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Estimation of Curie Depths, Heat Flow, Geothermal Gradient of Biu Plateau Basalts and Environs, North Eastern Nigeria

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Abstract

This study analyzes the geothermal framework of the Biu Plateau Basalts and their surrounding regions in northeastern Nigeria using aeromagnetic data interpretation. Through the application of Oasis Montaj software, key thermal parameters—including Curie point depth (CPD), geothermal gradient, and surface heat flow—were estimated to evaluate the crustal thermal structure. The derived CPD values range between 4 km and 21 km, with shallower depths occurring in the northeast and progressively deeper ones toward the southeast. These variations suggest that the Curie isotherm may coincide locally with the Moho discontinuity, reflecting differences in magmatic activity and tectonic evolution within the area. Calculated geothermal gradients vary from 25°C/km to 125°C/km, while heat flow values lie between 60 mW/m² and 320 mW/m². Zones in the northeast exhibiting high heat flow (up to 320 mW/m²) and shallow Curie depths (~4 km) indicate significant geothermal prospects. Conversely, the southeastern sector, characterized by deeper Curie depths (~21 km) and lower heat flow (~60 mW/m²), may be influenced by isostatic adjustment processes. The study identifies an inverse correlation between Curie depth and heat flow, while the geothermal gradient maintains a direct relationship with heat flow. Overall, the findings confirm that aeromagnetic data provide an effective approach for locating geothermal anomalies in areas with scarce subsurface thermal data. The spatial distribution of Curie depths, heat flow, and geothermal gradients further underscores active tectono-thermal interactions, marking the southeastern portion of the Biu Plateau as a promising target for future geothermal exploration and development.

Keywords: *Aeromagnetic data, Oasis Montaj, Curie Depth, Geothermal Gradient, and Heat flow.*

1. Introduction

Energy remains a fundamental driver of national development. In Nigeria, as in many developing countries, socio-economic progress has been significantly constrained by inadequate power generation and unreliable energy distribution. The nation's existing energy mix dominated by hydropower and gas-powered plants has proven insufficient to meet growing demand. Hydropower generation declines drastically during dry seasons due to reduced water levels, Gas-fired power plants remain a major source of greenhouse gases, which contribute significantly to environmental degradation and climate change (Salako et al., 2020; Adewumi et al., 2021; Adetona et al., 2023). Achieving sustainable industrial and economic growth depends on a reliable and diversified energy mix. Within this context, geothermal energy offers a clean, renewable, and largely undeveloped option that can complement conventional energy sources while helping to reduce Nigeria's reliance on fossil fuels. Hence, evaluating the thermal structure of the Earth's crust is essential for identifying locations with promising geothermal potential.

The Curie isotherm refers to the depth in the crust at which ferromagnetic minerals lose their magnetization due to high temperatures. This depth serves as a critical marker for subsurface thermal conditions and regions where geothermal energy could accumulate (Tselentis, 1991). The position of the Curie isotherm varies according to local differences in the geothermal gradient and heat flow (Hisarli, 1996). Areas characterized by shallow Curie point depths, high geothermal gradients, and elevated heat flow are often linked to strong geothermal activity and higher energy potential (Tselentis, 1991; Nuri et al., 2005). Moreover, the internal heat of the Earth plays a vital role in controlling tectonic and geodynamic processes, which manifest at the surface through volcanism, metamorphism, and crustal deformation (Okubo et al., 1985).

This study applies the spectral analysis technique developed by Spector and Grant (1970), which uses evenly spaced magnetic grid data to determine the average depths to the upper and lower limits of magnetic sources. The approach has become widely used in aeromagnetic investigations for estimating Curie Point Depths (CPD) by analyzing the magnetic power spectrum. Aeromagnetic data thus provide an indirect but reliable method for assessing CPD and related geothermal parameters in regions where direct temperature measurements are unavailable or economically impractical (Hisarli, 1996).

In this research, spectral analysis was employed to derive the Curie point depth, geothermal gradient, and heat flow across the Biu Plateau and its environs. The Curie point depth marks the boundary within the crust where dominant magnetic minerals transition from a ferromagnetic to a paramagnetic state as temperatures exceed their critical Curie threshold (Nagata, 1961).

Recent developments in geothermal studies across Nigeria have placed increasing emphasis on using aeromagnetic data to evaluate subsurface thermal conditions. Several researchers have utilized Curie point depth analysis to estimate geothermal parameters in different regions (Nwankwo & Shehu, 2015; Nwankwo & Sunday, 2017; Kasidi, 2019; Odidi et al., 2020). For example, Nwankwo and Shehu (2015) reported CPD values ranging from 11.3 km to 27.83 km within the Sokoto Basin, corresponding to heat flow values between 52.11 mW/m^2 and 130.28 mW/m^2, with an average of 84.97 mW/m^2.

The Curie temperature is a fundamental property of magnetic minerals, controlled by their chemical composition and crystal structure. Below this temperature, exchange interactions among magnetic domains maintain ordered alignment, resulting in ferromagnetic behavior. However, when temperatures exceed the Curie point, these domains lose their alignment, producing a paramagnetic state where both induced and remanent magnetization disappear (Nagata, 1961). Most rock-forming minerals are either paramagnetic or diamagnetic, possessing low magnetic susceptibility and contributing minimally to the overall geomagnetic field.

From a geological standpoint, the Biu Plateau lies within the northern extension of the Cameroon Volcanic Line (CVL) a reactivated Pan-African terrane that formed during the Neoproterozoic (~600 Ma) following the collision between the West African Craton, Congo Craton, and East Saharan block (Ferre et al., 1996; Ekwueme & Kröner, 1998). The region’s complex tectono-magmatic evolution and structural reactivation make it a highly prospective zone for geothermal energy exploration in Nigeria.

2. Location and Geology of the Study Area

The Biu Plateau (Figure 1) is situated in northeastern Nigeria, forming part of the Nigerian Basement Complex. It lies between latitudes 10°34′10″N and 10°44′22″N and longitudes 12°00′00″E and 12°03′15″E. Geologically, the plateau represents a segment of a Tertiary to Recent volcanic province that extends across Nigeria and Cameroon. It forms part of a broader continental alkaline volcanic belt that stretches through much of Africa (Turner, 1978).

The area is dominated by widespread basaltic lava flows, with smaller occurrences of trachyte and phonolite. These volcanic units rest upon the Precambrian Basement Complex, which consists primarily of granitic and metamorphic rocks. The topography of the plateau displays typical volcanic features such as cones, domes, and lava plains formed through successive eruptions. The tectonic and magmatic history of the Biu Plateau suggests lithospheric thinning and mantle upwelling along the Cameroon Volcanic Line conditions that are conducive to geothermal activity.

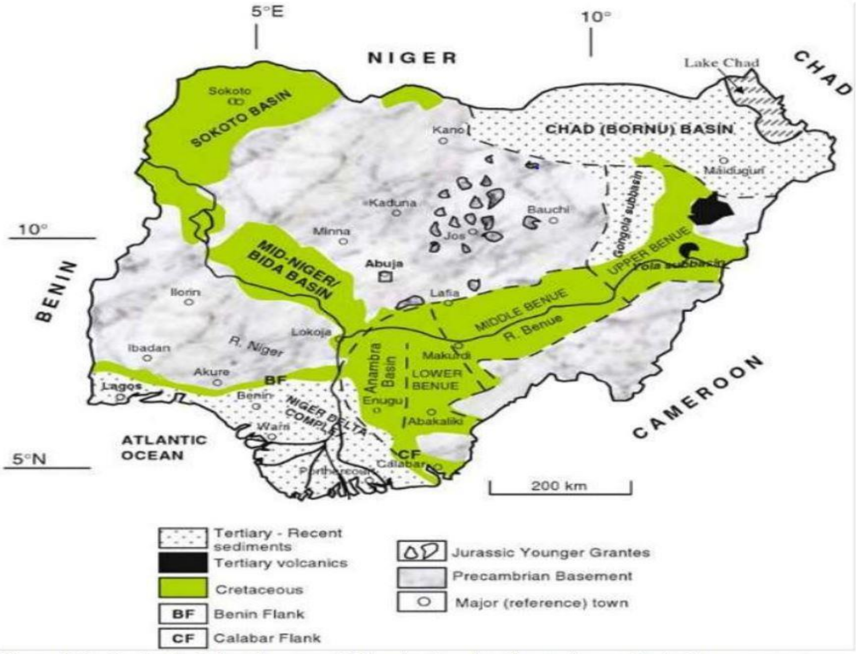

Figure 2.1: Geological sketch map of Nigeria showing the major geological components (Obaje, 2009)

Fig.1. Geologic Map of the study area

2.1 Geology of the Study Area

The Biu Plateau was first geologically described by Falconer (1911), who documented the region's distinct geomorphology and volcanic history. His observations indicated that in the southeastern part of Borno State, particularly toward Biu, volcanic cones become increasingly dominant, while the plateau surface transitions into dissected plains and rugged valleys. Falconer also reported that the lava flows had overlain older basement rocks, and that the basaltic formations have since experienced considerable weathering and erosion.

The Biu Plateau constitutes the largest volcanic province in Nigeria, occupying an area exceeding 500 km². It is predominantly composed of alkaline olivine basalts, with flow thicknesses ranging from 30 m to 250 m. Volcanic landforms within the plateau include tephra rings, cinder cones, and lava flows, composed mainly of basaltic agglomerates, volcanic bombs, ashes, and tuffs (Carter et al., 1963). Numerous volcanic cones, characterized by conical hills and caldera-like depressions, suggest Tertiary to Quaternary episodes of volcanism.

According to Carter et al. (1963), the Biu Plateau contains a more diverse and voluminous suite of volcanic materials than the Jos Plateau, located to the west. The two plateaus are separated by a structurally stable zone lacking Cenozoic volcanic activity. Structurally, the Biu Plateau occupies a tectonic and topographic boundary between the Benue Trough and the Chad Basin. This boundary is expressed as a broad west-facing basement ridge, whose surface manifestation terminates near the western edge of the plateau. Westward, Cretaceous sedimentary outcrops link the two basins, although the Zambuk Ridge a subsurface basement uplift persists beneath, resulting in localized thinning of the overlying Cretaceous sequence (Carter et al., 1963).

3. Materials and Methods

3.1 Data Acquisition

The aeromagnetic data used in this research were sourced from the Geological Survey Agency of Nigeria (GSN), specifically corresponding to Sheet 133 (Biu). These data were originally collected in 2010 by Fugro Airborne Survey Services under contract with the Nigerian Geological Survey Agency (NGSA).

During data acquisition, three Scintrex CS-3 Cesium vapor magnetometers were utilized to measure magnetic intensity. The survey was conducted along northwest–southeast (NW–SE) oriented flight lines with northeast–southwest (NE–SW) tie lines to ensure proper cross-checking and correction of magnetic variations. The flight line spacing was maintained at 500 meters, while tie lines were spaced 2 kilometers apart. An average flight altitude of approximately 80 meters above ground level was maintained throughout the survey. Magnetic readings were acquired at 0.1-second intervals, providing a high-resolution dataset suitable for detailed spectral and subsurface magnetic analyses.

The processed magnetic data were supplied in Oasis Montaj Geosoft raster format. The Total Magnetic Intensity (TMI) map of the study area (Figure 1) displays the spatial distribution of magnetic anomalies, which represent variations in magnetic susceptibility and the depth to magnetic sources within the crust beneath the Biu Plateau.

3.2 Estimation of Curie Point Depth, Geothermal Gradient, and Heat Flow

A number of techniques have been developed for determining Curie Point Depth (CPD), ranging from isolated anomaly-based methods to spectral analytical approaches (Bhattacharyya & Leu, 1975; Okubo et al., 1985; Onwuemesi, 1997; Tanaka et al., 1999; Stampolidis et al., 2005; Nwankwo et al., 2011; Kasidi & Nur, 2012). In this study, the spectral analysis technique originally proposed by Spector and Grant (1970) was adopted. This method utilizes the power spectrum of regional magnetic anomalies to estimate the mean depths of magnetic source layers.

Before performing spectral computations, the magnetic data were reduced to the magnetic equator (RTE) to correct for the low magnetic inclination characteristic of the region. The RTE-corrected grid was subsequently divided into nine spectral blocks, each covering an area of approximately 18.33 km × 18.33 km. This block size provided an optimal balance between spectral resolution and spatial representation, ensuring accurate estimation of Curie depth, geothermal gradient, and heat flow throughout the study area.

Within each sub-grid, power spectrum analysis was conducted to determine the depth to the top (Z_t) and depth to the bottom (Z_β) of the magnetic sources. The Curie Point Depth (Z_β) represents the level within the crust at which magnetic minerals lose their ferromagnetic properties due to elevated temperature.

Once the Curie depths were obtained, the geothermal gradient (G) and heat flow (q) were calculated using the following equations:

$$G = \frac{Tc}{Zb}$$

$$q = k \times G$$

where:

i. Tc = Curie temperature (assumed to be 580°C for magnetite),
ii. Zb = Curie Point Depth (km),
iii. G = Geothermal gradient (°C/km), and
iv. k = Thermal conductivity of crustal rocks (typically 2.5 W/m°C).

These computations provided the spatial variations in Curie depth, geothermal gradient, and surface heat flow, which collectively describe the thermal regime and geothermal potential of the Biu Plateau region.

The integration of spectral analysis with aeromagnetic data provided quantitative estimates of crustal thermal characteristics, which were subsequently used to infer the geothermal potential of the Biu Plateau and its surrounding regions.

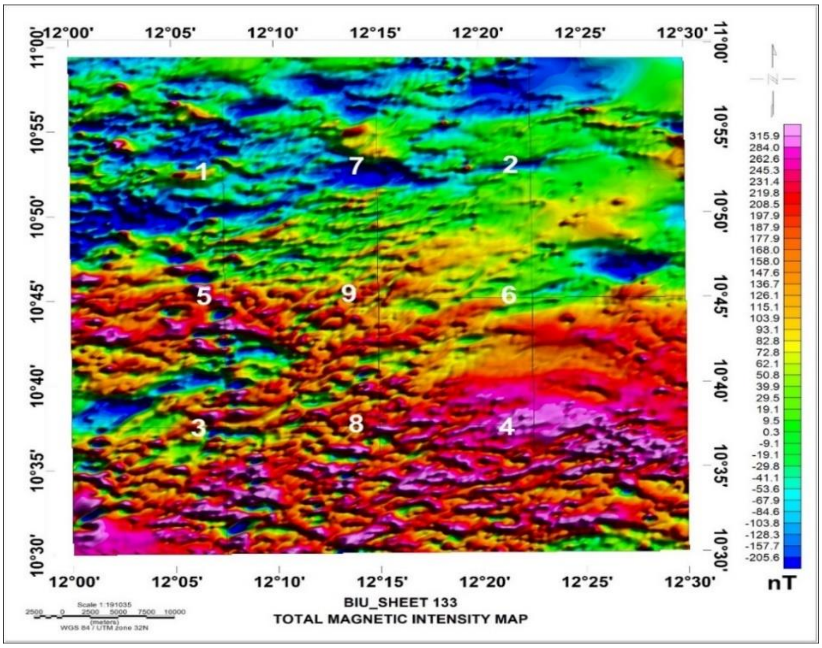

Fig. 2. Total Magnetic Intensity (TMI) Map of the study area

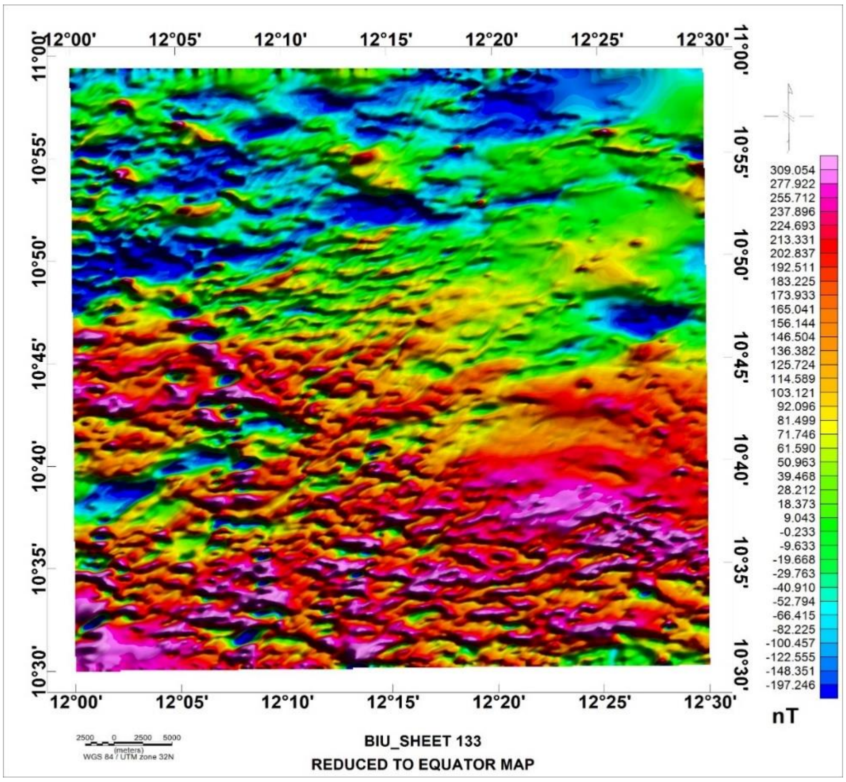

Figure 3: Total magnetic intensity reduced to an equator map of the study area

A Fast Fourier Transform (FFT) algorithm was used to compute the Discrete Fourier Transform (DFT) of a sequence, or its inverse, as given by Onwuemesi 1997:

$$Y_i(x) = \sum_{n=1}^{N}\left[a_n \cos\left(\frac{2\pi n x_i}{L}\right) + b_n \sin\left(\frac{2\pi n x_i}{L}\right)\right] \qquad (1)$$

Where (Yi(x)) represents the magnetic reading at position (Xi), (L) denotes the total length of the anomaly cross-section, (n) is the harmonic number corresponding to the partial wave number, and (N) refers to the total number of data points. The parameters (an) and (bn) represent the real and imaginary components of the amplitude spectrum, respectively, for (i = 0, 1, 2, 3, ldots).

The formula presented in Equation (1) was applied using Microsoft Excel (MS Excel) to each sub-block into its corresponding radial energy spectrum. Subsequently, the average radial transform the magnetic intensity data within energy spectrum for each block was determined and expressed as a logarithmic plot of energy versus frequency.

A Log E–frequency graph was then generated, illustrating the relationship between the logarithm of the energy spectrum (Log E) and the respective frequency values. This graphical representation provided the foundation for estimating the depths to the magnetic source bodies within the study area.

The gradients (m_1 and m_2) of two linear segments drawn from each graph were used to estimate the centroid depth (Z_o), the depth to top boundary (Z_t), Curie point depth (Z_b), geothermal gradient ($\frac{dT}{dZ}$) and heat flow (q) using the relations shown in equations 3 – 7 respectively Hinze *et al.*, 2013, Frost and Shive 1986, Stampolidis *et al.*, 2005 and Nwankwo *et al.*, 2011.

$$\text{Slope } (m_1, m_2) = \frac{Log\ Energy}{Frequency} \qquad (2)$$

$$Z_o = -\frac{m_1}{2\pi} \qquad (3)$$

$$Z_t = -\frac{m_2}{2\pi} \qquad (4)$$

Where m_1 and m_2 are slopes of the first and second segments of the plot, and the negative sign (-) indicates depth to the subsurface.

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

$$Z_b = 2Z_o - Z_t \qquad (5)$$

The geothermal gradient (dT/dz) between the Earth's surface and the Curie point depth (Zb) can be defined by Eq. (6) (Okubo *et al.*, 1985, and Takana *et al.*, 1999)

$$\frac{dT}{dZ} = \frac{\vartheta}{Z_o} \qquad (6)$$

The heat flow (HF) values are calculated using

$$q = \lambda\left[\frac{\vartheta}{Z_o}\right] \qquad (7)$$

In assessing the geothermal properties of the study area, key parameters such as the thermal conductivity (λ), Curie temperature (θ), and spectral characteristics are fundamental. The Curie temperature marks the point at which ferromagnetic minerals lose their spontaneous magnetization due to elevated temperatures. For magnetite, this threshold is approximately 580°C (Opdyke & Channell, 1996).

To extract the spectral parameters required for depth estimation, a Fast Fourier Transform (FFT) algorithm was employed to compute the Discrete Fourier Transform (DFT) of the magnetic data, or its inverse, as described by Onwuemesi (1997). This procedure converts spatial magnetic field data into the frequency domain, facilitating the determination of depths to magnetic source bodies by analyzing the slope characteristics of the energy spectra.

For detailed analysis, the Total Magnetic Intensity (TMI) grid of the study area was divided into nine equal sections. Spectral depth analysis was performed on each section using FFT to generate both energy spectra and their corresponding wavenumber components. These spectra were plotted in MATLAB (Fig. 4), allowing for the estimation of the depth to the top (Z_t) and the centroid (Z_0) of the magnetic sources.

The derived depth parameters were then incorporated into the Curie Point Depth (CPD) equation (Equation 5) to compute the depth to the Curie isotherm throughout the study area. Using the CPD values, the geothermal gradient (G) and heat flow (q) were subsequently calculated through established empirical relationships.

A summary of the computed geothermal parameters, including Curie Point Depth, geothermal gradient, and heat flow, is presented in Table 1. These results provide a foundation for evaluating the geothermal potential of the Biu Plateau and its surrounding regions.

Table 1. **Estimated Geothermal parameters**

S/N	LON	LAT	Depth to Top Z_T(km)	Depth to Centroid Z_0(km)	Curie point depth Zb(km)	Geothermal Grad (°C/km)	Heat Flow mW/m^2
1	12.125	10.875	2.26	6.11	9.96	58.23	145.58
2	12.375	10.875	1.84	3.25	4.66	124.46	311.16
3	12.125	10.625	1.80	5.31	8.82	65.76	164.40
4	12.375	10.625	2.66	11.80	20.94	27.70	69.25
5	12.125	10.75	1.69	4.33	6.97	83.21	208.03
6	12.375	10.75	3.00	4.35	5.70	101.75	254.39
7	12.25	10.875	2.63	6.69	10.75	53.95	134.88
8	12.25	10.625	1.95	5.78	9.61	60.35	150.88
9	12.25	10.75	1.37	6.24	11.11	52.21	130.51
	Average		2.13	5.98	9.84	69.74	174.34

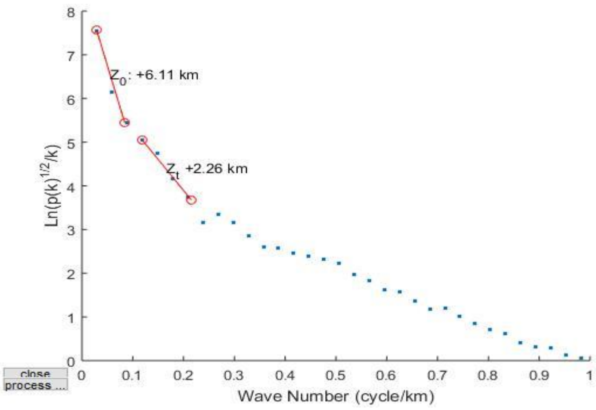

Figure 4: Plot of energy and wave number components

Results and Discussions

The Total Magnetic Intensity (TMI) map of the study area illustrates the spatial distribution of magnetic susceptibilities associated with different rock types. Relatively high magnetic intensities were observed in the southern parts of the region, likely reflecting the presence of rocks with elevated magnetic susceptibility. In contrast, the central and northern portions exhibited moderate to low magnetic intensities, which may correspond to weathered or structurally deformed rocks (Moghaddam et al., 2022; Telford et al., 1990).

The measured magnetic values ranged from -205.6 nT to 315.9 nT, and the data were represented using a color-coded scheme: blue for low values, green and yellow for moderate values, and red and pink for high values. Accordingly, the southern regions of the study area displayed strong magnetic signatures, while the central to northern areas were characterized by moderate to weak magnetic responses.

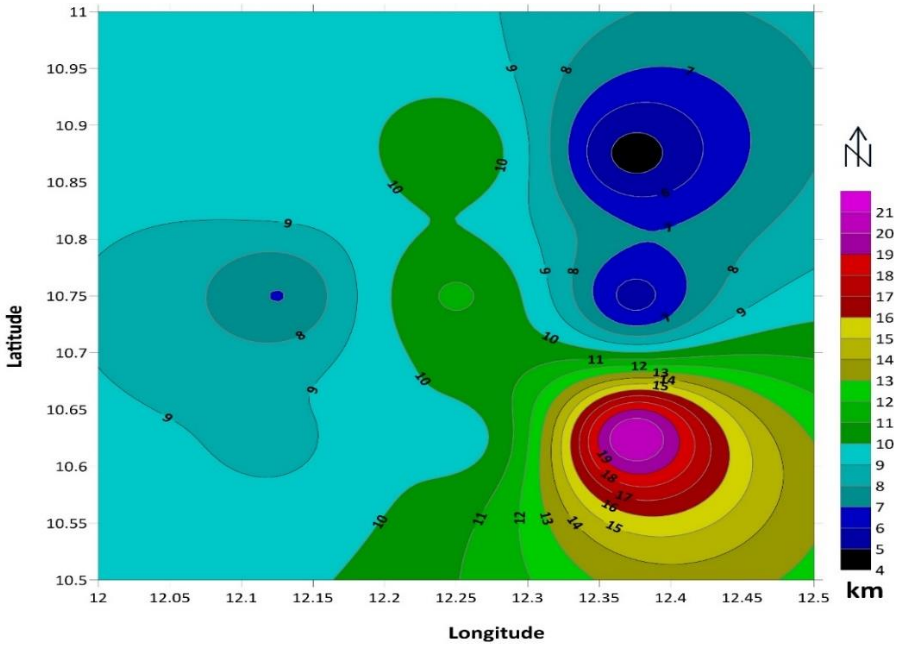

Figure 5: Curie point depth contour map of the study area

The TMI was reduced to equator (RTE) (Figure 2) for the purpose of enhancing the position of magnetic signals over their causative bodies. The feature is achieved by removing the effect of angles of inclination and declination so that both the magnetic signatures and causative bodies lie in the same magnetic plane (magnetic north).

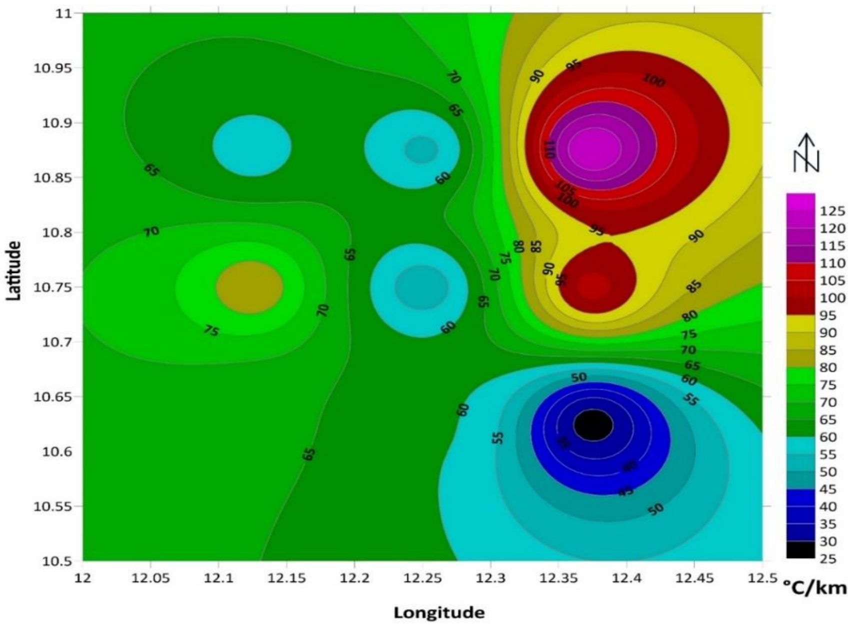

Figure 6: Geothermal gradient contour map of the study area

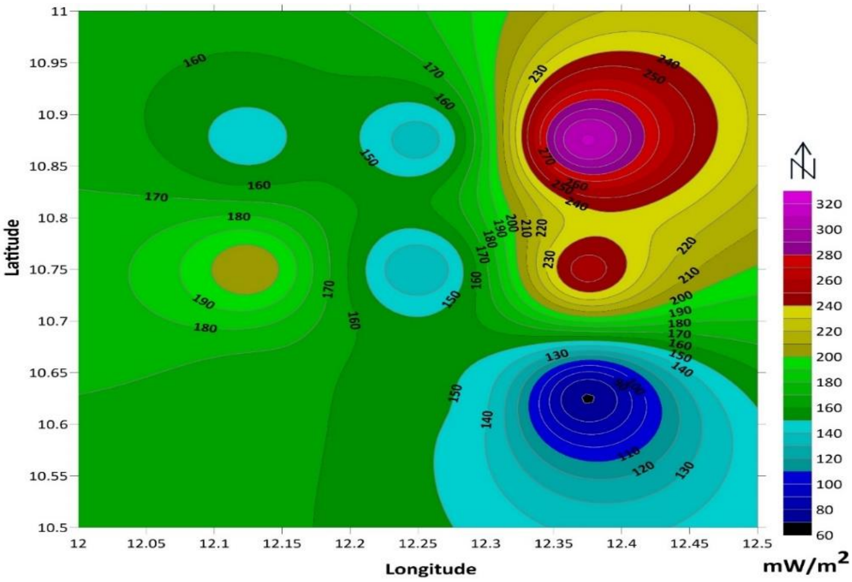

Figure 7: Heat flow contour map of the study area

Results and Discussion

The geological and structural characteristics of the Biu Plateau were examined using the first and second vertical derivatives of the aeromagnetic data. The derivative maps revealed several structural trends, predominantly concentrated in the northwestern (NW), southwestern (SW), and southeastern (SE) sectors. These near-surface structures are interpreted as faults, fractures, dykes, folds, and shear zones, typical of tectonically active volcanic terrains. Such structural discontinuities are crucial for geothermal studies, as they facilitate fluid circulation and heat transfer within the crust (Rowland & Sibson, 2004; Wood et al., 2018; Kumar et al., 2021; Yasin et al., 2023).

The subsurface thermal parameters, including Curie Point Depth (CPD), geothermal gradient (GG), and heat flow (HF), were computed to evaluate the geothermal regime of the Biu Plateau and adjacent areas. CPD values range from 4 km to 21 km, with the shallowest depths (4–10 km) primarily in the northeastern and western sectors. These shallow zones indicate elevated subsurface temperatures, pointing to potential geothermal anomalies. Typically, shallow Curie depths coincide with Curie isotherm temperatures, highlighting areas with possible geothermal reservoirs (Dimgba et al., 2020; Saada, 2016).

The geothermal gradient across the region varies from 25°C/km to 125°C/km, reaching its maximum in the northeastern sector, while heat flow ranges between 60 mW/m² and 320 mW/m². Notably, the southeastern and western sectors exhibit heat flow values ≥140 mW/m², surpassing the global continental average (~60 mW/m²) and exceeding the geothermal viability threshold of 80 mW/m² (Ranalli & Rybach, 2005; Dhansay et al., 2014; Adewumi et al., 2021; Adetona et al., 2024).

Spatial analysis shows a clear inverse correlation between CPD and heat flow: regions with shallow CPD correspond to high geothermal gradients and enhanced heat flow, whereas areas with deeper CPD display lower thermal activity. This pattern reflects the thermal structure of the crust, suggesting lithospheric thinning or magmatic underplating beneath the northeastern and western sectors. These regions are therefore promising targets for geothermal energy exploration, as heat concentration near the surface improves the feasibility of sustainable energy extraction.

Conclusions

The spectral analysis of aeromagnetic data over the Biu Plateau and surrounding regions has provided valuable insights into the crustal thermal structure and geothermal framework of northeastern Nigeria. Variations in the spectral frequency of magnetic anomalies effectively delineate the Curie Point Depth (CPD), which serves as a reliable indicator of subsurface temperature distribution.

The estimated CPD values range from 4 km to 21 km, corresponding to geothermal gradients of 25°C/km to 125°C/km and heat flow values from 60 mW/m² to 320 mW/m². The northeastern, western, and southeastern sectors exhibit particularly high heat flow and shallow CPD, indicating elevated geothermal potential. The observed inverse correlation between CPD and heat flow further supports the idea that shallow magnetic crust is associated with zones of concentrated heat and possible magmatic influence.

Overall, the findings suggest that the Biu Plateau possesses substantial geothermal prospects, with localized areas displaying thermal conditions favorable for geothermal energy development. This highlights the region's potential to contribute to renewable and sustainable energy generation in Nigeria, providing an environmentally friendly alternative to conventional fossil fuel-based power sources.

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