeria

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ABSTRACT

Data corresponding to high-resolution Aeromagnetic surveys obtained at the various positions across the upper Benue trough in northeastern Nigeria have been used to estimate Curie isotherm depth, and to create the radially averaged power spectrum. Processing and management of data were performed in Oasis Montaj TM software, which allowed obtaining the Total Magnetic Intensity (TMI) and the residual magnetic anomaly maps. These maps formed an approximation to estimating the depth to the Curie isotherm and analyzing the radially averaged power spectrum. The depth extent is shown on the power spectrum analysis as shallow magnetic sources are between 0.16 and 1.13 kilometers, and deeper sources between 0.2 an+d 4.04 kilometers. The deep source, which displays the maximum thickness of sediments in the area, is caused by a deep-seated basement, whereas the shallow source depth is most likely the result of near-surface or shallow intrusions. The Curie depth result, which varies from 16.55 to 23.05 kilometers, represents the average local Curie temperatures recorded throughout the study area. The regions of Biu, Dumne, Shani, Yola, and Mayo Belwa were found to have high curie depths, respectively. It is thought that active metasedimentary volcanic activity and crustal thinning beneath the sub-basin are the causes of the Curie isotherm's change across the trough. The variation of the Curie shows how important mantle plume activity is at the beginning of rifting in the upper Benue valley isotherm across the trough.

Keywords: Spectrum, Aeromagnetic, Total Magnetic Intensity.

1 Introduction

Higher Aeromagnetic data covering the upper Benue valley of northern Nigeria were used to calculate the Curie isotherm and the radially averaged power spectrum. The total magnetic intensity map was processed by Oasis Montaj software as a first step towards generation of a residual magnetic map whose Curie isotherm depth, along with that of radially averaged power spectrum, was thereafter derived. The area of study is across a total area of about 48,400km^2 towards the latitude of 09′ 00″N and 11′00″E and longitude of 10′30″N and 12′30″E. The upper part of the Benue Trough, which is one of the most notable aspects in the greater field of the Benue Rift system, divides into the Yola arm (east-west) and the Gongola arm (north-south). It is a linear Cretaceous sedimentary basin, which reaches far down in the center of the African continent, and is directly linked with the tectonic processes behind the separation of the African plate and that of South America. Although some scientists like Sengör [1] see the basin as an Aulacogen, which is part of a three-armed rift system, some ascribe that it is a true rift with comparisons to the Afar region in northeast Africa. The Trough is also an important part of the Benue Rift, and it is made up of two almost parallel branches being the Yola arm and the Gongola arm, which run east-west and north-south, respectively. Stratigraphically, several depository cycles are observed in the basin due to the deposition of the rocks of various lithologies over the period between Albian and Maestrichtian stages. The basin lies over the complicated basement of which three main units stand out, namely, the Migmatite-Gneiss complex, basal igneous rocks, and older granitic rocks (see Fig. 1).

2 Literature Review

Oceanic and continental Curie depths tend to be less deep in general, and the depths of continents exhibit bimodal distribution with shallow locations in ancient cratons. Hydrothermal activity and thermal variation affect oceanic depths with concentration at spreading centers and is associated with the flow of heat, and is in agreement with the theoretical values of thermal conductivity. In general, the average heat flow on the planet is approximately 70 mW/m², which equals about 34.6 to 36.6 TW heat loss, and has implication on the thermal/geologic processes of the planet [2]. Spectral analysis of Aeromagnetic data was used to estimate Curie point depth, heat flow and geothermal gradients in the eastern part of Kerman providing varying depths of 8.5-18.2 km, geothermal gradient of 31-67 o C/km and heat flow of 139-294 mW/m. The most superficial depths are aligned to volcanic and hot spring locations, which implies that there is a great potential of geothermal use to explore sustainable energy in this region [3]. High-resolution Aeromagnetic data and spectral centroid analysis were employed to provide estimates of the Curie-point depths (CPDs), geothermal gradients and crustal heat flow in Shelleng and near environments in northeastern Nigeria. The analysis of the data in overlapping blocks revealed CPDs between 4.95 and 7.69 km (average 6.69 km), 47.23 to 86.57 °C/km (average 58.73 °C/km) geothermal gradient, and 21.13 to 216.43 mW/m^2 (average 166.72 mW/m^2) heat flow. The results indicate that thermal structure of the Earth has a major effect on geodynamic processes in the region, heat flux variations and rheology of the crust in the region [4]. The analysis of Aeromagnetic anomalies measured in the Ikogosi Warm Spring

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region, Nigeria, was used to estimate Curie point depth (CPD) and showed shallow depths of about 15.1 km, which indicated enormous heat flow (~91.2 mW/m²) and possible geothermal activity. Magmatic intrusions, faults and fractured rocks have been identified to contribute towards the shallow CPD and also associated with seismic activity and the existence of warm springs. The results have indicated that the geothermal regime is abnormal due to lack of temperature data at depth, and that consequently further borehole temperature data would be necessary to further investigate the thermal and geological qualities of the crust to explore geothermal energy [5]. In this work, spectral analysis of high-resolution Aeromagnetic data of Shelleng region, northeastern Nigeria, was performed to conduct a regional evaluation of depth of the Curie-point (CPD), subsurface heat flow, and geothermal gradient. The analysis indicated CPD depths of between about 7.56 and 18 km with an average of about 11.72 km and geothermal gradients of between 52.76 and 191.8°C/m. The shallow CPD zones within the specific regions will relate to the geothermal gradients and the heat flow which implies that there are probable zones of the irregular thermal activity that can be explored as sources of geothermal energy. The results indicate the areas of focus in future geothermal energy development and give insights into geothermal depth thermal conditions with respect to the geological structure of the region [6]. High-resolution Aeromagnetic data processed with Oasis Montaj to estimate the Curie point depth, geothermal gradient, and heat flow in the Biu Plateau and surrounding areas of northeastern Nigeria, aiming to identify an alternative power source through geothermal energy. Spectral analysis of four overlapping blocks revealed that the depth to the top boundary ranges from approximately 5.90 to 7.16 km, while the depth to the centroid varies between 10.5 and 11.5 km, with the Curie depth averaging around 15.50 km. The calculated geothermal gradient (average of 37.53°C/km) and heat flow (average of 93.83 mW/m²) indicate significant geothermal potential, consistent with the area's geological setting as a plateau, making it a promising site for geothermal energy exploration to support power generation in Nigeria [7]. Magnetic survey of an area within Kwara State, Nigeria, used spectral analysis with Fast Fourier Transform to estimate the depth to the magnetic basement as it effectively filters noise without loss of important data. Findings showed that there were two primary sources, one at shallow depths of 0.1755 to 0.6323 km and the other at depths of 0.8772 to 1.8231 km and the largest depression was in the southwest and the least in the centre. The mean depth to basement (sedimentary thickness) was about 1.305 km and the depth to the basement was modeled using contour and 3D surface maps [8]. The size of the windows in estimating the depth to the bottom of magnetic sources (DBMS) when such magnetic data are represented as synthetical 2-D magnetic fields with fractal and random source distributions. It has been found that in fractal models the error in estimating the depths of fractal distributions lies within 70 percent of the true values, irrespective of window size, whilst in uncorrelated random sources the error in estimation is far more severe. Its modified centroid method is more accurate han scaling-spectral peak modeling, and on Iranian Aeromagnetic data with a 200 × 200 km² window, it identifies shallow DBMS at 12 to 20 km with the deepest sources at 40 km in the Makran, and correlates with geological structures such as ophiolites [9].

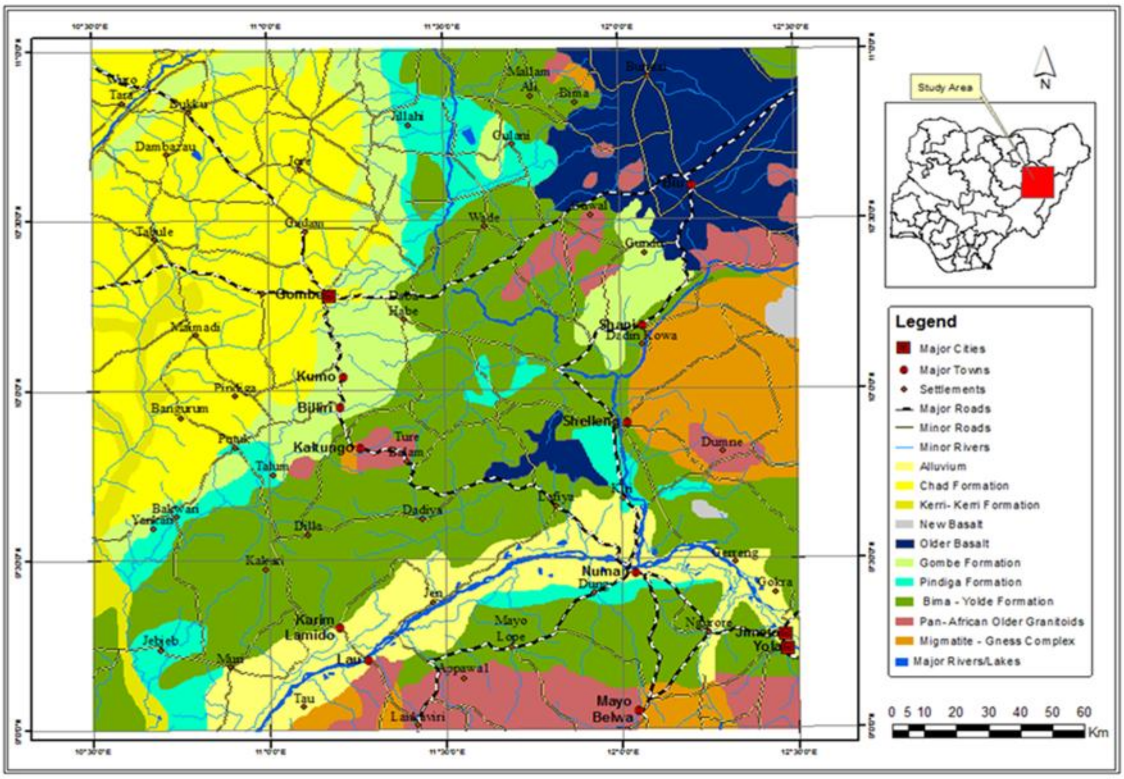

Fig. 1 Geologic map of the study area (modified from NGSA 2006).

The deepest occurrence of the sediment layer is visited at the Namtari Manga, where the basement is found to be under the thickness of 2.2 km implying the existance of a horst and graben geological structure according to study carried out on the radially averaged power spectrum on the Aeromagnetic data across the Yola segment of the upper Benue trough [10]. Aeromagnetic anomalies in the areas of southern Chad basin and upper Benue trough region in Nigeria were interpreted in terms of a two-source depth model with shorter magnetic source depths of 0.5 to 1.4 km and deeper magnetic source depths of 1.5 to 2.5 km [11]. Study of spectral inverse and Euler deconvolution on high-resolution Aeromagnetic data (HRAM) in the Yola arm of the upper Benue valley was done, showing lineaments trending NE-SW and N-S. The estimates of the spectral depth varied between 1.56 and 2.92 km, whereas Euler depths ranged between 0.5 and 2 km [12].

Curie depth in upper Benue trough as estimated by appraisal means [13] ranges between 23.8 to 28.7 km, meaning that the crust to the Moho is not non-magnetized. Also, geophysical methods generated ten vertical electrical soundings (VES), which were carried out in the Liji region of Gombe State to characterize three or more geo-electric layers and have basement rocks of basically infinite thickness due to them occurring between 5.7 to 24.0 meters deep. It is also interesting to note that the resistivity was high in the western, northwestern, and eastern parts, with the A-curve trend being common [14]. Therefore, with the help of magnetic anomaly data and a 2D Curie depth profile, it was determined that the Curie depth was slowly getting deeper in the southern part (14.8 km) and to the northern side (21.8 km) [14]. Curie depth and geothermal gradient measurements in Turkey allow determination of heat flow in the range 94.1-63.8 mW/m^2 in the south and north, respectively. In Taiwan, the magnetic figure spectrum analysis showed that a range of Curie depths of 6 km in the south and an 880/ km limit of geothermal gradient in the north [15].

3 Materials and Methods

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when we use cycles per kilometer as a unit of frequency, we obtain a relationship that we can write as,

$$Z = -M/2 \text{ or } -M/4 \text{ pi}. \tag{1}$$

The residual magnetic data were under the Fourier transform method in this research. The values could be presented in the form of a double Fourier series.

$$T(x,y) = \sum_{n=0}^{N} \sum_{m=-m}^{M} = P_m^n \cos[(2\pi/L)(nx + m - p)] + Q_m^n \, \mathrm{Sin}[(2\pi/L)(nx + my) \tag{2}$$

Here, the L is the length of a side of the square, P_m^n and Q_m^n are the Fourier terms, and N and M are the number of grid points along the X and Y axes, respectively.

The sum,

$$P_m^n \, Cos[(2\pi/L)(n_x + my)] + Q_m^n \, Sin[(2\pi/L)(n_x + my)] \tag{3}$$

Denote a single partial wave for which

$$(P_m^n)^2 + \left(Q_m^n\right)^2 = (C_m^n)2\,;\ (C_m^n) \tag{4}$$

Is the amplitude of the partial wave, even though the frequency of this wave is given as

$$f_m^n = (n^2 + m^2)^{1/2} \tag{5}$$

MATLAB was used in the computation of the radially averaged power spectrum of the data since it was divided into blocks of sixty-four (64) and windowing applied to them. Based on these analyses, attempts were made to find the depth of the basement that was in the study area. There was the use of power spectrum technique, which allowed estimation of depth and generating filters that differentiate between the residual fields or deeper-rooted sources and those that are shallow. When sources are magnetic and are at similar depths, the sources are usually found to line up along a straight line on a plot of log energy against wave number, indicating the depth characteristics of the sources. The spectrum plot gave rise to the power spectrum of the whole field of magnetic intensity, showing how the wave numbers varied from short to long within all overlapping wave number magnetic responses of different directions and depth within magnetic ensembles (see Fig. 2). This spectrum will show the distribution of the short to long stream of wave numbers of the series of overlapping magnetic signals, as it is mentioned in Ref. [15]. The Curie temperature or point is characterized as the temperature above which a ferromagnetic substance loses its ferromagnetic properties and turns paramagnetic, serving as a transition temperature that indicates the change in the magnetic or ferroelectric characteristics of a material, notably the shift from ferromagnetism to paramagnetism. The Curie temperature is the point at which magnetic minerals cease to exhibit ferromagnetism (around 580 °C for magnetite at atmospheric pressure [19].

The residual magnetic intensities vary between -134 nT at the western region and +116 nT at the eastern region. The sharpest anomalies are the southern ones, where the values are up to +116 nT near the Malleri and Dukul villages. On the other hand, the northeastern sector shows even smaller residuals that descend to -134 nT at Bajoga and Bage [20]. At the Curie temperature, the remanent magnetism in crustal rocks is lost, and the ferromagnetic minerals undergo transition to a paramagnetic state; hence, magnetic anomalies no longer occur. Nowadays, the distances between atoms inside the minerals have grown so big that the electron coupling was prevented, and the material acted as a regular paramagnetic material. Many rocks have a record of the strength and direction of the magnetic field along the Earth when they were formed. E.g., magnetite crystals growing in cooling lava flows are influenced by the magnetism of the Earth, and as they do so, become aligned with the magnetic moment in the phenomenon of magnetic alignment, thereby storing the direction of the geomagnetism at the time of solidification.

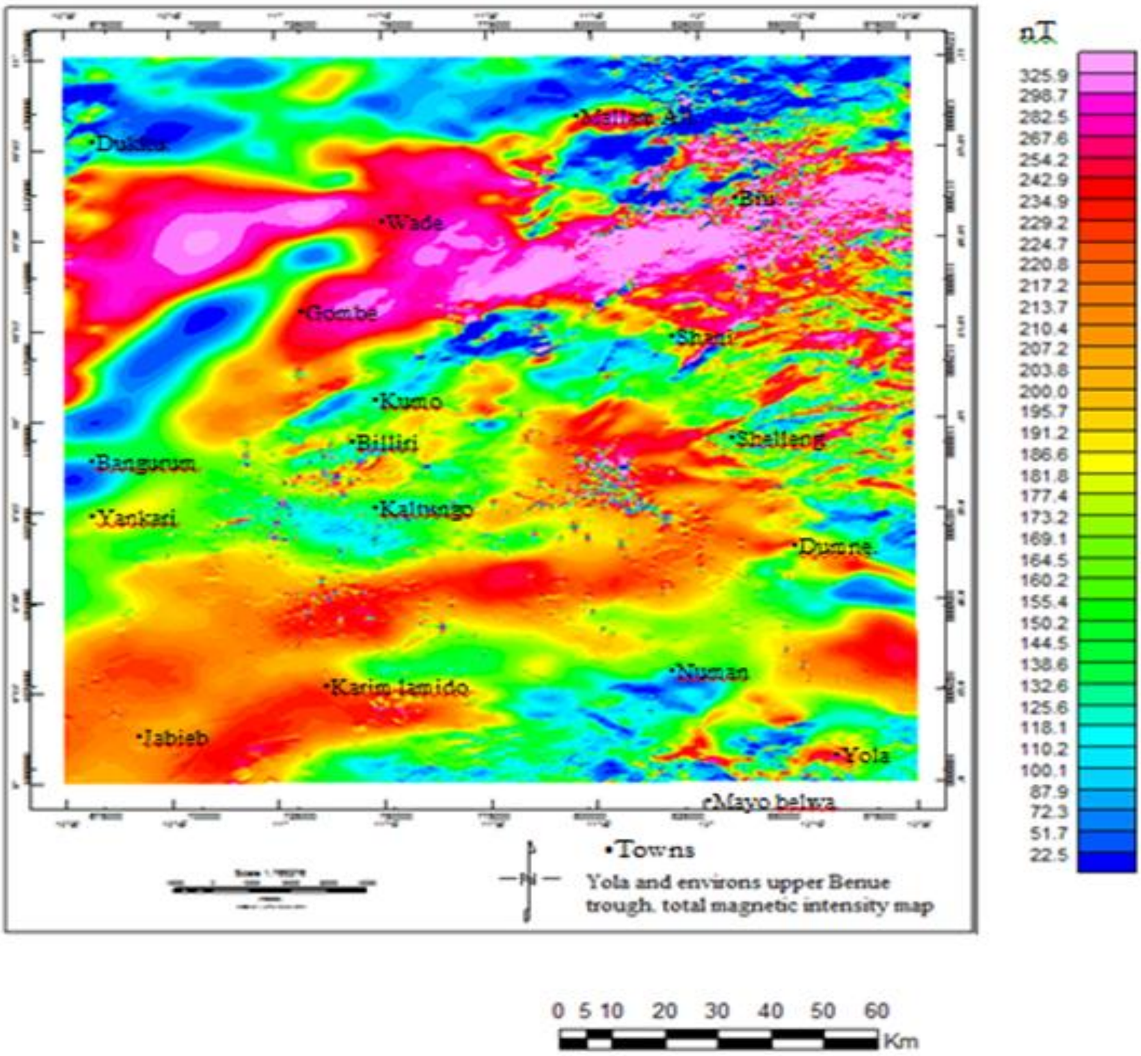

Fig. 2 Total magnetic intensity map of Upper Benue Trough. N. E. Nigeria.

After cooling below the Curie temperature (580 °C in the case of magnetite), this magnetic orientation is fixed in the rock as long as it is not again heated above the Curie point. Oceanic and continental Curie depths tend to be less deep in general, and the depths of continents exhibit bimodal distribution with shallow locations in ancient cratons. Hydrothermal activity and thermal variation affect oceanic depths with concentration at spreading centers and is associated with the flow of heat, and is in agreement with the theoretical values of thermal conductivity. In general, the average heat flow on the planet is approximately 70 mW/m², which equals about 34.6 to 36.6 TW heat loss, and has implication on the thermal/geologic processes of the planet [2]. The remanent magnetism is extrapolated in the rock matrix such that the researcher is able to perform an investigation into the direction of the magnetic field of the Earth at the period in which lava solidified. Spectral analysis of aeromagnetic data was used to estimate Curie point depth, heat flow and geothermal gradients in the eastern part of Kerman providing varying depths of 8.5-18.2 km, geothermal gradient of 31-67 o C/km and heat flow of 139-294 mW/m. The most superficial depths are aligned to volcanic and hot spring locations, which implies that there is a great potential of geothermal use to explore sustainable energy in this region [3]. High-resolution aeromagnetic data and spectral centroid analysis were employed to provide estimates of the Curie-point depths (CPDs), geothermal gradients and crustal heat flow in Shelleng and near environments in northeastern Nigeria. The analysis of the data in overlapping blocks revealed CPDs between 4.95 and 7.69 km (average 6.69 km), 47.23 to 86.57 °C/km (average 58.73 °C/km) geothermal gradient, and 21.13 to 216.43 mW/m^2 (average 166.72 mW/m^2) heat flow. The results indicate that thermal structure of the Earth has a major effect on geodynamic processes in the region, heat flux variations and rheology of the crust in the region [4]. The analysis indicated CPD depths of between about 7.56 and 18 km with an average of about 11.72 km and geothermal gradients of between 52.76 and 191.8 °C/m. The shallow CPD zones within the specific regions will relate to the geothermal gradients and the heat flow which implies that there are probable zones of the irregular thermal activity that can be explored as sources of geothermal energy. The results indicate the areas of focus in future geothermal energy development and give insights into geothermal depth thermal conditions with respect to the geological structure of the region [6]. These techniques will use two-step spectral analysis to find a depth (Zb) of the deepest magnetic sources. The first fraction is by estimation of the depth Zo of the centroid of the magnetic source; then, the upper limit (Zt) of the magnetized region is calculated. This is done by fitting straight lines to the high- and low-wavenumber regions of the radially averaged power spectrum to get the depths. Namely, depth to centroid (Zo) is mostly calculated using the slope of the longest wavelength fraction of the spectrum.

$$\ln\left[\frac{p(s)^{1/2}}{/s/}\right] = \ln A - 2\pi /s/Zo \qquad (6)$$

where Z_o is the observation height, S is the depth to magnetic source and A is the anomaly amplitude. With P(s) the radially averaged Power Spectrum of the anomaly, /s/ the wave number, and a constant A. The next is the estimation of depth to boundary top (Z_t) depends on the slope of spectral segments of the second-longest wavelength

$$\ln\left[P(s)^{1/2}\right] = \ln B - 2\pi /s/Zt \qquad (7)$$

where B is the sum of constants independent of /s/.

Then the basal depth (Z_b) of the magnetic source was considered from the equation below,

$$Zb = 2Zo - Zt \qquad (8)$$

The observed depth of magnetic sources at a basal level (Zb) is expected to be associated with the depth of Curie point. It is widely believed that the Curie temperature isotherm is the temperature where magnetic minerals, e.g., magnetite (that has a Curie point of about 580 degrees Celsius at atmospheric pressure), cease to be ferromagnetic at this portion. The power spectral analysis of the residual magnetic map (see Fig. 3) was used to determine the Curie isotherm of the area by dividing this map into blocks (55 by 55 km each). The spectral data was extrapolated upward into a depth of 23 km using the MATLAB software, whereby the map stabilized. This method was used to remove the effect of the shallow sources on the magnetic field.

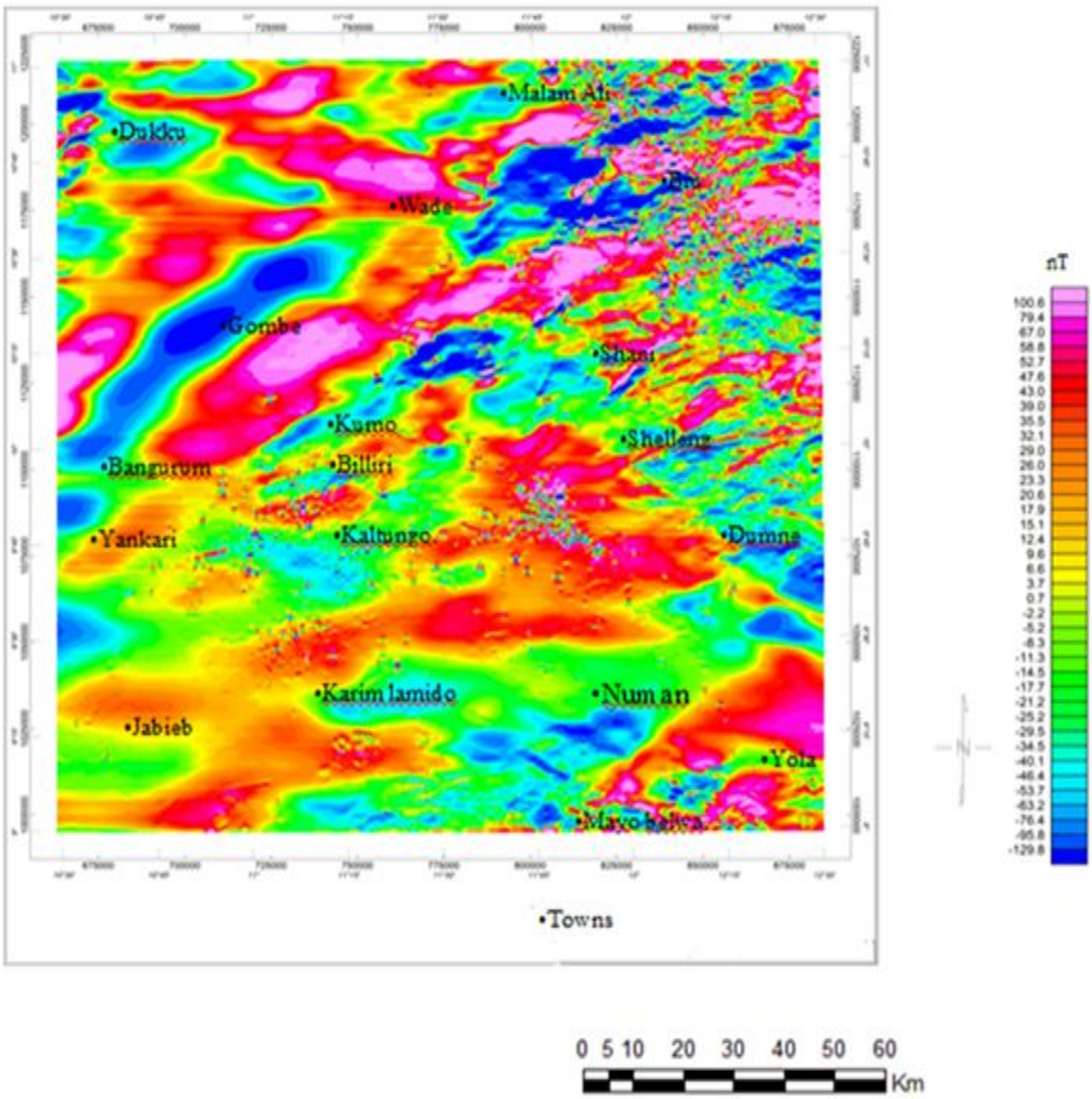

Fig. 3 Residual Aeromagnetic map of the upper Benue trough. N. E. Nigeria.

4 Results and Discussion

Power spectrum of magnetic data was computed and reviewed. A plot was created to show a correlation between radial frequency and logarithmic amplitude of the radially averaged power spectrum. The linear parts of the ensemble show the depiction of different depths. The power spectrum data are shown in Table 1, and shallow sources are between 0.16 to 1.13 kilometers, and deep sources are between 0.2 to 4.04 kilometers. Speaking of the plot of all the blocks radially averaged and presenting the power spectrum, it is possible to note the two-linear branch that is typical of both deep and shallow magnetic sources (see Fig. 4). Elevated Curie depths were observed in the regions of Biu, Dumne, Shani, Yola, and Mayo Belwa, respectively, as shown in Fig. 5. The deep source is attributed to a deep-lying basement and provides the thickest bed of sediments. The shallow source depth could be attributed to near-surface activity or shallow intrusions in the place. The results of this research work can be matched with those of others [9],[10],[11]. A two-dimensional Curie isotherm model was developed and assumed as a magnetized crustal layer, where the lower boundary of the model ranged between the depth of the Curie point isotherm within the area of study. This was identified as the plot of the log of Spectral energies against the wave number. The results about the Curie block are given in Fig. 6. Curie depth is an indicator of the average local Curie temperatures below every block. The study area lies within a depth of about 16.55 km to 23.05 km of the Curie point as shown in Table 2.

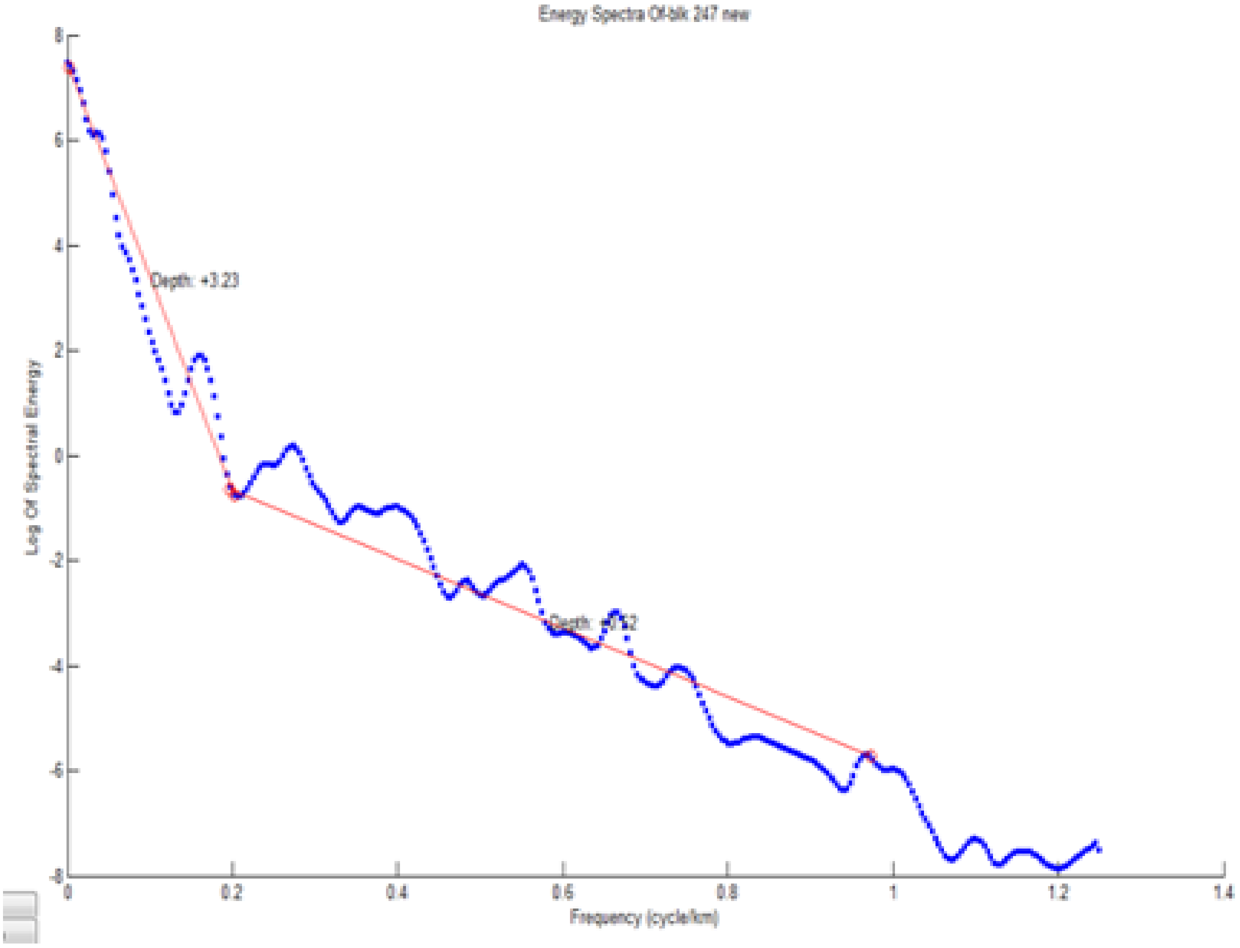

Fig. 4 An example of a spectral block of the study area.

Table 1 Spectral depth of the study area in km (D1 Deep sources, D2 Shallow sources)

BLOCK 1	BLOCK 2	BLOCK 3	BLOCK 4	BLOCK 5	BLOCK 6	BLOCK 7	BLOCK 8
D1=3.98	D1=1.43	D1=0.68	D1=1.06	D1=0.72	D1=0.67	D1=0.66	D1=0.74
D2=1.04	D2=0.032	D2=0.032	D2=0.03	D2=0.023	D2=0.018	D2=0.016	D2=0.15
BLOCK 9	**BLOCK 10**	**BLOCK 11**	**BLOCK 12**	**BLOCK 13**	**BLOCK 14**	**BLOCK 15**	**BLOCK 16**
D1=1.39	D1=1.11	D1=0.60	D1=0.45	D1=0.56	D1=3.56	D1=0.42	D1=0.56
D2=0.16	D2=0.22	D2=0.28	D2=0.16	D2=0.14	D2=1.13	D2=0.07	D2=0.087
BLOCK 17	**BLOCK 18**	**BLOCK 19**	**BLOCK 20**	**BLOCK 21**	**BLOCK 22**	**BLOCK 23**	**BLOCK 24**
D1=1.27	D1=3.59	D1=0.95	D1=0.95	D1=0.24	D1=0.56	D1=0.28	D1=30.2
D2=0.120	D2=0.89	D2=0.26	D2=0.13	D2=0.129	D2=0.129	D2=0.087	D2=0.91
BLOCK 25	**BLOCK 26**	**BLOCK 27**	**BLOCK 28**	**BLOCK 29**	**BLOCK 30**	**BLOCK 31**	**BLOCK 32**
D1=4.04	D1=2.64	D1= 4.11	D1=2.36	D1=3.76	D1=3.37	D1=3.42	D1=2.32
D2=1.12	D2=0.94	D2= 1.10	D2=0.73	D2=0.80	D2=0.60	D2=0.80	D2=0.77
BLOCK 33	**BLOCK 34**	**BLOCK 35**	**BLOCK 36**	**BLOCK 37**	**BLOCK 38**	**BLOCK 39**	**BLOCK 40**
D1=2.64	D1=3.28	D1=0.25	D1=0.25	D1=0.37	D1=0.37	D1=0.48	D1=0.32
D2=0.70	D2=0.76	D2=0.055	D2=0.087	D2=0.07	D2=0.06	D2=0.07	D2=0.095
BLOCK 41	**BLOCK 42**	**BLOCK 43**	**BLOCK 44**	**BLOCK 45**	**BLOCK 46**	**BLOCK 47**	**BLOCK 48**
D1=0.56	D1=1.39	D1=1.39	D1=0.32	D1=0.20	D1=2.64	D1=0.72	D1=0.22
D2=0.21	D2=0.16	D2=0.13	D2=0.08	D2=0.09	D2=0.70	D2=0.16	D2=0.064
BLOCK 49	**BLOCK 50**	**BLOCK 51**	**BLOCK 52**	**BLOCK 53**	**BLOCK 54**	**BLOCK 55**	**BLOCK 56**
D1=3.27	D1=0.39	D1=0.24	D1=0.28	D1=2.12	D1=0.37	D1= 3.18	D1=0.64
D2=0.62	D2=0.12	D2=0.13	D2=0.08	D2=0.50	D2=0.07	D2=0.7	D2=0.14
BLOCK 57	**BLOCK 58**	**BLOCK 59**	**BLOCK 60**	**BLOCK 61**	**BLOCK 62**	**BLOCK 63**	**BLOCK 64**
D1=2.56	D1=0.56	D1=2.37	D1= 3.42	D1=2.56	D1=2.28	D1=3.45	D1=3.56
D2=0.70	D2=0.17	D2=0.65	D2=0.73	D2=0.61	D2=0.5	D2=0.70	D2=0.61

Table 2 Determined Curie point depth through spectral analysis of the research region.

Block	Depth to centroid (Zo) in km	Depth to top boundary (Zt) in km	Curie depth (Zb) in km
1.	11.80	6.05	17.55
2.	11.50	5.31	17.69
3.	12.00	7.30	17.45
4.	11.90	5.20	18.60
5.	10.80	4.64	16.96
6.	12.00	6.55	17.45
7.	12.43	5.55	19.31
8.	12.50	5.40	19.60
9.	14.50	7.89	21.11
10.	13.90	4.75	23.05
11.	10.50	4.40	16.60
12.	11.00	5.45	16.55
13.	10.98	5.36	16.60
14.	11.20	4.50	17.90
15.	10.88	5.00	16.76
16.	11.70	6.84	16.56

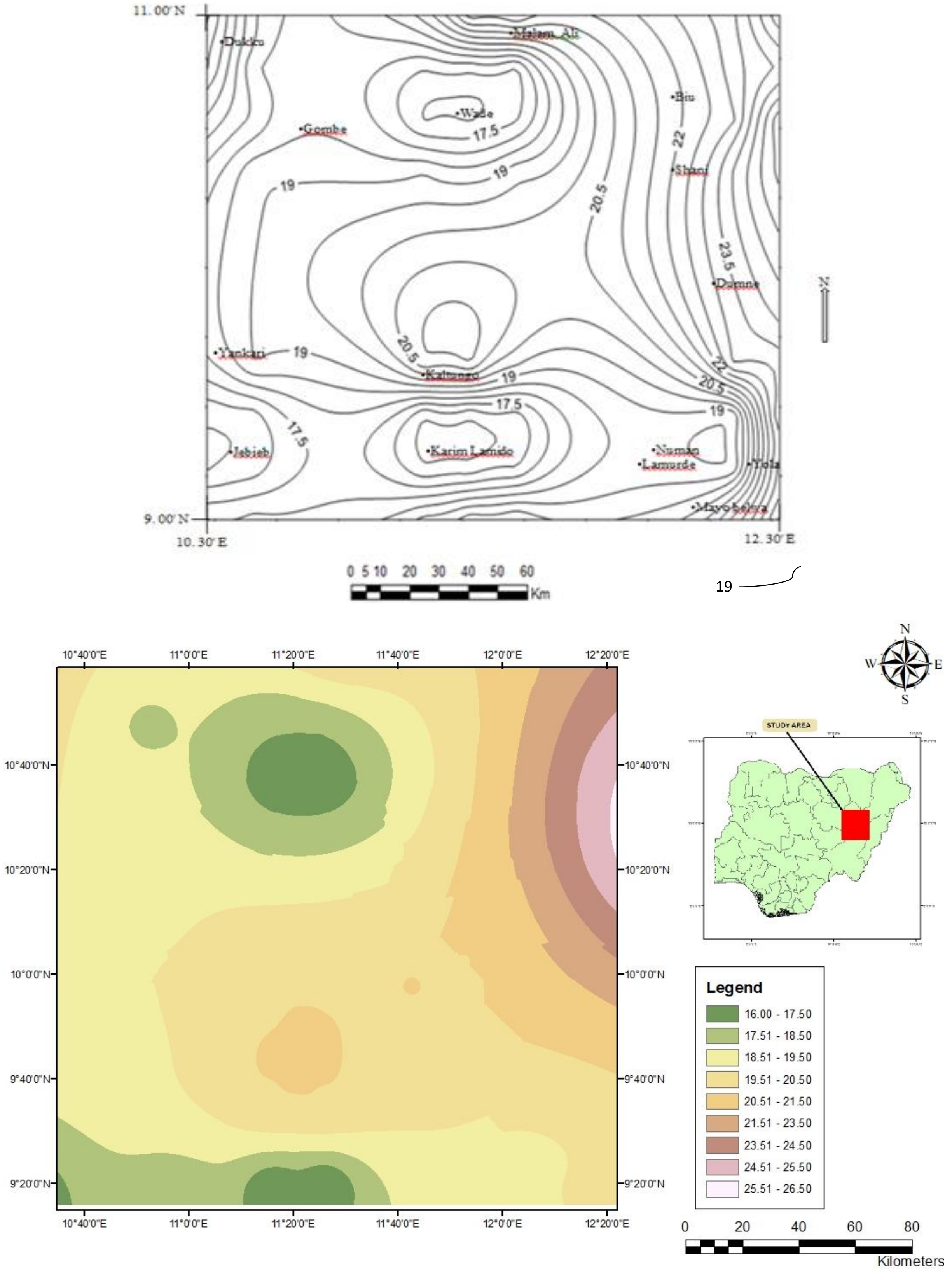

Fig. 5 Map showing the Curie depth contours of the study area, with contours spaced at 1 km intervals.

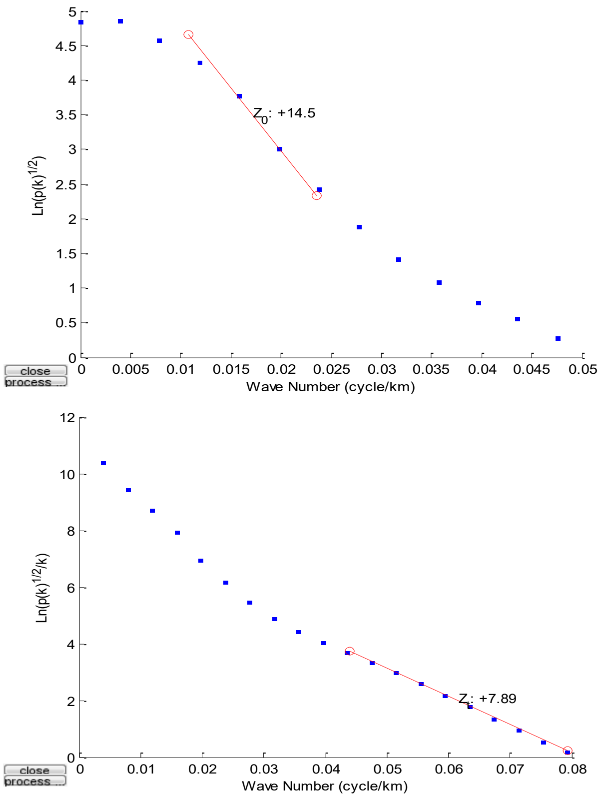

Fig. 6 Curie depth of Block 9 of the Analyzed region.

The change in the Curie isotherm throughout the trough is believed to indicate a reduction in crust thickness beneath the sub-basin and ongoing metasedimentary volcanic activities. These explain how mantle plume activity plays a role in initiating rifting in the upper Benue trough that can be observed in the area. These fluctuations in the Curie point indicate significant temperature changes in the area and reveal both lateral and vertical differences in the composition of the crust. The geologically important materials attain their Curie temperatures (ranging from 500 to 600 °C) in the lowest areas of normal continental crust, but beneath the Moho under the oceans. Given that the upper mantle has a weak magnetic property, the Moho located under the oceans and the Curie isotherm found beneath the continents act as the practical lower boundaries of magnetic rock sources. The crucial function of mantle plume activity in starting rifting in the upper Benue trough is demonstrated by the changes in the Curie depth throughout the trough. The Curie depths estimated in this study (between approximately 16.55 km and 23.05 km) are generally similar to that of previous studies but have some variation with the older studies reporting depths of 23.8 km to 28.7 km. Those differences may be explained by some differences in methods, including the spectral analysis methods used, the data resolution, and the processing algorithms used, and they affect depth estimations. Moreover, such discrepancies might be due to local geological and thermal variations and time variations of crustal temperature and magnetic mineralization, and therefore multiple methods should be used to obtain the complete picture of crustal modeling.

Quantitative measurement of the depths of the Curie (between about 16.55 km and 23.05 km) offers important evidence concerning the thermal conditions and heat conductivity of the Upper Benue Trough. The geothermal gradient (dT/dz) could be determined using the relationship between Curie depth and geothermal gradient and assuming an average Curie temperature of magnetite which is approximately 580°C. As an example, the geothermal gradient at a depth of 20 km and a Curie temperature of 580°C would be about 29°C/km (580°C/20 km). This gradient suggests it is within the relatively active geothermal processes and mantle active regime of heat flow. Furthermore, that Curie depth is higher in certain areas like along Biu and Yola, imply that there must be some localized thermal variation that could be attributed to the presence of active mantle plumes. Such anomalies can be related to a higher heat flux, which leads to crustal thinned processes and magmatic processes, both typical of rifting zones. The thermal conductivity of crustal rocks is around 2.5 W/mK/K and one can approximate the heat flow (q) as Fourier laws; $q = k\ (dT/dz)$ where k is the thermal conductivity of crustal rocks. Replacing the model geothermal gradient provides estimates of heat flows in the 70-75 mW/m^2 range, consistent with active tectonic and volcanic areas. This thermal model underpins the explanation that sources of mantle-origin heat play an important role in crustal processes, rifting, and geothermal resources in the area.

Moreover, one can determine the connection between heat flow and crustal thinning based on the observed change in Curie depths. Areas where Curie isotherms are less means larger geothermal gradients and greater heat flux, which can be attributed to active processes happening in the mantle, such as plume activity or local magmatism. That is, deeper Curie depths in Biu and Mayo Belwa regions imply that the crustal structure was affected by mantle upwelling, which favored increased heat flow and potential geothermal energy. In contrast, more profound Curie isothermal profiles elsewhere suggest relatively reduced heat flux, which is congruent with more stable crustal elements. These estimates of heat flow and Curie depth variations can be used quantitatively to model the distribution of heat flows, crustal temperatures and thermal evolution which are important in the study of rift formation, volcanic eruptions and assessment of geothermal resources in the Upper Benue Trough.

5 Conclusion

Radially averaged power spectrum and Curie isotherm analyses were conducted throughout the region to determine sediment thickness and the depth of the Curie isotherm. The power spectrum results range from 0.16 to 1.13 kilometers for shallow sources and from 0.2 to 4.04 kilometers for deeper sources. The depth from the radially averaged power spectrum chart shows two linear segments indicating magnetic groups at deep and shallow origins. The deeper source, which shows the most substantial sediment thickness in this area, results from a deep-seated basement, while the shallow source depth could stem from near-surface or shallow intrusions. The usual local Curie temperatures under each block are represented in the Curie depth. In the examined region, the depth to the Curie point is believed to range from 16.55 to 23.05 kilometers. The areas of Biu, Dumne, Shani, Yola, and Mayo Belwa were discovered to possess significant curie depths, respectively. Ongoing volcanic activity in metasedimentary formations and the reduction of crustal thickness beneath the sub-basin are thought to account for the alteration of the Curie isotherm throughout the trough. The essential function of mantle plume activity in the onset of rifting within the upper Benue trough is evidenced by the changes in the Curie isotherm throughout the trough. The depths of magnetic sources of the study area were estimated by using radially averaged power spectrum analysis which revealed low-range depths of 0.16 to 1.13 kilometers and high-range depths of 0.20 to 4.04 kilometers. These findings imply that the deeper geological features are due to the basement formations along with intensified sedimentary layers underneath the surface while the nearer ones are due to surface intrusion. Those depths of the Curie isotherms are between 16.55 and 23.05 kilometers with significantly more at Biu, Dumne, Shani, Yola, and Mayo Belwa. Curie depth variations indicate both horizontal and vertical crustal structures showing thinning and volcanic activity. Hot spots in the 500-600°C temperature regime emphasize regions of mantle processes, and Curie depth variations are attributed to mantle plume activity that is considered influential in the formation of rifts and the tectonic activities within the Upper Benue Trough.

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Authors Contribution

M. Hayatudeen: Conceptualization, Methodology, Visualization, Formal Analysis, Writing - Original Draft; **M. Ali Garba**: Methodology, Visualization, Formal Analysis, Writing - Original Draft, Review and Editing; **K. Ezekiel**: Formal Analysis, Writing - Original Draft, Resources, Supervision

Conflict of Interest Statement

We the authors declare that there are no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

The data will be made available upon reasonable request.

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