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Subsurface Thermal Structure of Gombi North and Environs, Northeastern Nigeria

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ABSTRACT

The subsurface thermal structure of Gombi North and environs in Northeastern Nigeria was investigated using aeromagnetic data obtained from the Nigerian Geological Survey Agency. The study aimed to estimate Curie point depth, geothermal gradient, and heat flow, which are essential parameters for assessing geothermal energy potential. Data were processed using Oasis and MATLAB, and total magnetic intensity data were subjected to upward continuation to eliminate shallow anomalies. Spectral analysis was then applied to determine the depths of the Top Boundary and the Centroid. Results showed that the depth to the centroid ranges from 9.15 km to 12.10 km, with an average of 10.49 km, while the Top Boundary depth ranges from 4.79 km to 5.56 km, with an average of 5.32 km. The Curie point depth ranged from 13.51 km to 18.64 km, with an average of 15.65 km. These values correspond to geothermal gradients of 31.12-42.93 °C/km, with an average of 37.53 °C/km, and heat flow values of 77.79-107.33 mW/m², averaging 93.88 mW/m². The findings suggest that blocks 2 and 3 exhibit favorable geothermal conditions, highlighting their potential for geothermal energy development in the region. This study provides valuable insights into the subsurface thermal regime and supports exploration of renewable energy resources in Northeastern Nigeria.

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INTRODUCTION

Geothermal energy is a renewable resource derived from the Earth's internal heat, primarily generated through tectonic processes that occurred during and after the planet's formation (Barbier, 2002). The principal sources of this heat include residual heat from Earth's formation, the decay of radioactive minerals, and magmatic activity (Feng et al., 2018). This energy often manifests at the surface through fissures and fractures, producing hot springs when groundwater interacts with subsurface heat sources. A notable example is the Ruwan Zafi hot spring in the Lamurde Local Government Area of Adamawa State. Harnessing such geothermal resources could provide significant benefits to local communities and the nation at large, supplementing existing power supplies and contributing to economic growth (Craig et al., 2013).

To explore and quantify geothermal energy potential, various geophysical methods are employed, including resistivity, gravity, seismic, and magnetic techniques. Among these, high-resolution aeromagnetic surveys have proven particularly effective in delineating subsurface thermal structures. This method has been widely applied in geothermal studies across different regions, as demonstrated in the works of Abraham et al. (2014, 2019), Chukwu et al. (2018), Bektaş et al. (2017), Elbarbary et al. (2018), Ezeh & Magbo (2023), and Suleiman et al. (2021).

Building on these approaches, the present study utilizes aeromagnetic data to investigate the subsurface thermal characteristics of Gombi North and its environs in Northeastern Nigeria. The objective is to assess the geothermal potential of the area by estimating Curie point depth, geothermal gradient, and heat flow through upward continuation, spectral analysis, and empirical modelling techniques.

Geothermal energy, derived from beneath Earth's surface, offers a cleaner, more sustainable alternative to conventional energy sources. Considering Nigeria's current economic challenges, harnessing such renewable resources could play a vital role in revitalizing the economy. By providing reliable power to industries and other critical sectors, geothermal energy has the potential to enhance productivity and national development significantly. Accordingly, this study uses aeromagnetic data over Gombi North and its environs in Northeastern Nigeria to investigate the region's subsurface thermal characteristics. The analysis focuses on determining the Curie point depth, geothermal gradient, and heat flow through upward continuation, spectral analysis, and empirical formulas, using Oasis software as the primary tool.

Study Area

The study area is situated between latitudes 9°30′ and 10°30′N and longitudes 12°00′ and 13°00′E. It covers a total area of approximately 12,056.04 km², with a lateral extent of about 109.8 km by 109.8 km. The region is well-connected and accessible via an established network of roads and walkways (Fig. 1).

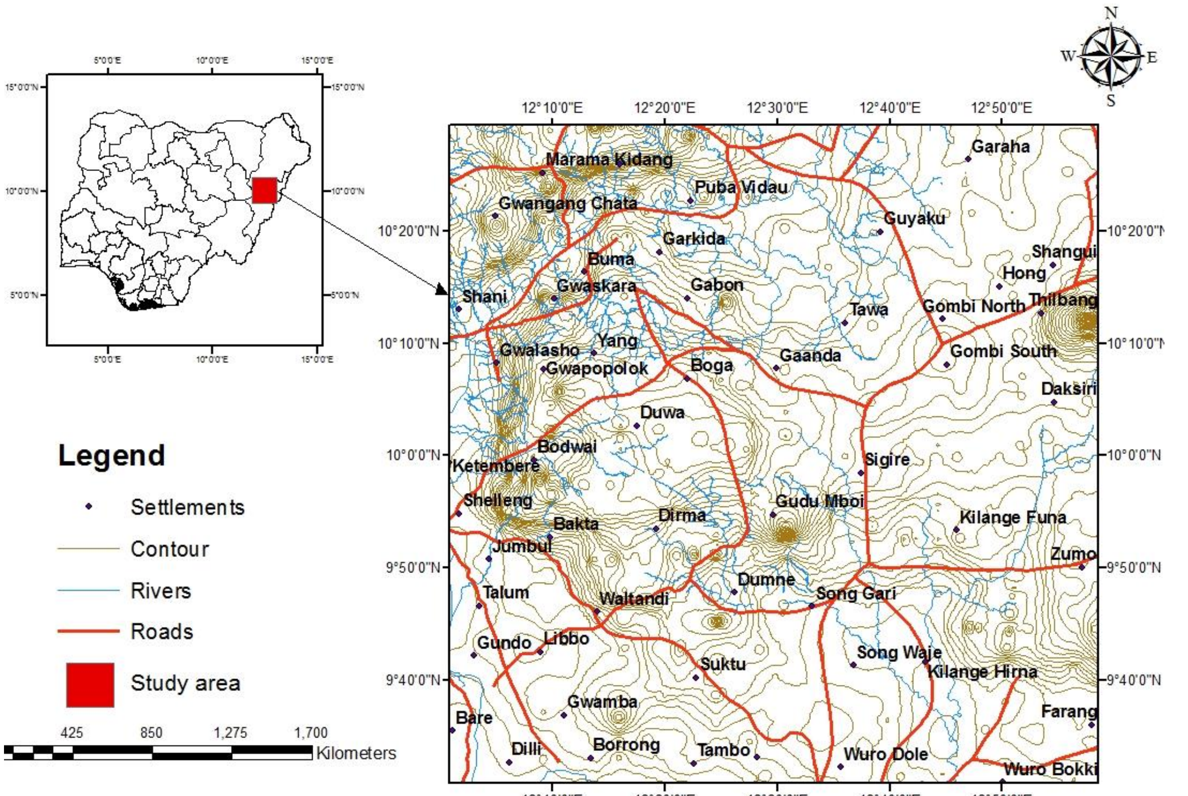

Fig. 1: Topographic map of Gombi North and environs (After SRTM/ASTER global DEM, 2006).

The area lies within the Adamawa highlands, characterized by rugged hills with elevations ranging between 800 and 1500 m above sea level. These landforms include inselbergs and whaleback ridges that define the region's physiographic setting. Climatic conditions exhibit relatively small diurnal, monthly, and seasonal variations. April is typically the hottest month, with temperatures reaching 37 °C in the northern part and 39.6 °C in the southern part of the area (Adebayo & Dayya, 2004). Conversely, December and January are the coldest months, with minimum temperatures of 15.3 °C in the north and 18.3 °C in the south.

Soils within the River Kilange catchment range from sandy loam to sandy clay, occasionally underlain by concretionary iron pans. In the northern part of the catchment, weakly developed erosion soils and non-leached ferruginous tropical soils dominate. The area is drained primarily by the Kilanye and Shashau Rivers (Bassey et al., 2006). Climatically, the region experiences two distinct seasons: a dry season from October to March and a wet season from April to September. Vegetation belongs to the Sudan Savannah type, consisting of grasses, shrubs, and scattered trees, with denser growth along river channels (Dada, 2006).

Several geothermal investigations have been conducted across Northeastern Nigeria. For instance, Ezekiel and Peter (2023) used aeromagnetic data to examine the crustal thermal structure of the Chad Basin, focusing on the Potiskum area and surrounding areas in Yobe State. Their study estimated Curie point depth, Geothermal gradient, and heat flow using spectral analysis and empirical modelling of aeromagnetic data. Results revealed centroid depths ranging from 10.50 to 11.50 km, top boundary depths between 5.90 and 7.16 km, and Curie point depths from 14.84 to 16.83 km. The Geothermal gradient ranged from 34.462 to 39.083 °C/km, while heat flow ranged from 86.135 to 97.707 mW/m².

The inferred Curie point depth suggests crustal thinning associated with thermal upwelling of magma, with values decreasing moderately toward zones of past Tertiary volcanic activity. The Geothermal gradient indicates a moderate temperature regime, which may contribute to partial thermal maturation of sediments and potential hydrocarbon generation as temperatures increase over time. Furthermore, the study established a proportional relationship between the Geothermal gradient and heat flow, whereas the Curie depth showed an inverse linear correlation with heat flow. These findings align with the region's prevailing geotectonic regime and demonstrate that the measured heat flow is sufficient to support geothermal energy exploitation.

Onyejiuwaka and Iduma (2020) conducted a geothermal study using aeromagnetic data over Ruwan Zafi, Adamawa State, and its environs in Northeastern Nigeria. Their analysis aimed to identify areas with potential for geothermal energy applications, including electricity generation and direct heating. Spectral analysis of the magnetic dataset revealed sediment thicknesses ranging from 4273.58 to 8693.32 m, while the depth to the top boundary of magnetic sources was estimated at 89.62 to 235.38 m. Basal depths ranged from 8.40 to 17.16 km. The Geothermal gradient ranged from 33.79 to 69.01 °C/km, with associated mantle heat flow values of 84.48 to 172.53 mW/m². The study concluded that geothermal prospects are most likely located in areas where thin layers of thermally insulating sediments cover basement rocks or volcanic features, particularly in Lamurde, Ruwan Zafi, Lafia, Kiri, Banjiram, and Shelleng. Geothermal gradients exceeding 48.11 °C/km and heat flow values above 120.26 mW/m² in these locations indicate high geothermal potential.

Similarly, Odidi et al. (2020) estimated Curie point depth, heat flow, and Geothermal gradient from spectral analysis of aeromagnetic data covering parts of the Benue Trough (including the lower Upper Benue, middle Benue, and upper Lower Benue), as well as the Gongola and Yola Basins, the Precambrian Basement, the Jurassic Younger Granites, and two prominent hot springs Wiki in Bauchi State and Akiri in Nasarawa State. Using radial power spectrum analysis across 48 square blocks, they determined depths to the top, centroid, and bottom of magnetic sources. Curie point depths ranged from 7.63 to 34.52 km, with a mean of 14.79 km. Geothermal gradients ranged from 16.80 to 75.97 °C/km, averaging 45.70 °C/km, while heat flow ranged from 42.01 to 189.94 mW/m², with a mean of 114.26 mW/m². These results suggest significant geothermal potential within the study area, warranting further detailed exploration.

Regional Geology and Tectonic Setting

The study area lies within the Pan-African mobile belt, a segment of the Nigerian Basement Complex located east of the West African Craton. This belt, bounded by Benin to the west and Cameroon to the east (Mathew & Emmanuel, 2013), comprises Barremian gneisses of the internal zone of the Pan-African belt, extensive reactivated high-grade gneisses believed to be Archaean, and a supracrustal succession thought to be Paleoproterozoic (Schluter, 2006). Two distinct granite generations are recognized within the basement rocks. The older granites, first described by Falconer (1911), vary widely in composition and age, ranging from 750 Ma to 450 Ma (Obaje, 2009). The younger granites, of Jurassic age, occur prominently in the North-Central Nigerian Basement as ring complexes, forming part of a broader province of alkaline anorogenic magmatism.

The study area lies within the Hawal Massif in central and northern Adamawa State, Northeastern Nigeria. According to Rahaman (1988) and Dada (2006), these rock assemblages represent one of the most significant components of the Nigerian Basement Complex. The lithologies include mica schist, tremolite schist, graphite schist, marble, dolomite, calc-silicate rocks, metaconglomerate, and banded iron formations. In addition, the Precambrian granites are diverse, comprising porphyritic and non-porphyritic muscovite granites, biotite granites, hornblende-biotite granites, aplites, granodiorites, diorites, quartz-diorites, syenites, quartz-enstatite granites, and enstatite-bearing charnockites.

The Hawal Massif, a subdivision of the Nigerian Basement Complex, lies between the Archaean blocks of the West African Craton and the Congo Craton. Few studies have examined its geology, stratigraphy, and tectonic evolution. The basement rocks are emplaced within the Pan-African Mobile belt of Late Proterozoic age (500–750 Ma) (Caby, 1989). The dominant lithologies include massive granitic plutons associated with diorite and gabbro, collectively referred to as the "Older Granites," dated between 500 and 750 Ma. Other rock units comprise migmatites and gneisses, with ages ranging from Archaean (ca. 2700 Ma) to Proterozoic (2000 Ma) (Annor, 1995). These granites are products of Pan-African tectono-metamorphic events and are characterized by high-grade metamorphism.

As part of the Pan-African Mobile Belt, the Nigerian Basement Complex has also been intruded by Mesozoic ring complexes, particularly around Jos in central Nigeria (Haruna, 2014). The Cretaceous unconformably overlies these intrusions and Quaternary sediments, which subsequently gave rise to the present sedimentary basins. Several coarse-grained granitic occurrences have been documented across Nigeria.

In the study area (Fig. 2), the geology comprises Basement rocks of the Hawal Massif and sedimentary units of the Yola Arm of the Upper Benue Trough. Migmatites and Pan-African rocks dominate the Basement.

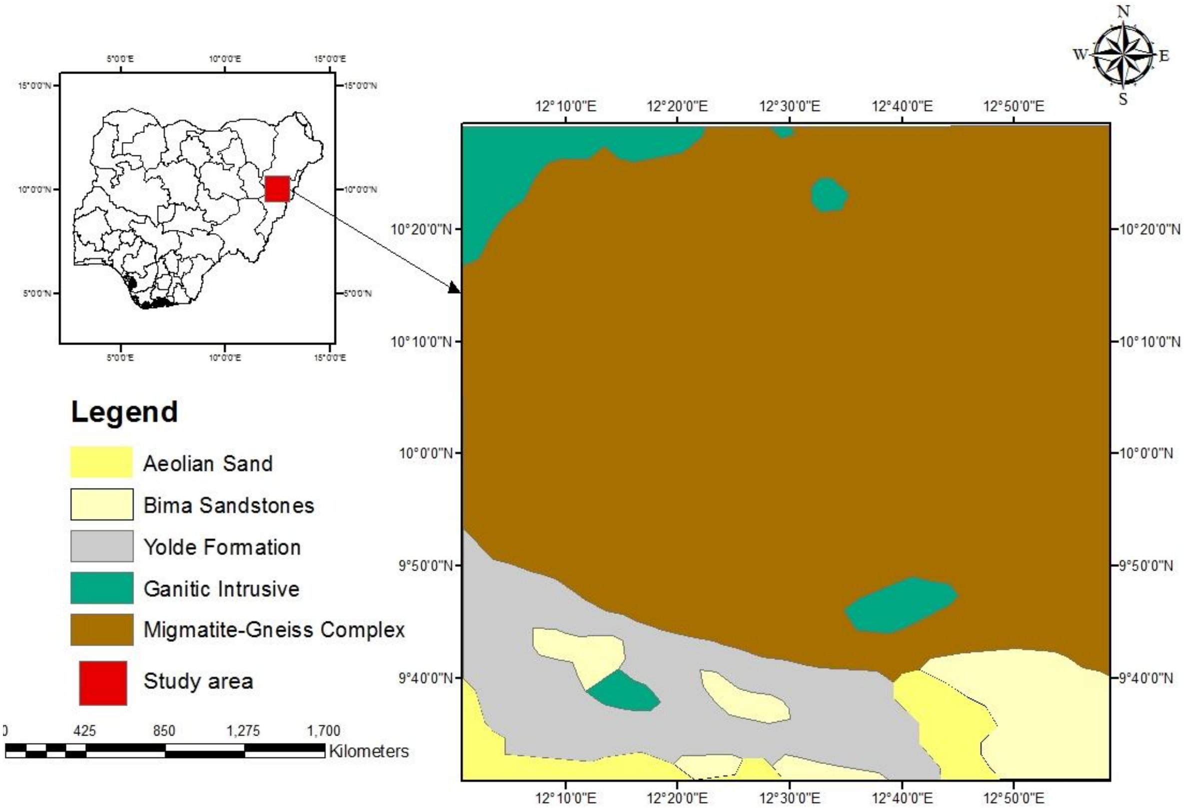

Fig. 2: Geologic map of Gombi North and environs (After United States Geological Survey (USGS), 2006).

Porphyritic granites. The migmatites consist of weakly banded, fine-grained granitic rocks cut by pegmatitic and aplitic veins, while the porphyritic granites form elongated domes and inselberg clusters. The sedimentary succession of the Yola Arm includes the Bima Sandstone, Yolde Formation, and Aeolian Sands. The Aeolian Sands represent Quaternary dune fields formed under arid-to-semiarid conditions, now stabilized by vegetation and serving as indicators of past climatic fluctuations and wind-driven sediment transport (Nabegu, 2023). The Yolde Formation is a transitional Cretaceous sequence between continental and marine environments, characterized by sandstones, shales, and carbonates deposited in fluvio-deltaic to shallow marine settings (Amodu et al., 2023). The Bima Sandstones, the oldest and thickest Cretaceous unit in the Upper Benue Trough, are subdivided into three members (B1–B3) and deposited in alluvial fan-to-braided river systems with fluvio-deltaic influences (Haruna et al., 2023). The Granitic Intrusive consists of Pan-African granites emplaced as stocks, plugs, and batholiths, including porphyritic biotite granite, coarse biotite granite, pegmatite, and microgranite, reflecting tectono-magmatic activity during the Pan-African Orogeny (~600 Ma). Finally, the Migmatite-Gneiss Complex comprises Precambrian basement rocks of banded gneisses, migmatites, and granitoids formed through multiple episodes of crustal reworking from the Paleoarchean to the Neoproterozoic, with Pan-African overprints, representing the oldest crustal foundation of Nigeria (Dada et al., 2024).

MATERIALS AND METHODS

Data Collection

The high-resolution Aeromagnetic data for this work were acquired from the Nigerian Geological Survey Agency (NGSA) in Abuja and comprise four sheets at half-degree-by-half-degree resolution. The Airborne Surveys were conducted in Nigeria by Fugro for the Nigerian Geological Survey Agency from 2004 to 2009. The Aeromagnetic surveys were carried out at a nominal flying height of 80 meters and along a sequence of 500-meter-spaced NW-SE flight lines with 2km tie-line spacing in the NE-SW direction. The Federal Government of Nigeria and the World Bank jointly funded the acquisition, processing, and compilation of the high-resolution aeromagnetic data.

Upward Continuation

Upward continuation is a geophysical technique employed to simplify the appearance of regional magnetic maps (Peters, 1949). Regional magnetic features are often obscured by numerous local anomalies, making interpretation difficult. By applying upward continuation, these short-wavelength disruptions are smoothed out, while the primary regional features remain intact. The main objective of upward continuation is to simulate the magnetic field Intensity at a higher elevation above the flight level, thereby suppressing short-wavelength anomalies and enhancing longer-wavelength anomalies that correspond to regional structures (Coles & Haines, 1979).

The mathematical expression for upward continuation is provided by Kearey et al. (2002). The upward continued magnetic anomaly F at a higher level *($Z=-h$)* is given as:

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

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.

Although there is no specific standard of depth for upward continuation (Oladejo & Ogunkoya, 2023), in this study, the total magnetic Intensity data were upward continued to a depth of 5 km. At this level, near-surface noise and intermediate anomalies are effectively suppressed, thereby enhancing the regional anomalies for subsequent analysis.

Spectral Analysis

The aeromagnetic dataset was subdivided into four 30′ × 30′ (approximately 54.9 km × 54.9 km) square grids, forming a 2 × 2 block arrangement. Upward-continued data from each block were subjected to spectral analysis to estimate the depths to the centroid *(Z_o)* and the top boundary *(Z_t)* of magnetic sources. Spectral analysis was conducted using the MAGMAP package in the Oasis Montaj environment, where the data were windowed and processed with a Fast Fourier Transform (FFT). The resulting radial SPC files were imported into Microsoft Excel and subsequently converted into a MATLAB-compatible format for further analysis. From these processed spectra, the depths to Z_t and Z_o were determined for each block. The block size was chosen based on the resolution of the aeromagnetic data: high-resolution datasets permit smaller subdivisions, while coarser data require larger blocks to ensure reliable spectra. Given the structurally complex nature of the study area, smaller blocks (minimum standard of 50 km × 50 km) were employed to capture local variations in thermal structure (Carrillo-de la Cruz et al., 2020).

Curie-Point Depth

Curie depth estimation has been approached through two main techniques: analysis of isolated magnetic anomalies and analysis of anomaly patterns (Spector & Grant, 1970; McCurry, 1976; Onwuemesi, 1997; Tanaka et al., 1999; Stampolidis et al., 2005; Nwankwo et al., 2011; Kasidi & Nur, 2012). Both methods relate the spectrum of magnetic anomalies to source depth by transforming spatial data into the frequency domain. In this study, the latter approach was adopted, whereby the depths to the centroid (Z_o) and top boundary (Z_t) of magnetic sources were derived from spectral analysis and used to estimate basal depths. High-resolution aeromagnetic data were divided into four blocks, with grid dimensions determined by a minimum 12:1 ratio between block size and source dimensions, following Tselentis (1991). The relationship used is as follows: the first step is to estimate the depth to the magnetic source centroid (Zo) from the slope of the longest-wavelength part of the spectrum.

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

Where *P(s)* is the radially averaged power spectrum of the anomaly, /s/ is the wave number, and *A* is a constant. The second step is the estimation of the depth to the top boundary *(Z_t)* of that distribution from the slope of the second-longest wavelength spectral segment (Spector & Grant, 1970)

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

Where *B* is the sum of constants independent of */s/.* Then the basal depth *(Z_b)* of the magnetic source was calculated from the equation below,

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

The obtained basal depth *(Z_b)* of magnetic sources is assumed to be the Curie-point depth (Bhattacharyya & Leu, 1975).

Heat Flow and Geothermal Gradient

In the absence of heat-flow data in the study area, an empirical formula and a one-dimensional heat-conductivity transport model were used to estimate heat flow and the geothermal gradient. The model is based on Fourier's law. In a one-dimensional case under certain assumptions, the direction of temperature variation is vertical, and the temperature gradient is. dZ/dT It is assumed constant. Fourier's law then takes the form:

$$q = \lambda[\frac{dT}{dZ}] \quad 5$$

Where q is the heat flow, and λ is the coefficient of thermal conductivity. According to Tanaka et al. (1999), the Curie temperature (θc) can then be defined as:

$$\theta c = \left[\frac{dT}{dZ}\right] Z_b \quad 6$$

In addition to that, from equations (5) and (6), a relationship was determined between the Curie point depth *(Z_b)* and the heat flow *(q)* as follows.

$$q = \lambda[\frac{d\theta}{db}] \quad 7$$

From equation 7, it is evident that the Curie point depth is inversely proportional to the heat flow. With this equation, the heat flow (q) was calculated in the study area. We also compute the thermal gradient from Equation (5) using a Curie point temperature of 580°C and a thermal conductivity of 2.5 $Wm^{-1}°C^{-1}$ (Nwankwo et al., 2011). The choice of thermal conductivity depends on rock type because different rocks conduct heat differently; therefore, the dominant rock type in the study area determines the value to use. A thermal conductivity value of 2.5 $W\,m^{-1}\,°C^{-1}$, reported as the lower limit for crystalline rocks (Elbarbary et al., 2018), was adopted in this study to compute subsurface heat flow, given the dominance of crystalline rocks comprising granites and migmatite-gneiss. The error margins for heat flow and geothermal gradients are 30 ± 5 ºC/km and 80 ± 15 mW/m^2 (Sclater & Christie, 1980)

RESULTS AND DISCUSSION

The total magnetic Intensity (Fig. 3) ranges from approximately –51.1 nT to 236.2 nT, with intense colour contrasts indicating variations in subsurface magnetic properties. High Magnetic Zones (pink to red colors) correspond to shallow magnetic sources, likely igneous intrusions, granitic plutons, or basaltic flows. Their clustering suggests tectono-magmatic activity, consistent with Pan-African reactivation and later Mesozoic intrusions. Low magnetic zones (blue to green colours) indicate deeper magnetic sources or thick sedimentary cover, typical of the Yola Arm of the Upper Benue Trough. Such zones are often associated with sedimentary basins that may host hydrocarbons or geothermal reservoirs. The anomalies appear elongated, reflecting fault-controlled intrusions and basement lineaments. These structural features are consistent with the tectonic framework of the Hawal Massif and adjoining Benue Trough, where basement reactivation and magmatism are well documented.

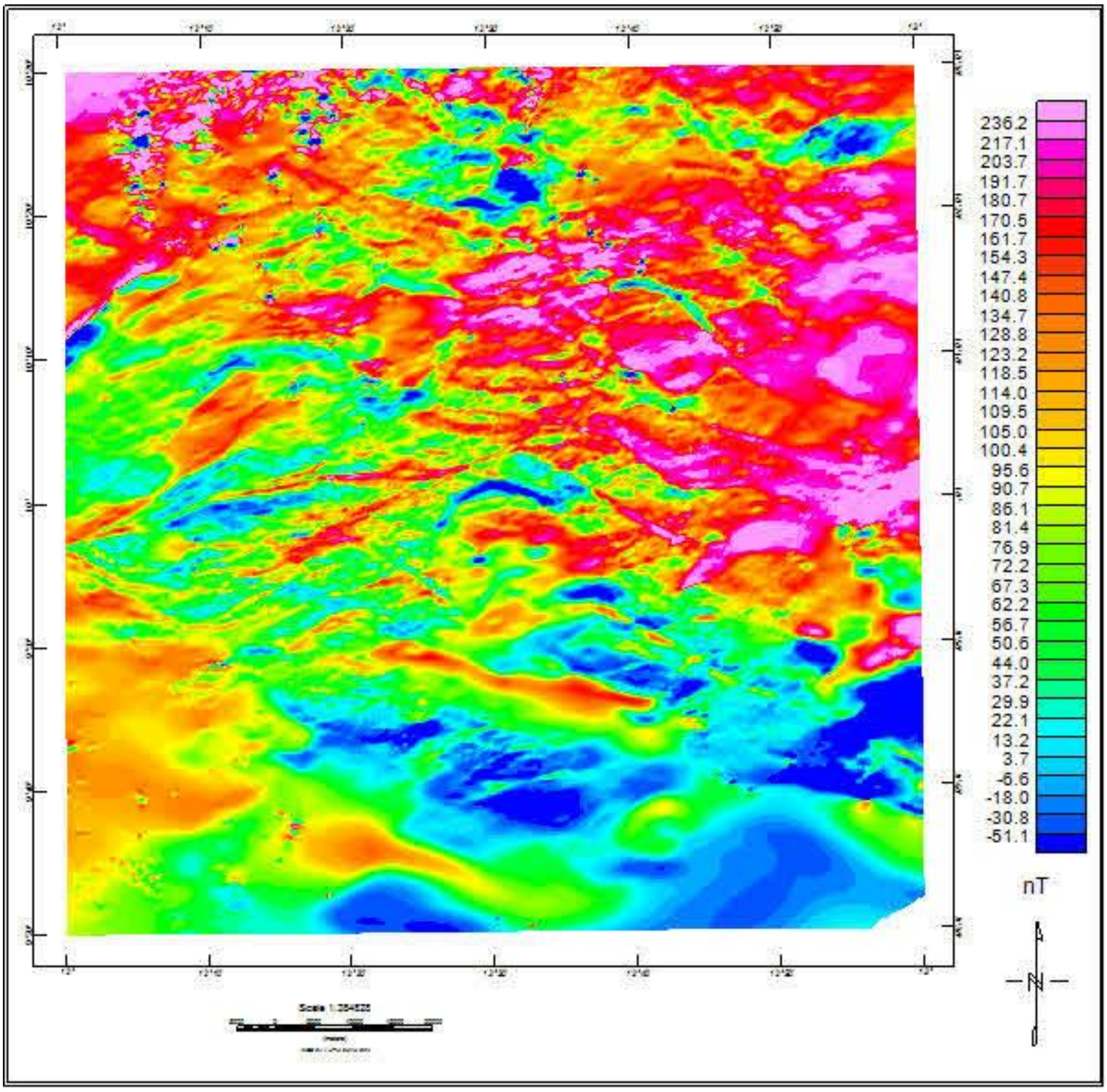

Fig. 3: Total magnetic intensity map of Gombi North and environs obtained from the Nigerian Geological Survey Agency, Abuja.

Figure 4a is the upward continuation map of Gombi North and environs. The purpose of upward continuation is to suppress short-wavelength (local, near-surface) anomalies and enhance long-wavelength (regional, deeper) anomalies. This allows more precise visualization of basement structures, tectonic lineaments, and deeper intrusions. Broad magnetic highs (pink-to-red zones) represent deeper-seated igneous intrusions or basement uplift.

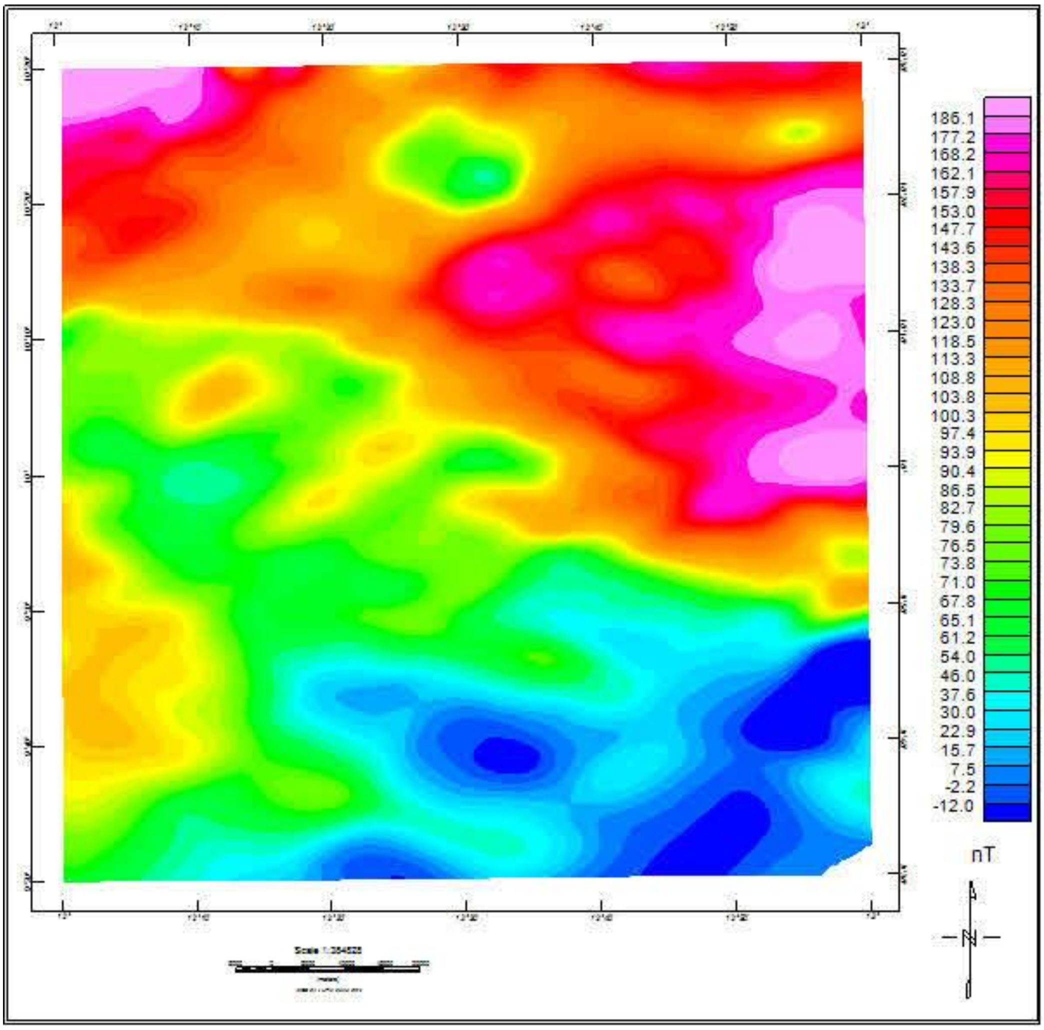

Fig. 4a: Total magnetic Intensity map upward continued to 5km of Gombi North and environs.

Their persistence at 5 km depth suggests large-scale tectono-magmatic activity, consistent with Pan-African granitic plutons and later Mesozoic intrusions (Déléris et al., 2009; Ajayi et al., 2019; Singh, 2017). Magnetic low (blue zones) indicates thicker sedimentary cover. The anomalies show elongated patterns, reflecting fault-controlled intrusions and basement lineaments.

Dividing the map (Fig. 4b) into four blocks enables localized spectral analysis, facilitating the estimation of the top boundary (Z_t), centroid (Z_o), and basal depth (Z_b) of magnetic sources. Block 1 (Northwest) is dominated by broad magnetic highs, suggesting deep-seated basement intrusions or uplifted granitic plutons. Block 2 (Northeast) shows mixed highs and lows, reflecting fault-controlled structures and variations in sedimentary cover. The elongated anomalies indicate NE–SW-trending tectonic lineaments, consistent with the regional orientation of the Benue Trough. Block 3 (Southwest) is characterized by magnetic lows, indicating thicker sedimentary sequences in the Yola Arm of the Upper Benue Trough. These zones are essential for hydrocarbon maturation and may also trap geothermal heat due to the insulating effect of the sediments. Block 4 (Southeast) displays intense magnetic highs, likely linked to igneous intrusions and crustal reactivation. The Gombi North magnetic low in Blocks 2 and 3 reflects similar crustal thinning and the development of sedimentary basins. The four-block analysis highlights dual-setting magnetic highs (Blocks 1 & 4) and deep intrusions. Magnetic low (Blocks 2 & 3) shows thick sedimentary cover and deeper sources. The NE–SW structural trends confirm regional tectonic continuity with the Benue Trough and Hawal Massif.

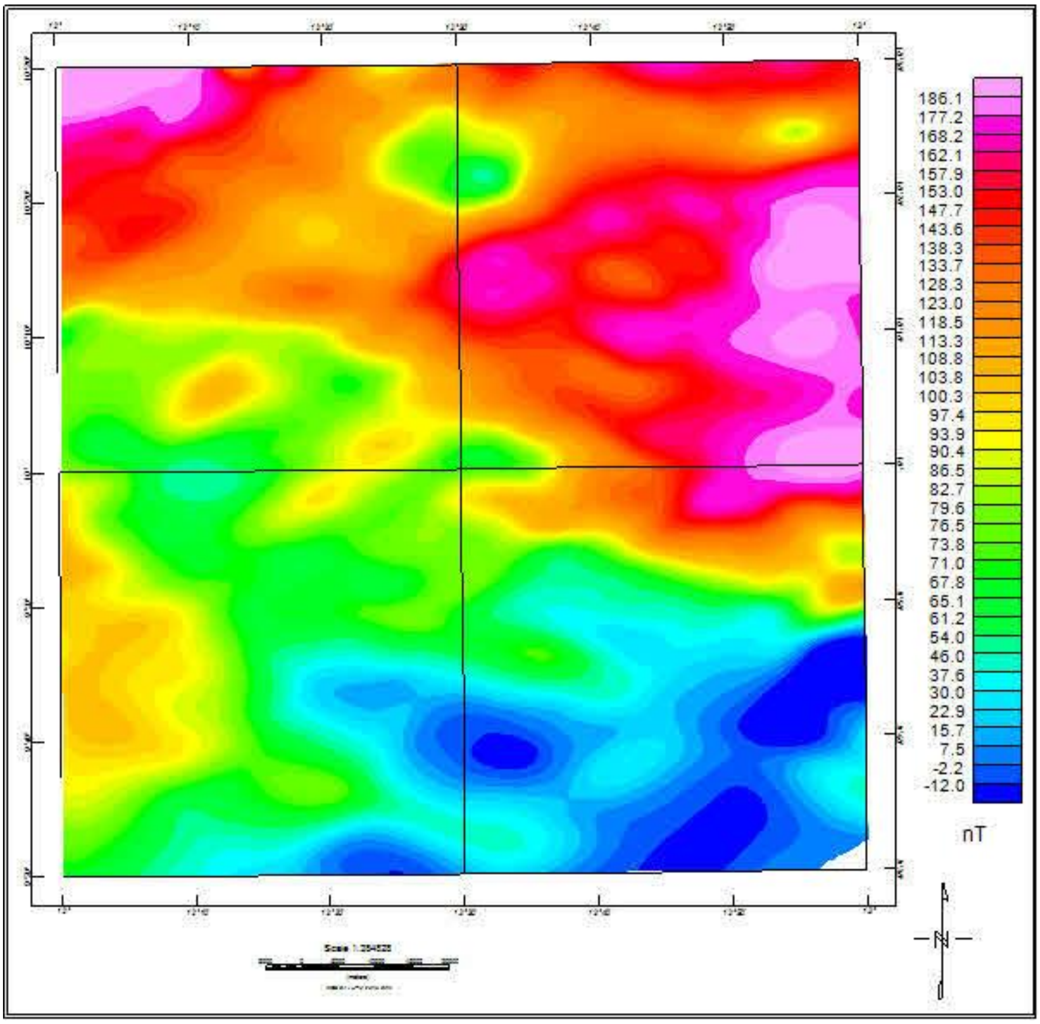

Fig. 4b: Total magnetic Intensity map, upward continued to 5km, gridded for Gombi North and environs.

Two segments characterize the graphs of spectral blocks (Fig. 5); the first segment of the slope is the deeper magnetic source depth (Z_o), while the second segment of the slope is the shallow magnetic source depth (Z_t). Table 1 summarizes the depth to the centroid, depth to the top boundary, Curie point depth, geothermal gradient, and heat flow. The depth to the centroid ranges from 9.15 km to 12.10 km, with an average of 10.49km. The depth to the top boundary ranges from 4.79 km to 5.56 km, with an average of 5.321km, which was used to calculate the Curie point depth, the Geothermal gradient, and the Heat flow. The shallow centroid and top boundary depths reflect elevated geothermal gradients and a hotter-than-average crust. These conditions accelerate organic matter maturation, enhance geothermal potential, and indicate crustal thinning associated with Pan-African plutons and later Mesozoic intrusions. With geothermal reservoirs accessible at ~5 km, exploration costs are reduced, while elevated heat flow favors mixed oil–gas systems. Overall, the results point to a thermally active crust undergoing extension, rifting, and magmatic reactivation (Hilemichaeil et al., 2024)

The Curie point depth (Table 1) ranges from 13.51 km to 18.64 km, with a calculated average of 15.65km. The Curie point depth of this value indicates that the crust is thinning, given the crust's average thickness of 40 km in continental areas (Hilemichaeil et al., 2024; Miller, 2021; Ravat et al., 2017).

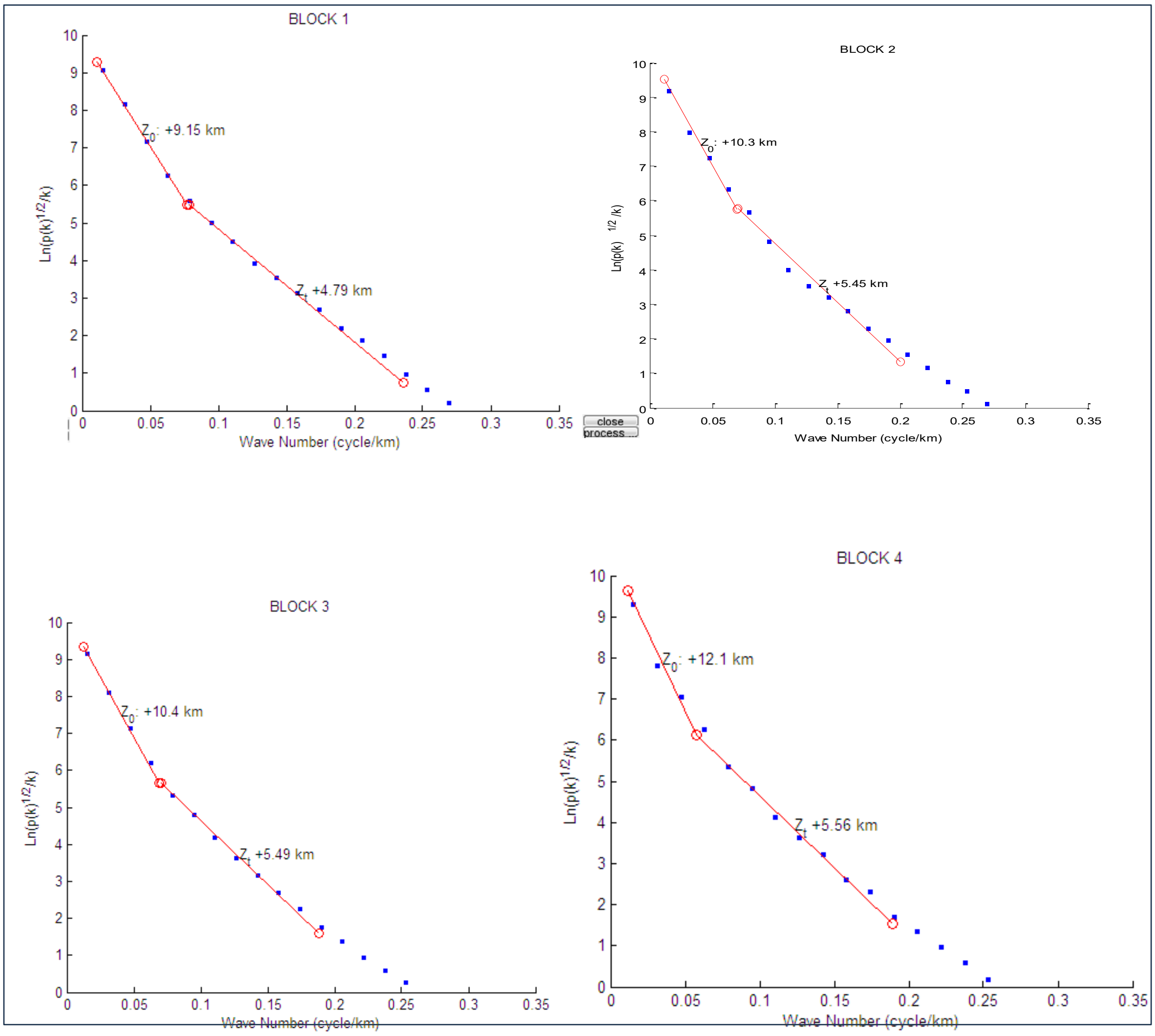

Fig. 5: Total magnetic Intensity map upward continued to a 5km gridded map. Graphs of spectral blocks 1-4 of Gombi North and environs.

Table 1: Summary of depth to the centroid, depth to the top boundary, Curie point depth, Geothermal gradient, and Heat flow of blocks 1 to 4 of the study area.

Block	Depth to the centroid *(Z_o)* km	Depth to the top boundary *(Z_t)* km	Curie point depth *(Z_b)* km	Geothermal gradient *dZ/dT)* °CKm^{-1}	Heat flow *(q)* mWm^{-2}
1	9.15	4.79	13.51	42.93	107.33
2	10.3	5.45	15.15	38.28	95.71
3	10.4	5.49	15.31	37.88	94.71
4	12.1	5.56	18.64	31.12	77.79
Total	41.95	21.29	62.61	150.21	375.54
Average	10.49	5.32	15.65	37.55	93.88

The geothermal gradient (Table 1) ranges from 31.12 to 42.93 °C km-1, with a calculated average of 37.53 °C km^{-1}, which is inversely proportional to the Curie point depth. The increase in temperature with burial depth plays a vital role in the thermal maturity of sediments for petroleum generation. That is the amount of change in organic matter in a rock layer due to heat. The Geothermal gradient determines whether the sediments are sufficiently cooked to generate oil, insufficiently cooked to generate oil, or overcooked to convert oil to gas (Momta, 2014; Ogunlana et al., 2020; Tissot & Welte, 2020). These values are notably higher than the global continental average of ~25–30 °C/km. This elevated gradient signifies a hotter crust, which enhances geothermal energy potential, accelerates organic matter maturation in sedimentary basins, and supports the development of mixed oil–gas systems. Such values are also consistent with crustal thinning and tectono-magmatic activity, reflecting long-lived thermal reactivation processes (Ogunlana et al., 2020).

The heat flow values (Table 1) obtained from the study area range from 77.79 to 107.33 mW m-2, with an average of 93.88 mW m-2. These values correspond to heat flow measurements from boreholes in the Upper Benue Trough, ranging from 43–117 mW/m2, and differ slightly from those from boreholes in Gombe State, ranging from 48–72 mW/m^2 (Odidi et al., 2023). The findings revealed that blocks 2 and 3 have heat flows of 95.71 and 94.71 mWm^{-2}, which are within the recommended range of 80 to 100 mWm^{-2} for potential geothermal areas (Kasidi et al., 2018). While block 1 has a high heat flow of 107.33 mW m-2, slightly above the recommended value, this indicates anomalous geothermal conditions. Block 4 has a heat flow value of 77.79 mWm^{-2}, which is slightly below the recommended range for potential areas. Therefore, these research findings indicate that the two blocks are potential areas for geothermal energy exploitation and, if other conditions are met, for siting a geothermal plant.

CONCLUSION

The findings of this research revealed that:

1. Depth to Centroid (Zo) ranges from 9.15 km to 12.10 km, averaging 10.49 km. This reflects the mid-level position of magnetic sources within the crust, indicating moderate crustal thickness and tectonic reactivation in the study area.
2. Depth to Top Boundary (Zt) varies between 4.79 km and 5.56 km, with an average of 5.32 km. These shallow magnetic sources suggest basement intrusions and fault-controlled structures that may facilitate geothermal fluid circulation.
3. Curie Point Depth (Zb) ranges from 13.51 km to 18.64 km, averaging 15.65 km. This depth marks the transition at which ferromagnetic minerals lose their magnetism (~580 °C). The relatively shallow Curie depths imply elevated heat flow and strong geothermal potential.
4. Geothermal Gradient ranges from 31.12 °C/km to 42.93 °C/km, with an average of 37.53 °C/km. These values exceed global continental averages (~25–30 °C/km), highlighting significant crustal heating and favourable conditions for geothermal energy development.
5. Heat Flow varies from 77.79 mW/m^2 to 107.33 mW/m^2, averaging 93.88 mW/m^2. Elevated heat flow confirms thermal anomalies, strengthening the case for geothermal exploration.
6. Priority Zones blocks 2 and 3 exhibit the most favourable combination of shallow Curie depths, high geothermal gradients, and elevated heat flow. These zones are identified as prime targets for geothermal energy exploration in Gombi North and environs.
7. The results provide quantitative evidence of crustal heating and tectonic reactivation in northeastern Nigeria. The shallow Curie depths and elevated heat flow suggest that the region could serve as a natural laboratory for studying crustal thermal regimes in intraplate settings. The findings contribute to the broader geophysical understanding of basement-controlled geothermal systems in West Africa.
8. Nigeria's energy mix is heavily dependent on fossil fuels; these findings highlight geothermal energy as a viable renewable alternative. Identifying priority zones (Blocks 2 and 3) provides a scientific basis for targeted investment and exploration policies. Policymakers can leverage this evidence to diversify energy sources, reduce carbon emissions, and enhance energy security in northern Nigeria. The study supports the formulation of national geothermal development strategies that

align with global commitments to sustainable energy.

9. This research represents one of the first systematic geothermal assessments in Gombi North, filling a critical gap in Nigeria's geothermal database. It demonstrates the utility of aeromagnetic data for geothermal exploration in regions where direct subsurface data are limited. By integrating geophysical parameters (Zo, Zt, Zb, geothermal gradient, and heat flow), the study establishes a framework for evaluating geothermal potential applicable to other parts of Nigeria and West Africa.

RECOMMENDATIONS

The study highlights Blocks 2 and 3 as priority areas for geothermal energy exploration due to their shallow Curie depths, elevated geothermal gradients, and high heat flow. To validate these findings, detailed geophysical and geochemical surveys, including resistivity, magnetotellurics, and hydrothermal fluid sampling, should be conducted. Small-scale pilot drilling in these high-potential zones is recommended to confirm subsurface temperatures and fluid availability, thereby providing a basis for assessing the feasibility of geothermal power generation or direct-use applications such as heating and agro-processing.

Integrating geothermal potential into Nigeria's renewable energy roadmap is crucial, particularly in Adamawa and the Northeast, where energy access remains limited. Government and private sector investment should be encouraged to support geothermal exploration and development. In addition, complementary hydrocarbon maturation studies in the sedimentary basins of Blocks 2 and 3 can maximize resource utilization in the Yola Arm of the Upper Benue Trough, ensuring a dual approach to energy resource development.

Finally, regional comparative studies with other geothermal prospects, such as the Ruwan Zafi, Wiki, and Akiri hot springs, can help establish a geothermal atlas for Northeastern Nigeria. Capacity building through training of local geoscientists and engineers, coupled with collaboration among universities, research institutes, and energy agencies, will sustain long-term geothermal research. Environmental and socioeconomic considerations must also be addressed, including potential impacts on groundwater and land use, while emphasizing benefits such as job creation, rural electrification, and sustainable energy supply.

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DECLARATION

Conflict of interest

The authors declared no conflict of interest.

Availability of Data

Data shall be made available upon request.

Ethical Consideration

Not applicable

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Author Contributions

Ezekiel Kamureyina designed and supervised the study, coordinated data interpretation, and prepared the initial manuscript. Saidu Ahmadu processed HRAM data and assisted in understanding anomalies. Kasidi Simon and Hayatudeen Musa contributed to the in-depth analysis and geological evaluation. Barka Jonathan supported calculations of Curie point depth, Geothermal gradient, heat flow, and thermal interpretation. Mohammed Ali Garba prepared maps, validated results, and improved the presentation of findings.