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Exploring Geothermal and Hydrocarbon Potential with Aeromagnetic Data in Guri and Environs in Chad Basin

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This study analyses aeromagnetic data over Guri and environs to evaluate geothermal and petroleum prospects. The Total Magnetic Intensity (TMI) anomalies, ranging from –1324.43 nT to +997.75 nT, reveal significant subsurface heterogeneity, with strong positive anomalies linked to igneous intrusions and crystalline basement highs, and negative anomalies marking sedimentary basins and low-susceptibility rocks. Upward continuation to 4 km effectively suppresses shallow sources, enhancing deeper tectonic lineaments and basement structures critical for hydrocarbon and mineral exploration, while gridded continuation provides localized insights into anomaly orientations consistent with Nigeria's basement complex geology. Spectral analysis identifies dual-depth magnetic sources, with shallow crustal features (~7–9 km) and deeper basement anomalies (20–45 km), underscoring a multi-layered crustal architecture. Curie point depth and geothermal gradient analysis highlight Blocks 1 and 2 as favourable for oil generation and geothermal exploitation, whereas deeper centroids in Blocks 3 and 4 suggest gas-prone systems with reduced geothermal viability. Overall, the integration of TMI mapping, upward continuation, and spectral analysis demonstrates the effectiveness of aeromagnetic methods in delineating intrusive bodies, tectonic lineaments, and geothermal potential across Nigeria's inland basins. Based on these findings, hydrocarbon exploration should prioritize Blocks 3 and 4 for gas-prone systems and Blocks 1 and 2 for oil-prone zones. Geothermal energy development is best concentrated in Blocks 1 and 2, which exhibit favourable heat flow and gradients, while large-scale geothermal investment in Blocks 3 and 4 should be avoided due to limited viability. These results provide a robust framework for guiding exploration strategies, supporting both hydrocarbon prospectivity and geothermal energy development in the region.

Keywords: Aeromagnetic data; Spectral analysis; Curie Point Depth; Geothermal gradient; Heat Flow; Hydrocarbon generation

Introduction

Nigeria is richly endowed with natural resources such as groundwater, crude oil, and minerals, which, when harnessed, improve living conditions and societal development (Siloko, 2024). However, these resources remain underutilized, limiting their potential to provide basic amenities. Globally, many nations have advanced in resource prospecting, particularly geothermal energy and petroleum, which have significantly boosted their economic growth, and Nigeria is no exception, though it must expand exploration into hinterlands for additional oil blocks and geothermal opportunities (Akagbosu *et al*., 2024). In the search for geothermal and petroleum resources, geophysical methods such as magnetic, gravity, and seismic surveys are employed to image the subsurface, identifying basins with sediment thickness, thermal maturity, and structural traps capable of accumulating hydrocarbons (Upadhyay, 2025). Specifically, the magnetic method aids petroleum exploration by revealing basin architecture, depositional patterns of sediments, and the thermal structure of a region. Aeromagnetic surveys have been used by several authors, such as Upadhyay (2025), Abbas *et al*. (2024), Abdulmumin *et al*. (2024), Ohaegbuchu *et al*. (2025), Simon *et al*. (2025), Smith (2003) and Xu *et al*. (2024) to explore petroleum prospects of different areas, which prove to be effective in the early stage of geothermal and petroleum exploration.

This research employed high-resolution aeromagnetic data to investigate geothermal and petroleum prospects in Guri and its environs, an inland part of the Chad Basin in North-eastern Nigeria. Analytical techniques such as upward continuation, spectral analysis for Curie point depth estimation, geothermal gradient, heat flow, and sediment thickness determination were applied to assess the area's potential. If the findings prove promising, the region could serve as an additional block to existing ones, thereby enhancing Nigeria's oil production capacity while also contributing geothermal resources for power generation. Petroleum exploration in Nigeria has largely been restricted to coastal areas, neglecting inland basins, which has constrained economic growth and overall development. Expanding exploration into these hinterlands would not only improve livelihoods in many communities but also help mitigate the insecurity challenges facing the nation. Thus, the study aims to evaluate the geothermal and petroleum potential of Guri and environs using sediment thickness, Curie point depth, geothermal gradient, and heat flow as key parameters.

The study area lies within parts of Yobe, Jigawa, Bauchi, and Gombe States in northern Nigeria, covering a section of the Chad Basin between longitudes 9°30′E–11°30′E and latitudes 11°30′N–13°30′N (Figure 1), with a lateral extent of 219.6 × 219.6 km and a total area of 48,224.16 km². It is accessible through a network of roads and paths, and the terrain is largely undulating plains at an average elevation of 378 m, drained by Rivers such as the Hadejia, Jama'are, Komadugu Yobe River, and its tributaries, which are prominent features shaping floodplains and wetlands with a dendritic drainage pattern flowing into Lake Chad (Goni *et al*., 2024).

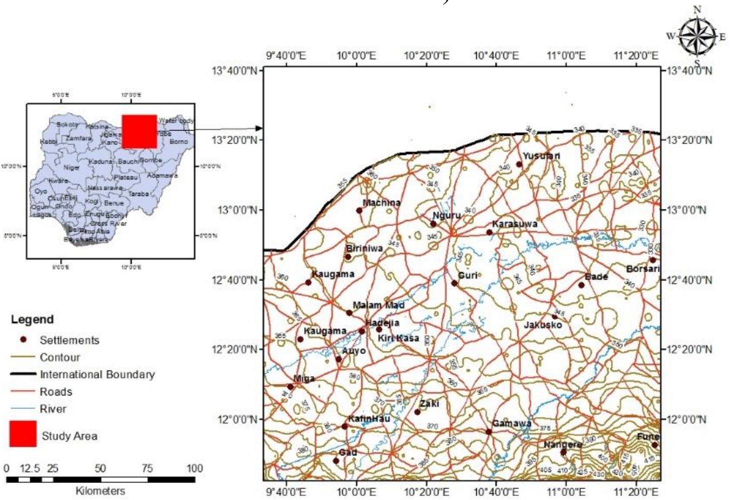

Figure 1: Topographic Map of the Study Area (SRTM/ASTER global DEMs, 2006)

Geothermal resource assessment and sediment maturity evaluation rely on Curie point depth (CPD), geothermal gradient, and heat flow, which together determine whether sediments can generate hydrocarbons. The Curie point (~580 °C) marks the temperature at which ferromagnetic minerals lose magnetism, while the geothermal gradient indicates the rate of temperature increase with depth, and heat flow measures the transfer of heat from the Earth's interior to the surface. These parameters define whether sediments fall within the oil window (60–120 °C), remain immature below it, or become over-mature above it (Ekpo *et al*., 2024; Yassah *et al*., 2024; Guimaraes *et al*., 2024). Collectively, these findings underscore CPD, geothermal gradient, and heat flow as critical parameters for guiding geothermal exploration and hydrocarbon generation strategies across Nigeria's inland and coastal basins.

Geology of the Area

The Chad Basin in north-eastern Nigeria exemplifies this geological complexity, which was formed by peripheral uplifts approximately 25 million years ago. The basin accumulated ~0.5 km of sediments during the Neogene and Quaternary periods, aided by repeated episodes of sediment and water loading from Lake Megachad (Magyar *et al*., 2025). Its stratigraphy (Fig. 2) consists of Quaternary Chad Formation, Tertiary Kerri-Kerri Formation, Mesozoic Extrusives (Basalt), and Precambrian Basement (Migmatite). The Chad Formation comprises unconsolidated sands, clays, and silts deposited in fluvial and lacustrine environments of the Chad Basin. It is significant for groundwater and agricultural resources (Didi *et al*., 2020). The Kerri-Kerri Formation is made up of sandstones, clays, and ironstones deposited in continental environments. It is associated with lateritic soils and plays a role in land use and agriculture (Lailai *et al*., 2025). The volcanic rocks represent igneous activity during the Mesozoic, occurring as basaltic flows and intrusions. They mark tectonic and magmatic events in the basin's evolution (Geolex Database, 2024). The basement complex consists of migmatites and gneisses, forming the structural foundation of the basin. These rocks influence sedimentary deposition and regional tectonics (Geolex Database, 2024).

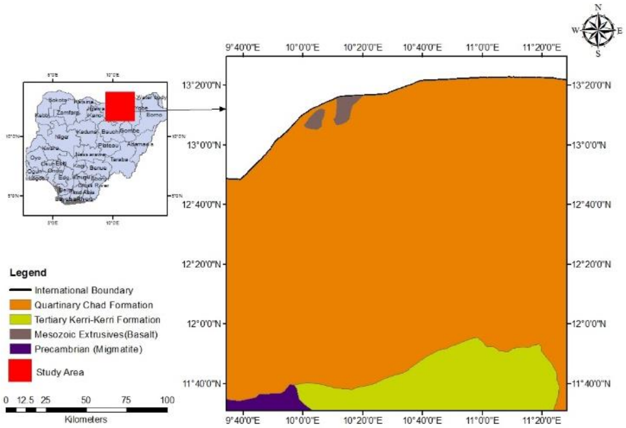

Figure 2: Geologic Map of the Study Area (United States Geological Survey (USGS), 2006)

This stratigraphy and tectonic evolution highlight the basin's dynamic history and its significance for geothermal and hydrocarbon exploration, where CPD, geothermal gradient, and heat flow remain essential for evaluating sediment maturity and resource potential.

Materials and Methods

Source of data

The high-resolution aeromagnetic data for sixteen 2° × 2° sheets across the study area were collected by Fugro Airborne Surveys (2004–2009) at 80 m altitude, with 500 m flight-line spacing and 2000 m tie-line spacing. Measurements were taken every 0.1 seconds, ensuring fine resolution. Fugro revised the data, and the project was jointly funded by Nigeria's Federal Government and the World Bank under the Sustainable Management for Mineral Resources Development initiative.

Methods of data processing

Upward continuation

Upward continuation is a geophysical technique used to reduce the influence of local magnetic anomalies and highlight broader regional features. By projecting the magnetic field intensity to a higher level above the flight altitude, it smooths short-wavelength disruptions without altering the main regional structures. This process emphasizes long-wavelength anomalies that correspond to deeper, regional geological features, thereby simplifying magnetic maps for clearer interpretation (Issa *et al.*, 2024).

$$F(x, y, -h) = \frac{h}{2\pi} \iint \frac{f(x,y,0)\,\partial x\,\partial y}{\left((x-x')^2+(y-y')^2+h^2\right)^{½}} \ldots\ldots 1$$

Where $F(x, y, -h) =$ total field at a point $F(x', y', -h)$ above the surface on which $F(x', y', -0)$ is known. $h =$ continuation height.

For this study, the data were continued upward to 4 km to better resolve Curie point depths, geothermal gradients, and heat flow while reducing the influence of shallow magnetic sources.

Spectral analysis and Curie-point depth

The aeromagnetic dataset was divided into four square grids, each measuring 60′ × 60′ (about 109.8 km × 109.8 km) and subjected to spectral analysis of the upward-continued data to estimate Curie point depth. Using the MAGMAP package in Oasis Montaj, each block was windowed, transformed with Fast Fourier analysis, and processed to determine depths to the top (Z_t) and centroid (Z_o) of magnetic sources. The radial spectral files were then converted for MATLAB analysis, enabling precise depth estimation. According to El-Sadek and Zaeimah (2024), the first step in this process involves using the slope of the longest wavelength component of the spectrum to estimate the centroid depth (Z_o).

$$\mathrm{In}\left[\frac{p(s)^{½}}{/s/}\right] = \mathrm{InA} - 2\pi/s/Z_o \ldots\ldots\ldots 2$$

where A is a constant, /s/ is the wave number, and p(s) is the anomaly's radially averaged power spectrum. The slope of the second-longest wavelength special segment is used to estimate the depth to the top boundary (Z_t) of that distribution in the second step.

$$\mathrm{Inp}\left[(s)^{½}\right] = \mathrm{InB} - 2\pi/s/Z_t \ldots\ldots 3$$

where B is the sum of the constant, the basal depth, independent of $/s/$.

In Curie point depth estimation, the basal depth ((Z_b)) of the magnetic source is taken as the Curie point depth. This value is calculated using the centroid and top depths of the magnetic source (El-Sadek & Zaeimah, 2024).

$$Z_b = 2Z_o - Z_t \ldots\ldots 4$$

Heat flow and geothermal gradient

The transfer of heat from the Earth's interior to its surface is known as heat flow. The Earth's core cooling process and radioactive heat generation in the upper 20 to 40 kilometres of the crust are the main sources of heat on Earth. Fourier's law is the fundamental formula for conductive heat transfer (Kovács, 2024). Using Fourier's

Law and the following formula, the estimate of heat flow and thermal gradient will be computed:

$$q = \lambda[\frac{\partial T}{\partial Z}] \text{ ……5}$$

To relate the Curie point depth (Z_b) to the Curie point temperature variation, the vertical direction of temperature variation, and the constant thermal gradient were assumed. The geothermal gradient $\left(\frac{\partial T}{\partial Z}\right)$ between the Earth and the Curie point depth (Z_b) was defined by the equation:

$$\frac{\partial T}{\partial Z} = \frac{580℃}{Z_b} \text{ ……6}$$

where 580°C is the Curie temperature at which ferromagnetic minerals are converted to paramagnetic minerals. Furthermore, the geothermal gradient was related to heat flow (q) using the formula:

$$q = \lambda(\frac{\partial T}{\partial Z}) = \lambda(\frac{580℃}{Z_b}) \text{……7}$$

where λ is the coefficient of thermal conductivity

A thermal conductivity of 2.5 $Wm^{-1}\,{}^{o}C^{-1}$ (Nwankwo, 2021), as the average for igneous rocks, was used to compute the subsurface heat flow. In the above equation, the Curie point is inversely proportional to the heat flow.

Results and Discussion

The Total Magnetic Intensity (Figure 3) reveals anomalies ranging from –1324.43 nT to +997.75 nT, reflecting subsurface variations in lithology, structural features, and source depth. Strong positive anomalies, often linked to igneous intrusions, basaltic flows, or crystalline basement highs, contrast with negative anomalies associated with sedimentary basins and low-susceptibility rocks. This wide anomaly range highlights the geological diversity of the area, with orientations suggesting fault systems and lineaments that influence basin development and mineralization. The distribution of anomalies highlights the interplay between basement highs and sedimentary covers, both of which are critical for hydrocarbon exploration. Comparative geophysical studies across Nigeria highlight the effectiveness of TMI mapping in delineating subsurface features. In Southwestern Nigeria, ground magnetic surveys revealed contrasts between basement highs and sedimentary basins (Layade *et al*., 2025). On the Mambilla Plateau, integrated methods identified basaltic intrusions with strong positive anomalies, which are linked to younger basalts (Yohanna *et al*., 2023). Similarly, research in the Oban Massif associated manganese deposits with magnetic highs, confirming correlations between TMI anomalies and mineralization zones (Okon *et al*., 2022). Collectively, these findings underscore TMI's value in detecting intrusive bodies, tectonic lineaments, and mineralization potential across Nigeria. Collectively, these findings demonstrate the effectiveness of TMI mapping in identifying intrusive bodies, tectonic lineaments, and mineralization potential across Nigeria.

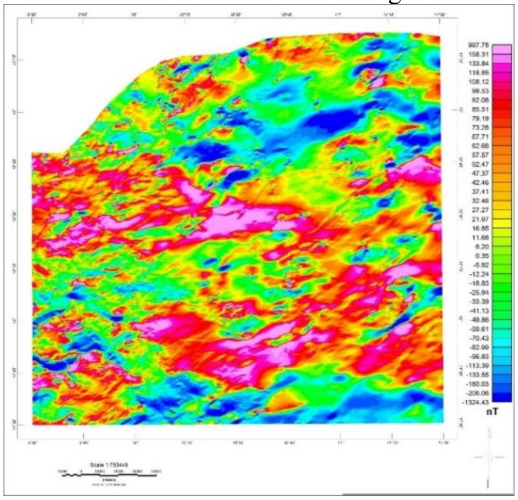

Figure 3: Total magnetic Intensity map of the area

The upward continuation of the magnetic field (Figure 4a) to 4 km effectively suppresses shallow, high-frequency anomalies and enhances deeper regional structures. Positive anomalies (~+46 nT) are linked to basement highs, intrusive bodies, or deep-seated magnetic rocks, while negative anomalies (~–54 nT) correspond to sedimentary basins or low-susceptibility zones.

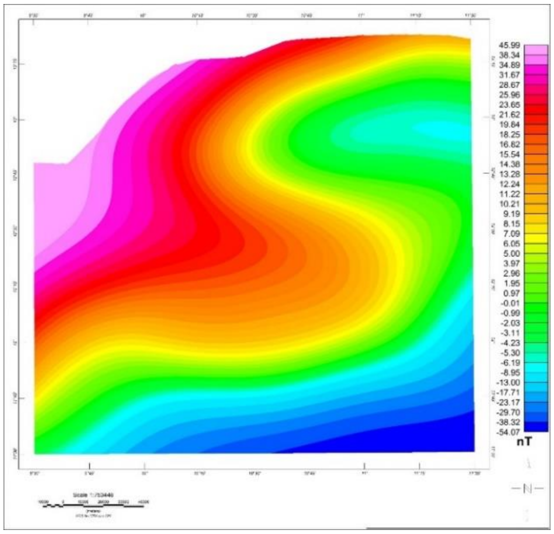

Figure 4a: Upward Continued to 4 km Map of the area

The elongated anomaly patterns suggest tectonic lineaments and fault-controlled structures, consistent with Nigeria's basement complex geology. By filtering out shallow sources, this method highlights deeper basement features critical for mineral exploration and hydrocarbon assessment.

This technique has been widely applied in Nigerian geophysical studies to distinguish shallow anomalies from deeper regional features. In the Bida Basin, upward continuation revealed deep-seated anomalies associated with petroleum system structures, thereby improving hydrocarbon prospectivity (Issa *et al*., 2024). In the Ibadan area, it was combined with reduction-to-pole methods to clarify basement structures and separate shallow from deep sources (Ganiyu *et al*., 2013). Similarly, in the Lower Benue Trough, upward continuation with reduction-to-equator filters exposed regional tectonic features, aiding structural mapping and mineral exploration (Nnaemeka *et al*., 2023). Collectively, these studies confirm its effectiveness in revealing tectonic trends across Nigeria's basement complex and sedimentary basins, supporting both hydrocarbon and mineral exploration.

The upward continuation of the magnetic field (Figure 4b) to 4 km, gridded into four equal sections (109.8 km × 109.8 km), allows localized analysis of magnetic anomalies and provides a clearer regional view of subsurface structures.

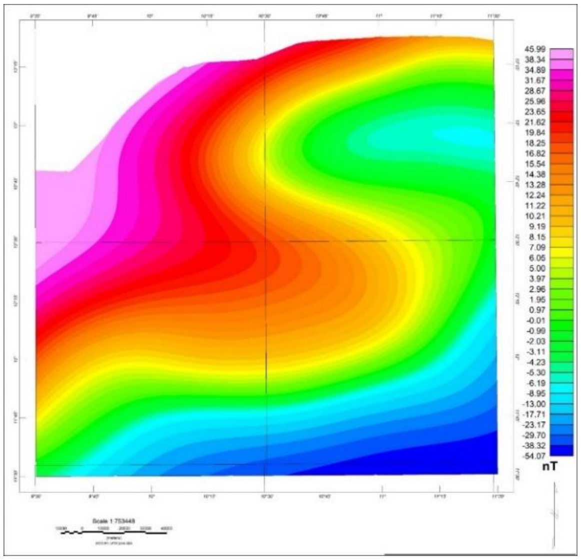

Figure 4b: Upward continued to a 4km gridded map of the area

The orientations of anomalies across the grids point to tectonic lineaments and fault-controlled structures, consistent with Nigeria's basement complex geology. By suppressing shallow anomalies, the gridded continuation emphasizes deeper basement features and facilitates comparisons across different quadrants of the study area, making it a valuable tool for distinguishing shallow anomalies from deeper tectonic features.

Spectral analysis of the aeromagnetic data across the four blocks revealed dual-depth magnetic sources, highlighting both shallow crustal features and deeper basement structures (Fig. 5). Block 1 showed depths of ~8.55 km (shallow) and ~24 km (deep), while Block 2 identified ~7.64 km and ~27.1 km. Block 3 recorded ~8.92 km for shallow sources and ~34.2 km for deeper basement anomalies, and Block 4 revealed ~7.63 km for shallow crustal features alongside an unusually deep lithospheric source at ~44.8 km. These results reflect a multi-layered crustal architecture consistent with Nigeria's basement complex, where sedimentary basins overlie crystalline basement. Comparative studies in the Benue Trough, Bida Basin, and Ibadan area reported similar shallow depths of 6–10 km and deeper basement structures ranging from 20–35 km, confirming the reliability of these findings and underscoring the structural heterogeneity and tectonic complexity of the region (Nnaemeka *et al*., 2023; Issa *et al*., 2024; Olurin, 2012).

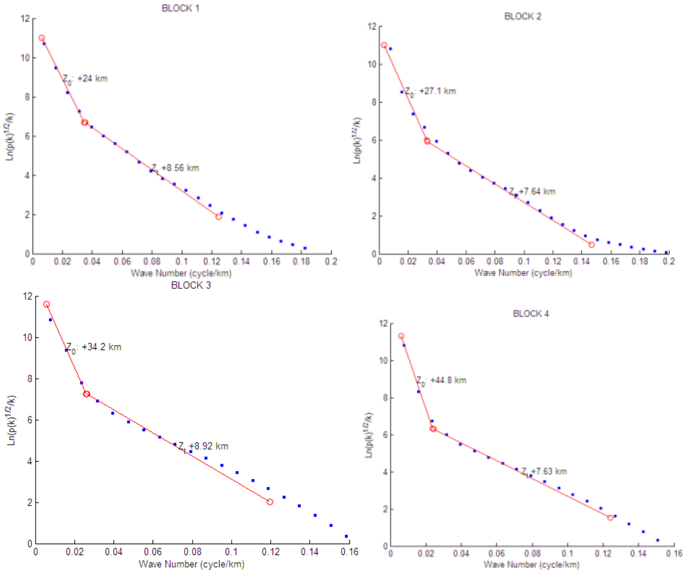

Figure 5: Spectral Blocks 1 to 4 of the area

The analysis of Curie point depth (CPD), centroid depth (Z_o), and top depth (Z_t) (Table 1) demonstrates the combined influence of burial depth and geothermal parameters on hydrocarbon and geothermal potential. Z_t values of 7.6–8.9 km mark the onset of source rock burial, with geothermal gradients of 7–15 °C/km sufficient for organic matter maturation. Blocks 1 and 2, characterized by shallower centroids (~24–27 km), higher gradients (>12 °C/km), and heat flow above 30 mW/m², are favourable for oil generation and geothermal exploitation. In contrast, deeper centroids (~34–45 km) with lower gradients (<10 °C/km) in Blocks 3 and 4 suggest gas-prone systems and reduced geothermal potential. These findings are consistent with comparative studies in the Bornu Basin, Kolmani Field, and Southern Benue Trough, where burial depths and moderate gradients have yielded gas-prone or mixed oil-gas systems (Hamza & Hamidu, 2012; Didi *et al*., 2024; Nwokoma *et al*., 2021).

Overall, geothermal viability across the blocks is primarily controlled by gradient and heat flow rather than burial depth alone. Blocks 1 and 2 emerge as promising zones for geothermal energy extraction, while Blocks 3 and 4 show limited potential. Hydrocarbon implications point toward gas-prone systems due to deeper burial and moderate heat flow, aligning with trends observed in Nigeria's inland basins.

Table 1: Summary of depth to the centroid, top boundary, geothermal gradient and heat flow

Block	Z_o (km)	Z_t (km)	Z_b(km)	dT/dZ ($^oCKm^{-1}$)	q (mWm^{-2})
1	24.0	8.56	39.44	14.71	36.77
2	27.1	7.64	46.56	12.46	31.14
3	34.2	8.92	59.48	9.75	24.38
4	44.8	7.63	81.97	7.08	17.69
Total	130.1	32.75	227.45	44.0	109.98
Average	32.53	8.19	56.86	11.0	27.50

Aeromagnetic analysis reveals strong TMI contrasts between basement highs, intrusions, and sedimentary basins, with orientations indicating fault systems and tectonic lineaments. Upward continuation highlights deeper regional structures, while spectral analysis identifies dual-depth crustal sources (7–9 km shallow, 20–45 km deep), consistent with Nigeria's basement complex. These results, supported by comparative basin studies, confirm the reliability of aeromagnetic methods for mapping subsurface structures and mineralization zones. Geothermal and hydrocarbon assessments show distinct potentials across Nigeria's inland basins. Blocks 1 and 2, with shallow centroids, high gradients, and heat flow above 30 mW/m², favour oil generation and geothermal use, while blocks 3 and 4, with deeper centroids and lower gradients, are more gas-prone and less viable for geothermal energy. Overall, geothermal potential is controlled by gradient and heat flow rather than burial depth. Compared to the East African Rift, Nigeria's basins have lower gradients, though localized zones like the Benue Trough and Bornu Basin remain promising. Integrating TMI mapping, upward continuation, and spectral analysis provides a robust framework for evaluating subsurface structures, hydrocarbon prospectivity, and geothermal potential.

Conclusion

This study successfully identifies the potentials of the area for geothermal and hydrocarbon resources. The Total Magnetic Intensity (TMI) anomalies, ranging from –1324.43 to +997.75 nT, reveal strong contrasts between basement highs and sedimentary basins. Positive anomalies correspond to igneous intrusions and crystalline basement, while negative anomalies highlight sedimentary covers and low-susceptibility rocks. The orientations of these anomalies suggest fault systems and tectonic lineaments that play a significant role in basin development and mineralization.

Upward continuation proves effective in suppressing shallow, high-frequency anomalies while enhancing deeper regional structures. This method highlights basement highs, intrusive bodies, and tectonic lineaments critical for hydrocarbon and mineral exploration. Gridded continuation further improves localized analysis, offering clearer regional comparisons across quadrants and emphasizing deeper basement features consistent with Nigeria's basement complex geology.

Spectral analysis identifies dual-depth magnetic sources, with shallow crustal features (~7–9 km) and deeper basement anomalies (20–45 km), confirming a multi-layered crustal architecture. Curie point depth and geothermal gradient analysis show Blocks 1 and 2 as favourable for oil generation and geothermal exploitation, supported by higher gradients and heat flow above 30 mW/m². Conversely, blocks 3 and 4, with deeper centroids and lower gradients, suggest gas-prone systems and limited geothermal viability. These findings align with trends in Nigeria's inland basins, where deeper burial favours gas generation, underscoring the reliability of aeromagnetic methods in guiding both hydrocarbon and geothermal exploration.

Hydrocarbon exploration should be directed toward Blocks 3 and 4, where deeper burial depths and moderate heat flow indicate gas-prone systems, while Blocks 1 and 2 should be prioritized for oil-prone prospects due to their shallower centroids and higher geothermal gradients. Geothermal energy development is best concentrated in Blocks 1 and 2, which exhibit favourable heat flow values above 30 mW/m² and geothermal gradients exceeding 12 °C/km, making them suitable for sustainable energy projects. Conversely, large-scale geothermal investment in Blocks 3 and 4 should be avoided, as their deeper centroids and lower gradients significantly reduce viability for effective geothermal exploitation.

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