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Assessment of Sustainable Geothermal Heat Flow Potential in Parts of the Nigerian Benue Trough for Green Energy Development

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ABSTRACT
The growing demand for sustainable energy has increased interest in the Benue Trough as a potential geothermal resource region due to its tectonic structures, intrusive bodies, and elevated heat flow signatures identifiable through aeromagnetic investigations. This study evaluates the sustainable heat flow potential in parts of the Benue Trough for geothermal green energy development using aeromagnetic data from the Nigerian Geological Survey Agency (NGSA). Data processing involved reduction to the magnetic equator, upward continuation, regional-residual separation, and spectral analysis using Geosoft Oasis Montaj, ArcGIS, QGIS, and Golden Software Surfer. Results revealed significant geological structures and magnetic anomalies linked to geothermal and mineral resources. TMI and RTE maps identified high magnetic intensity zones around Ankpa, Gboko, and Igumale. Spectral analysis indicated shallow magnetic sources (0.3–3 km) and deeper sources (4–8 km, averaging 5.8 km), while Curie Point Depth estimates ranged from 8–15 km. Geothermal gradients varied between 40°C/km and 73°C/km, with heat flux values of 100–183 mW/m², confirming strong geothermal potential. High heat flow zones, including Abakaliki, Otukpo, and the Ejekwe–Ogoja structural zone, showed extensive faults, fractures, and lithological boundaries favourable for geothermal exploration. Major fault systems and intrusive bodies such as dykes, sills, and batholiths were identified as possible heat transfer pathways and heat sources, while vector mapping aligned magnetic anomalies with structural trends indicative of active geothermal reservoirs. These findings highlight promising locations for geothermal drilling, subject to further geophysical validation.

Keywords:
Sustainable,
Green energy,
Renewable,
Alternative source,
Curie depth,
Geothermal,
Heat flow.

INTRODUCTION

The increasing global demand for sustainable and renewable energy sources has driven extensive research into geothermal energy as a viable alternative to fossil fuels. Geothermal energy, derived from the Earth's internal heat, provides a consistent and environmentally friendly source of energy, making it a crucial component of the global transition toward green energy (Letcher, 2013; Dipippo and Renner, 2014; Ayuba and Lawal, 2019). In this context, the study of heat flow patterns and geothermal potential in sedimentary basins is of paramount importance. One such basin that holds significant promise for geothermal energy exploitation is the Benue Trough, a structurally complex intracontinental rift basin in Nigeria (Ayuba and Lawal, 2019; Ijeh *et al*., 2023; Onwubuariri *et al*., 2025).

The Benue Trough, which extends in an NE-SW direction across Nigeria, is characterized by a unique geotectonic framework, substantial sedimentary cover, and variable heat flow regimes (Ijeh *et al*., 2023; Onwubuariri *et al*., 2025). These attributes make it an intriguing site for geothermal investigation, particularly in the wake of increasing interest in sustainable energy solutions.

Heat flow is a fundamental parameter in geothermal studies, as it provides insights into the thermal regime of the Earth's crust and potential geothermal resources. The assessment of heat flow within a given geological region helps in identifying geothermal anomalies, understanding subsurface temperature distribution, and evaluating the heat generation capacity of underlying rocks (Kasidi, 2019). The exploitation of geothermal resources depends significantly on the magnitude and sustainability of heat

flow in a given area. Higher heat flow values often indicate regions of enhanced geothermal potential, which are crucial for sustainable green energy production.
The study of heat flow in sedimentary basins such as the Benue Trough is particularly relevant because these basins may harbour significant geothermal energy reserves within their deep-seated formations. Understanding the geothermal gradient, thermal conductivity of rocks, and heat production rates within the basin will provide essential insights into its viability as a green energy source (Ayuba and Lawal, 2019). Additionally, integrating geophysical, geological, and geochemical data will enable a comprehensive evaluation of the region's geothermal energy potential.

Geology of the study area

Figure 1 is the geologic map of the sub region of the Benue Trough (the study area) showing its localities and the sedimentary formations. The Benue Trough is an extensive sedimentary basin that forms part of the larger West and Central African Rift System regimes (Ijeh *et al*., 2023; Onwubuariri *et al*., 2025). It is subdivided into three main sections: the Lower, Middle, and Upper Benue Trough. The basin is filled with Cretaceous sedimentary sequences that were deposited in response to the rifting and subsequent subsidence associated with the opening of the South Atlantic Ocean (Fatoye and Gideon, 2013; Nwosu *et al*., 2015; Ijeh *et al*., 2023). The tectonic evolution of the Benue Trough has played a crucial role in shaping its subsurface heat flow characteristics, with significant geothermal implications.

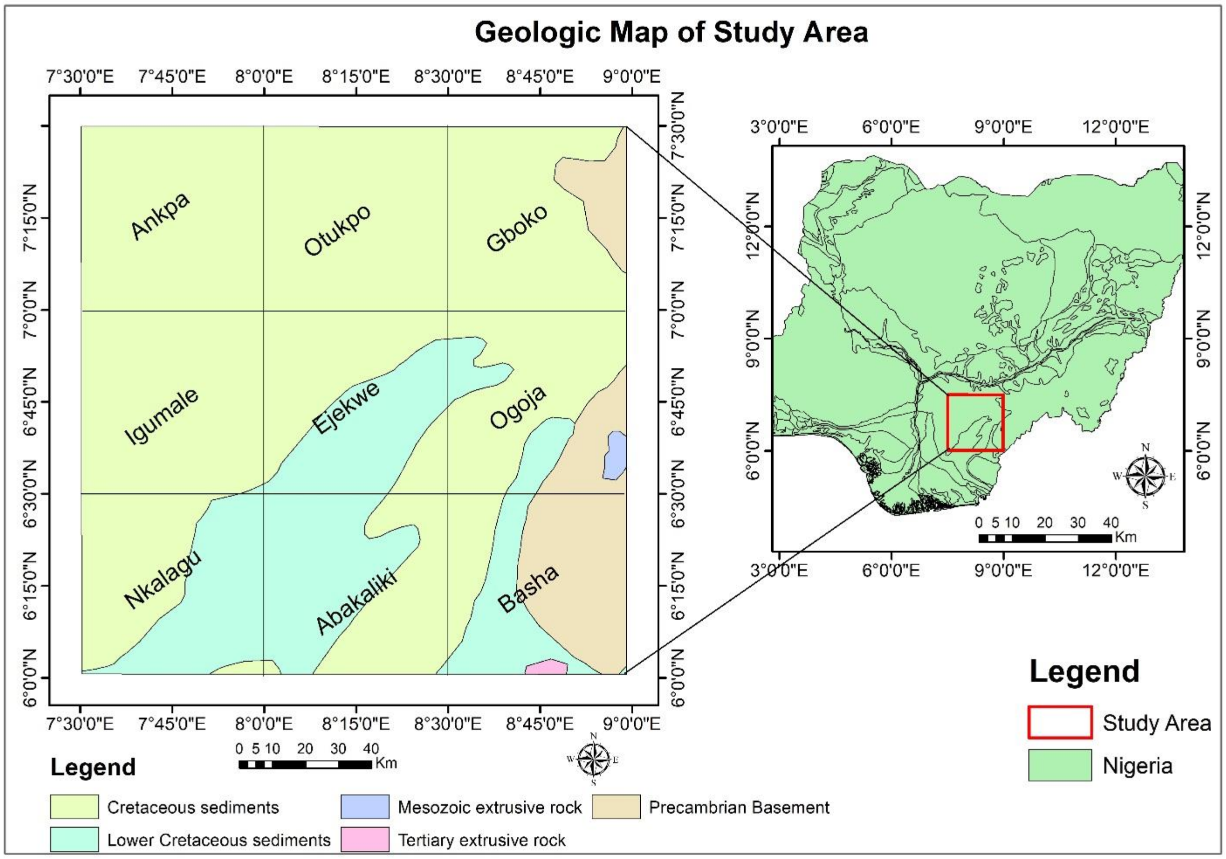

Figure 1: Geologic map of the study area

Geophysical investigations in the Benue Trough indicate the presence of deep-seated fault systems, intrusive igneous bodies, and thermally active basement rocks (Salako and Udensi, 2015; Igbokwe *et al*., 2023). These factors contribute to the region's thermal regime by influencing heat flow distribution and localized geothermal anomalies. Studies have suggested that parts of the Benue Trough exhibit elevated heat flow values, which may be linked to magmatic intrusions and radiogenic heat production from the basement rocks (Ayuba and Lawal, 2019; Ijeh *et al*., 2023; Ohaegbuchu *et al*., 2025). Understanding these geological and geophysical controls on heat flow is essential for assessing the feasibility of geothermal energy development.

MATERIALS AND METHODS

Data Source

The airborne magnetic data was sourced from the Nigerian Geological Survey Agency (NGSA). It is part of the data acquired by the Fugro Airborne Survey for the NGSA. It was collected using Scintrex Cesium vapour magnetometers on Cessna aircraft at a terrain clearance of 80 m and line spacing of 500 m. The portion of the data used for this research work covers Ankpa, Otukpo, Gboko, Igumale, Ejekwe, Ogoja, Nkalagu, Abakaliki, and Basha in Kogi, Enugu, Ebonyi, Cross River, and Benue States, respectively. These locations are part of the Lower Benue Trough in Nigeria.

The data, processed with Universal Transverse Mercator (UTM) projection and WGS 84 datum, consists of nine aeromagnetic sheets merged into one composite map for the sub regions of the Lower Benue Trough region.

Data processing involved several filtering techniques like reduction to the magnetic equator, upward continuation, regional/residual separation, and spectral analysis. Software tools included Geosoft Oasis Montaj, ArcGIS, QGIS, Golden Software Surfer, and Microsoft Excel.

Methods of Data Analysis

Two methods of data analysis are employed in this research work, vis: Qualitative and Quantitative analyses. Qualitative Analysis focuses on identifying geological features based on anomaly patterns using techniques like: Reduction to Magnetic Equator that adjusts data for better anomaly interpretation near the equator; Regional-Residual Filter, which separates long (deep) and short (shallow) wavelength anomalies; Vertical Derivatives and Analytical Signal that enhance geological structures like faults and lithological boundaries; while Upward Continuation helped to distinguish deep-seated from shallow magnetic sources.

Quantitative Analysis involves mathematical modelling to estimate the depth and characteristics of magnetic sources using Spectral Analysis to determine the depth of magnetic sources based on power spectrum methods.

An estimate of the Curie-Point Depth (CPD), which is the depth where rocks lose their magnetism at temperatures (~580°C), was done using the empirical relationship between the depths of the magnetic sources at the Curie isotherm, given as

$$Z_b = 2Z_0 - Z_t \quad (1)$$

where Z_b is the Cuire depth, Z_0 is the depth to centroid (depth to deep magnetic source), and Z_t is the depth to top (depth to shallow magnetic source).

The Geothermal gradient, measuring temperature changes with depth in $°C/km$, highlighting geothermal energy prospects was calculated using the mathematical relation between the Curie temperature and the Curie depth, given as

$$dT/dZ = 580°C/Z_b \quad (2)$$

The Heat Flow calculations estimate the average thermal energy flow within the Earth's crust and identify geothermal hotspots as a direct dependent of the geothermal gradient while accounting for the thermal conductivity (λ) of rocks within the Earth’s crust used

$$q = \lambda(dT/dZ) = \lambda(580°C/Z_b). \quad (3)$$

Equation (3) shows that the heat flux measured in mW/m^2, is inversely proportional to the Curie depth, indicating that most viable geothermal resource zones are those with shallow Curie depths.

RESULTS AND DISCUSSION

Reduction to magnetic equator (RTE)

The Total magnetic intensity map of the area was reduced to the magnetic equator as shown in Figure 2 below. This is because the data was acquired in a location that is along the equatorial zone, and hence, it is more appropriate to reduce it to the equator than to the pole, as the shape of the magnetic anomaly depends on the shape of the causative body, and hence, reducing it to the pole helps in easily preserving the original shape of the anomaly. RTP operator becomes unstable at lower magnetic latitudes because of a singularity that appears when the azimuth of the body and the magnetic inclination both approach zero, even though the magnetic susceptibility at the equator is inversely proportional to the observed magnetic intensity value, i.e. the areas with high magnetic susceptibility are depicted as having low intensity and vice-versa, this understanding is vital in the process of interpretation.

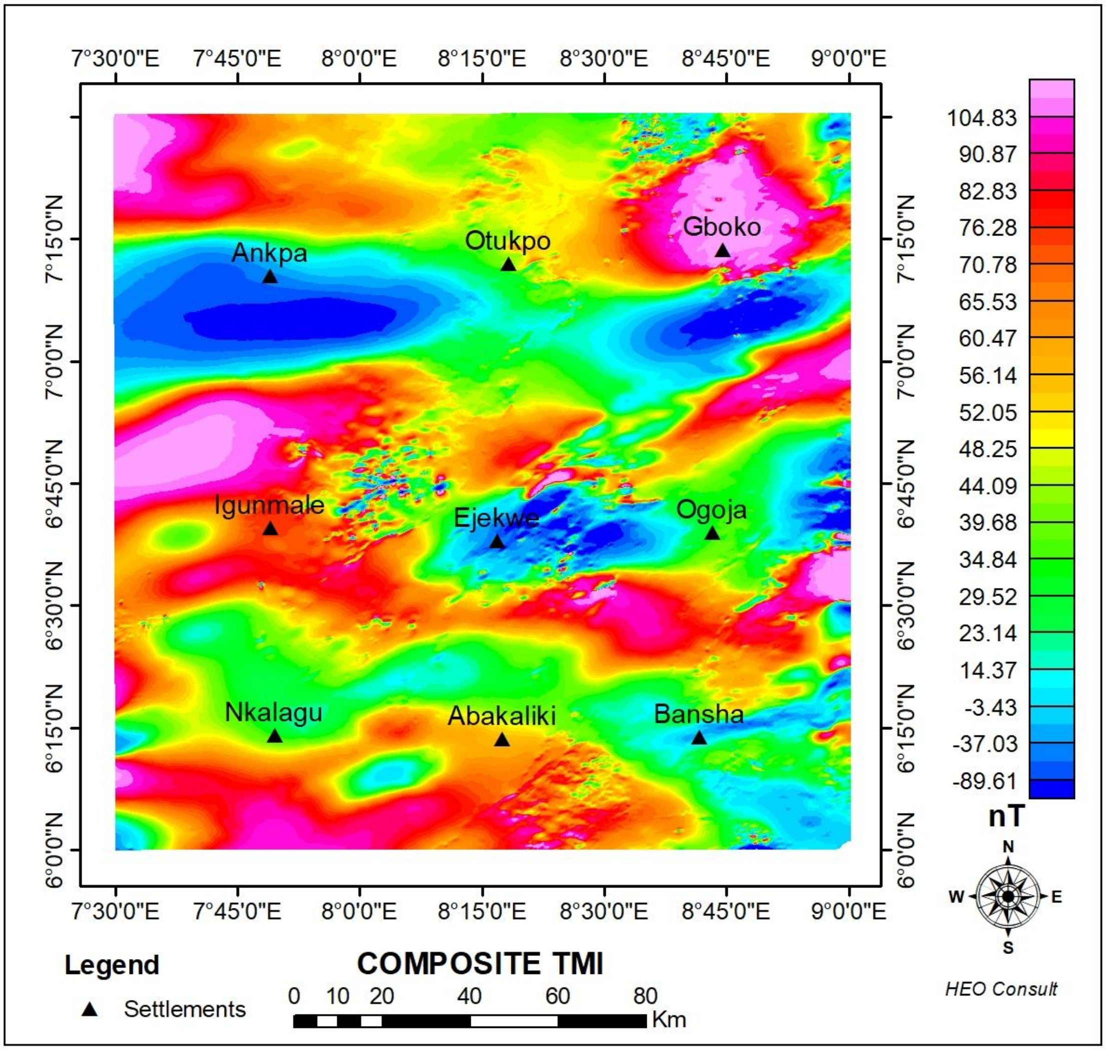

Figure 2: The RTE map of the study area shows variations in magnetic intensity due to underlying geological structures

The RTE map ranges in intensity from -89.6 to 104.8 nT. The areas with high observed intensity (pink colouration) are widespread but more prominent around Ankpa, Gboko, and Igumale, corresponding to the NW, NE, and the western part of the study area. Also, high magnetic intensity is observable around Nkalagu, Abakaliki, and Ejekwe, and at the Ogoja – Basha, Gboko – Ogoja boundaries. On the RTE map, however, low magnetic intensity can be seen in the southeastern parts of Ejekwe, the southern part of Ankpa, and the areas south of Gboko and east of Ogoja. These areas include both regional and residual anomalies.

Regional-Residual Separation

This technique differentiated deep-seated from near-surface magnetic sources, aiding in identifying tectonic and intrusive features. Figure 3 is the regional anomaly map of the study area. It shows more prominent long-wavelength anomalies due to deep-seated rocks, irrespective of their magnetic susceptibility.

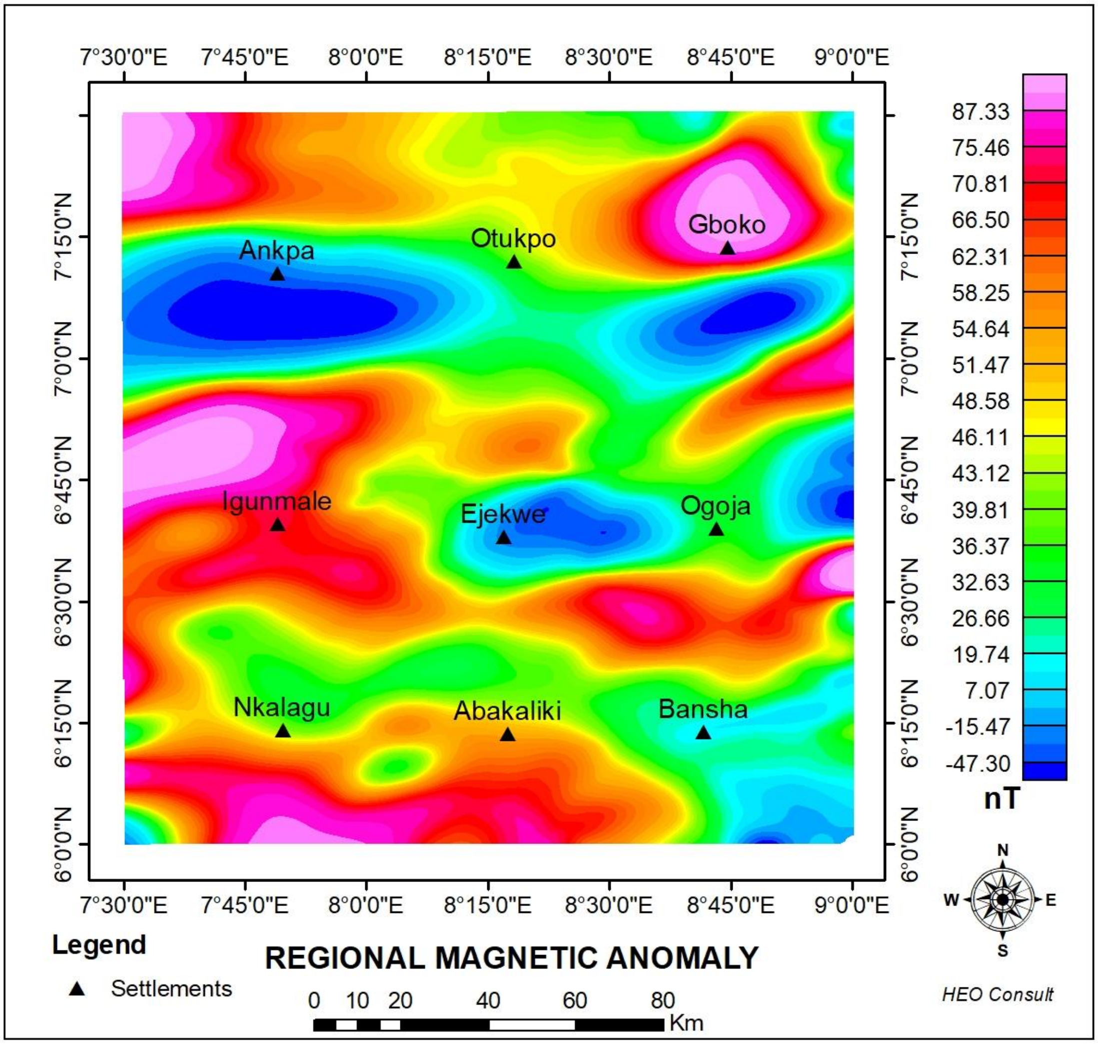

Figure 3: The regional magnetic anomaly of the study area shows the trend of long-wavelength anomalies

The map exhibits a systematic variation in magnetic intensity values, ranging from approximately -47.30 nT to 87.33 nT. The anomaly distribution follows a gradual gradient from the southwest to the northeast, indicating a regional magnetic field variation.

High magnetic intensity (pink-red-orange zone) is found in the southwestern portion of the map. This suggests the presence of highly magnetic materials such as mafic or ultramafic rocks, possibly indicative of igneous intrusions or basement uplift.

Low magnetic intensity (blue zone) is located in the northeastern region, suggesting the presence of less magnetic lithologies, possibly sedimentary cover or altered rock formations.

The presence of a strong linear gradient suggests a regional structural control, likely due to deep-seated faulting, crustal flexure, or lithological boundaries. This trend could correspond to tectonic features such as shear zones or regional-scale fault systems, which influence magnetic properties by juxtaposing rocks of differing susceptibilities.

The gradual and smooth anomaly variation suggests deep-seated sources rather than shallow localised bodies. The northwest-southeast trending gradient suggests a possible geological contact or a faulted boundary between different lithological units. The anomaly could be attributed to regional basement variations, indicating that the area might be underlain by a transition between different basement rock types.

Figure 4 is the residual anomaly map, which displays localised magnetic variations after the regional trend has been removed. Magnetic intensity values range from approximately -46.5 nT to +23.81 nT, indicating both positive (high) and negative (low) magnetic anomalies across the study area.

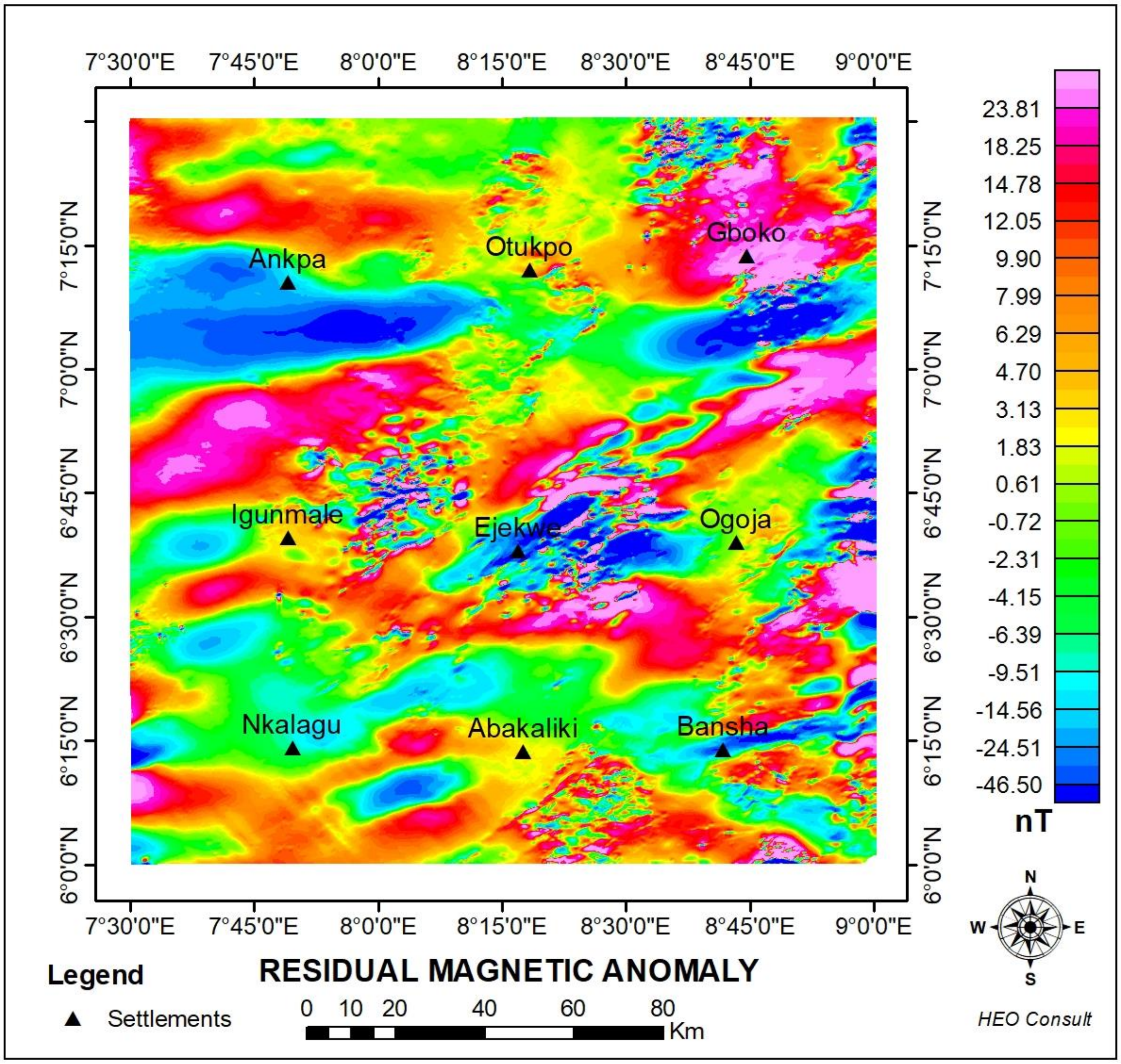

Figure 4: Residual magnetic anomaly map showing the short-wavelength anomalies in the study area

High magnetic anomalies (red to pink zones) are found in areas such as Ejekwe, Igumale, Abakaliki, and parts of Ogoja. These anomalies suggest the presence of shallow magnetic sources, likely associated with igneous intrusions, mafic dykes, or highly magnetic basement rocks.

The presence of clustered high anomalies in Ejekwe and Abakaliki suggests possible fractured or mineralised zones, which could be linked to economic mineral deposits (e.g., iron-rich formations or sulphide mineralisation).

Low magnetic anomalies (blue to deep blue zones) are prominent in regions such as Ankpa, Gboko, Nkalagu, and Basha. These negative anomalies suggest areas with low magnetic susceptibility, possibly indicating thicker sedimentary cover, altered basement rocks, or demagnetised zones.

The broad low anomaly around Ankpa and Gboko could be related to deep-seated structures such as faults, fractures, or sedimentary basins. The sharp contrasts between high and low magnetic anomalies suggest the presence of faults, shear zones, or lithological boundaries.

The elongated magnetic highs and lows trending in an NE-SW and NW-SE direction may indicate major fault zones and basement structural trends.

The Ejekwe region, with an intense localised magnetic high, could represent a possible intrusive body or a mineralised zone along a fault line.

The Abakaliki region, part of the Benue Trough, is known for its lead-zinc mineralisation. The observed anomalies here might be linked to mineralised fractures or intrusive bodies associated with hydrothermal activity. The low magnetic zones (e.g., Nkalagu, Ankpa, and Gboko) may correspond to thick sedimentary sequences, making them potential targets for hydrocarbon exploration if the area has the right geological setting. The high anomalies around Igumale and Ejekwe could be prospective for iron-bearing or other metallic deposits, possibly associated with basement uplift or igneous activity.

Vertical Derivatives

The first vertical derivative (FVD) map (Figure 5a), highlights the high-frequency components of the magnetic field, allowing for better detection of near-surface geological structures. Here, colour gradients are also used to represent variations in the vertical derivative of the magnetic field. High positive values (red, pink, and yellow regions) as visible in the Ankpa, Igumale, Gboko, Ogoja, and Basha areas, indicate strong magnetic susceptibility contrasts, suggesting shallow, high-magnetization bodies such as mafic intrusions, igneous bodies, highly magnetic basement rocks.

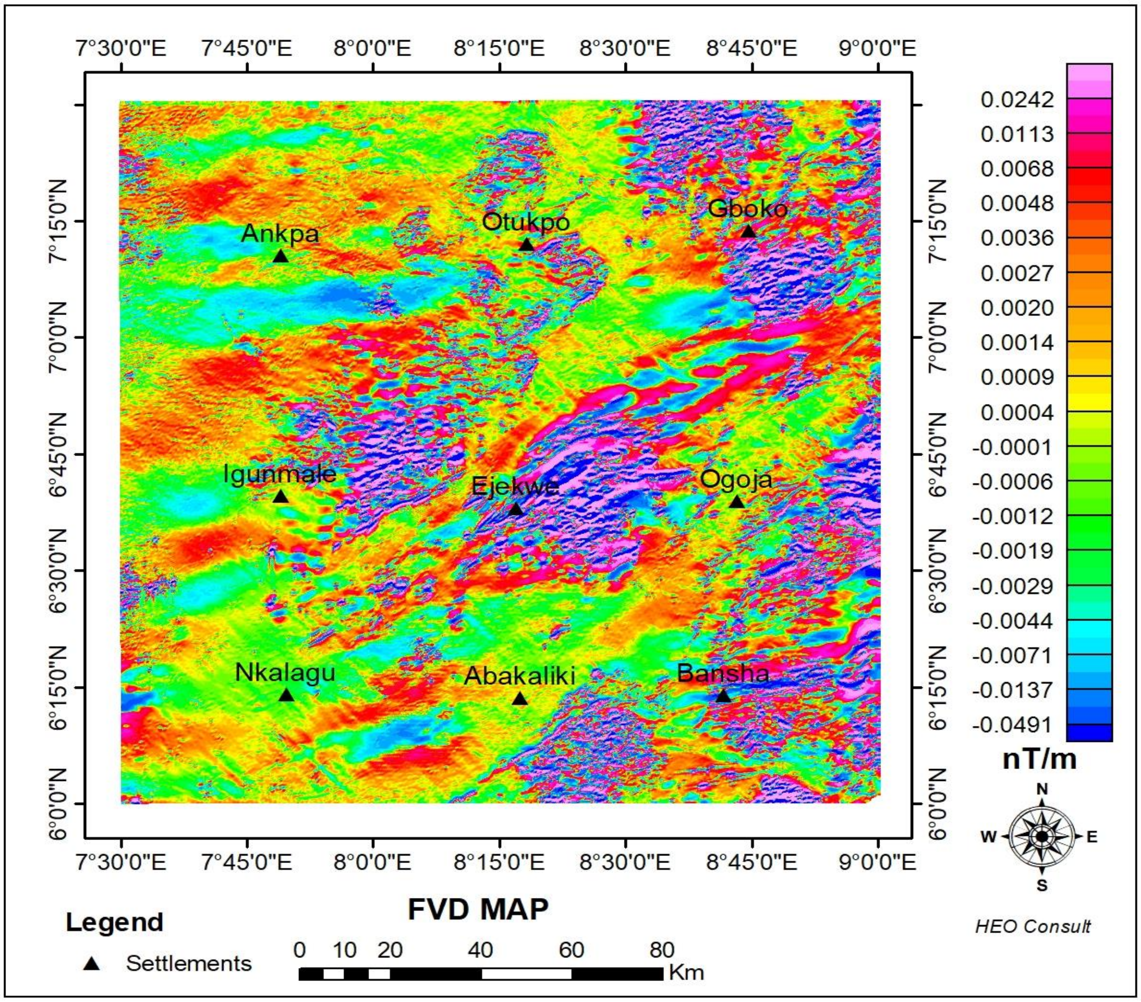

Figure 5a: First vertical derivative map of the study area showing enhanced shallow and near-surface anomalies

Low negative values (blue and purple regions) correspond to areas with lower magnetic susceptibility, possibly indicating sedimentary cover, faults, or demagnetised zones, and such is the case with some parts of Ejekwe, Gboko, Ogoja, Basha, and Abakaliki vicinities.

The linear features seen in the map, where colour gradients sharply change, suggest the presence of faults, fractures, or lithological boundaries. Several NE-SW and NW-SE trending structures can be observed, which likely represent regional tectonic trends. Some zones exhibit a high concentration of short-wavelength anomalies, which could be linked to intense deformation zones or intrusive rock formations. The alignment of magnetic highs and lows suggests faulted or folded geological formations. The areas where intense magnetic anomalies cluster together may be indicative of intrusive bodies, possibly associated with basement uplift or magmatic activities. Broader, smoother transitions between high and low magnetic values could suggest gradational geological contacts, whereas sharp, abrupt changes typically denote faulted contacts.

Locations such as Ankpa, Otukpo, Gboko, Abakaliki, and Ogoja indicate that the study area encompasses regions with diverse geological settings. The Abakaliki area is known for its sedimentary basin, and the magnetic response here may reflect deeper basement structures beneath the sediment cover. The regions of high gradient suggest tectonic activity, possibly associated with the Benue Trough or other structural lineaments in the area.

Figure 5b is the lineaments superimposed on the FVD map, showing geological structures such as faults, fractures, and lithological boundaries. Their orientations, densities, and intersections provide significant insights into the tectonic framework and possible intrusive bodies in the study area. The map reveals a high density of lineaments, particularly in the central and northeastern parts, indicating intense deformation and structural complexity. The lineaments exhibit dominant NE-SW and NW-SE trends, consistent with regional tectonic forces that have shaped the study area.

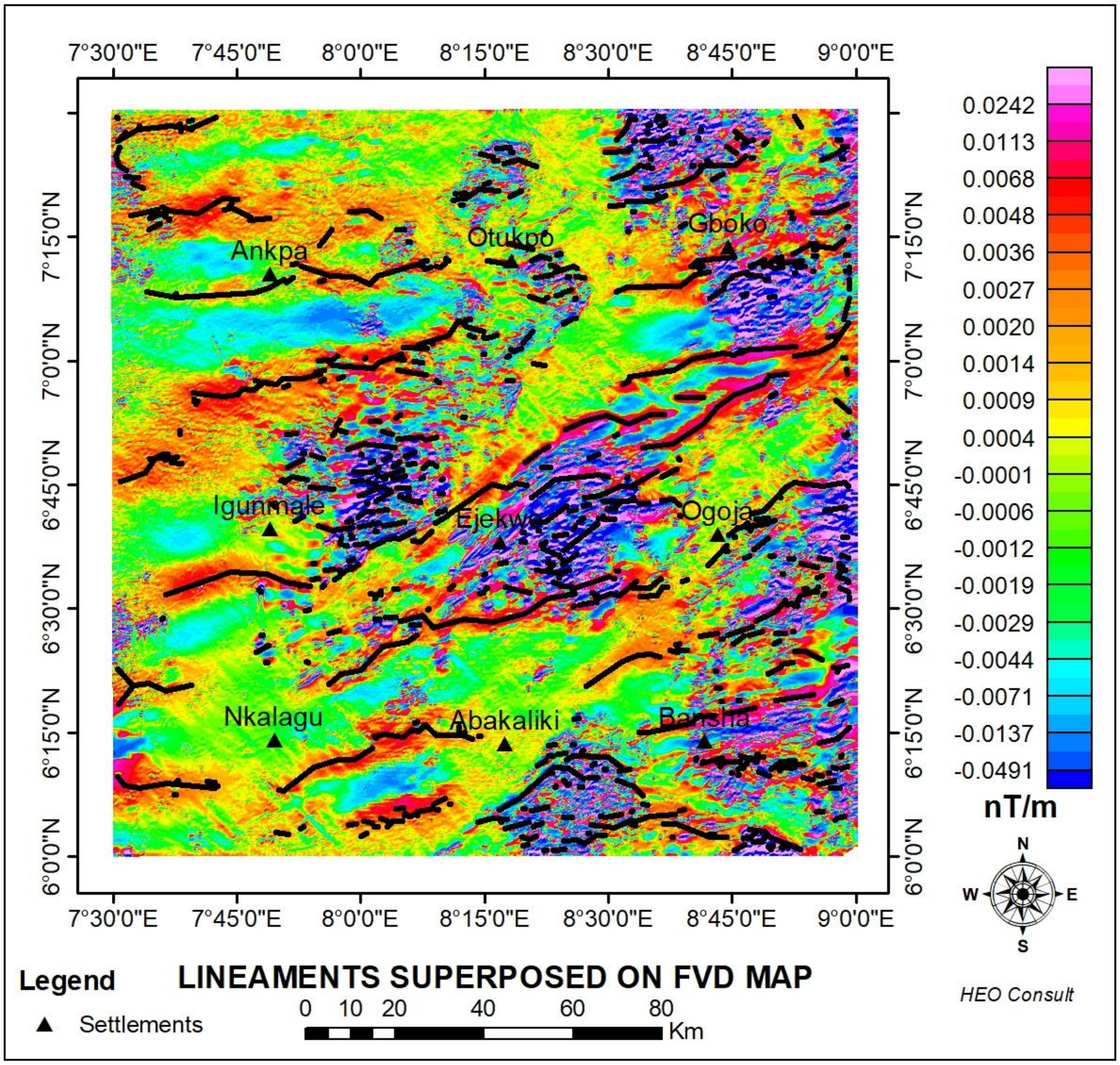

Figure 5b: Lineaments superimposed on the FVD map, showing the tectonic framework in the study area

Many lineaments are aligned with high-gradient zones (red and yellow regions), indicating structural controls on magnetic source bodies. Some lineaments are associated with low-magnetic areas (blue and green regions), suggesting possible fault-induced demagnetisation or sediment-filled fracture zones.

Ankpa & Otukpo (Northwest & North-Central) are characterised by several NW-SE and NE-SW trending lineaments, suggesting a highly faulted basement terrain, possibly influenced by deep-seated crustal fractures or older tectonic shear zones. Gboko (Northeast) displays numerous intersecting lineaments, indicative of a structurally complex region. The high lineament density suggests an area of possible shearing and deformation, possibly associated with strike-slip or transform faulting.

Igumale & Ejekwe (Central) areas exhibit strong NE-SW lineaments, suggesting regional faulting or basement fractures extending through this zone. The presence of high magnetic intensity in some regions could indicate igneous intrusions or basement uplift. Ogoja (East-Central) is marked by a significant number of short, discontinuous lineaments. This may indicate localised faulting and possible intrusive bodies, disrupting the surrounding geology.

Analytical signal map

The Analytical Signal Map (Figure 6) provides insights into the magnetic properties of the subsurface geology. The variations in colour intensity on the map represent different magnetic intensities, which can be correlated with the presence of geological structures such as faults, fractures, and mineralised zones. The elongated patterns of anomalies suggest fault lines or fold structures, which could control the localisation of mineral deposits.

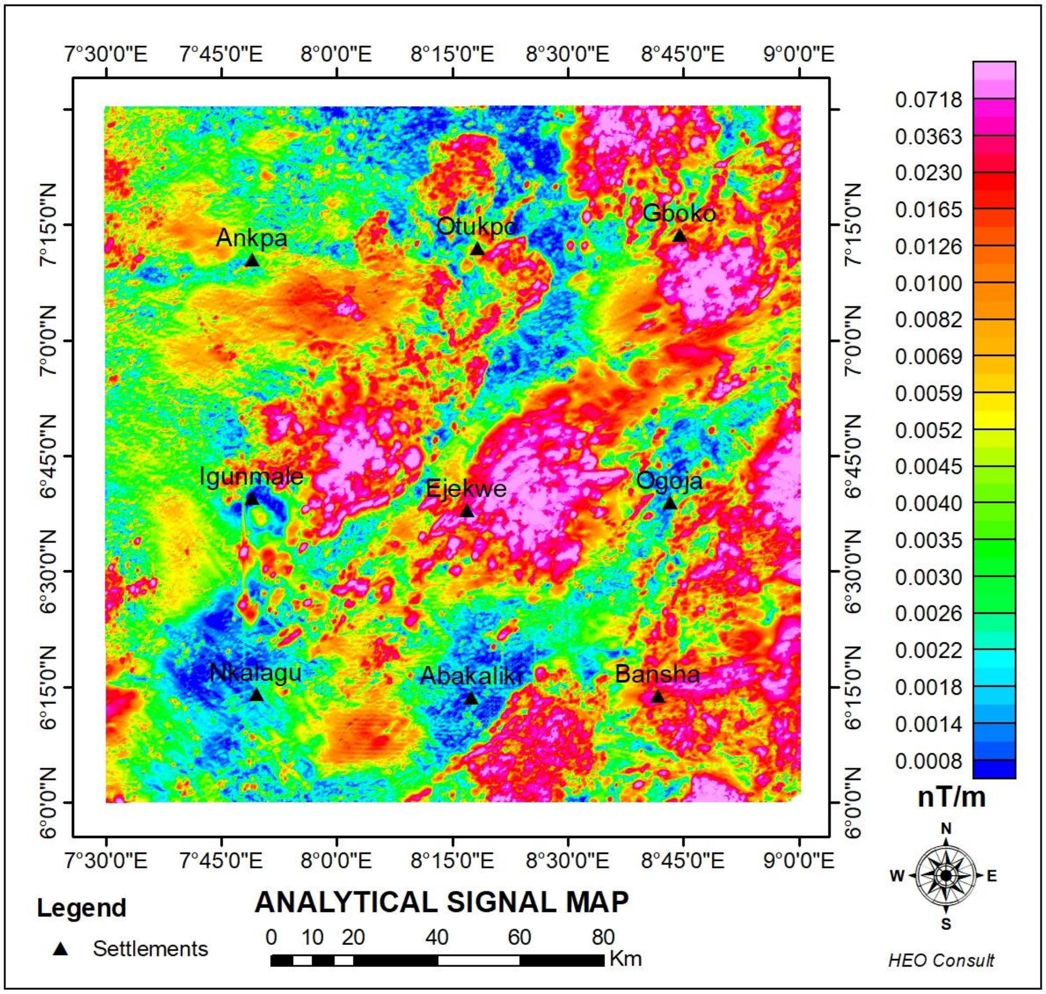

Figure 6: The Analytical signal map of the study area

Ankpa and Gboko (Northwest, Northeast) exhibit high-intensity magnetic signals (red to pink zones), which indicate the presence of strongly magnetised bodies, possibly due to igneous intrusions or metamorphic formations.

Otukpo (Central-North) has a mix of moderate (green/yellow) and high (red/pink) magnetic intensities. This could suggest variable lithology, with some intrusive or highly magnetic formations. Gboko (Northeast) is similar to Otukpo, but with a higher presence of intense magnetic zones. This could be related to structural features like faults or deep-seated mineralised zones.

Igumale (West-Central), which has lower magnetic intensity (blue and green areas), suggests less magnetised sedimentary rocks and could indicate non-magnetic formations such as shale or sandstone. Ejekwe (Central) has a strong concentration of high magnetic intensity (red and pink colours), which is likely associated with subsurface igneous intrusions or mineralised formations. Ogoja (East-Central) has mixed moderate to high magnetic responses, suggesting complex geology with possible structural deformations.

Abakaliki (South-Central) is characterised by low to moderate magnetic intensity (blue to green colours). This indicates a region with sedimentary formations, possibly associated with the Abakaliki Basin, containing shale, sandstone and limestone.

Nkalagu (Southwest) is a low-intensity zone and suggests sedimentary environments, likely limestones and shales.

Basha (Southeast) displays high magnetic anomalies in certain areas, indicating possible intrusive bodies or mineralised zones.

Upward Continuation

Upward continuation is a filtering technique which was used to enhance deeper subsurface features in the RTE map while suppressing shallower noise. Comparing the 500 m and 10,000 m upward continuation maps shown in Figures 7a and 7b provides insight into the depth of magnetic sources and potential mineralised structures.

The 500 m upward continuation map shows a highly detailed magnetic anomaly distribution with sharp variations in intensity, indicating shallow magnetic sources and near-surface geological structures. The 10,000 m upward continuation map smooths out these variations, revealing deeper and more regional structures while removing small-scale near-surface anomalies.

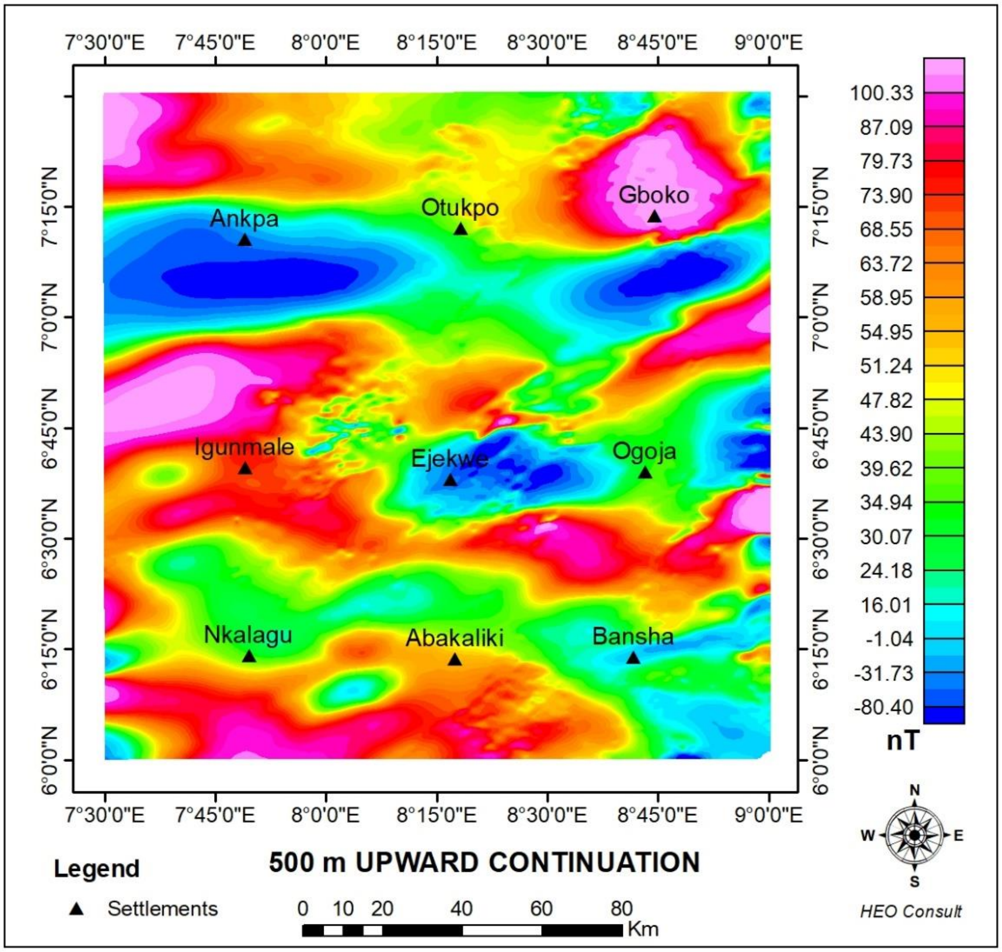

Figure 7a: Upward Continuation for 500 m Depth

Figure 7a shows high-frequency anomalies (sharp variations in colour) suggesting near-surface magnetic sources, likely related to small intrusive bodies or localised mineralised zones. The Ejekwe, Gboko, Igumale, and Nkalagu areas show strong magnetic highs (red to pink regions), which may be due to highly magnetic minerals like magnetite, pyrrhotite, or possibly iron-rich formations.

More regional-scale anomalies appear in Figure 7b, indicating deep-seated geological structures. Some anomalies persist at depth, such as around Gboko and Igumale, suggesting deep-rooted magnetic bodies, possibly large intrusive igneous bodies (plutons), mafic dykes, or mineralised zones.

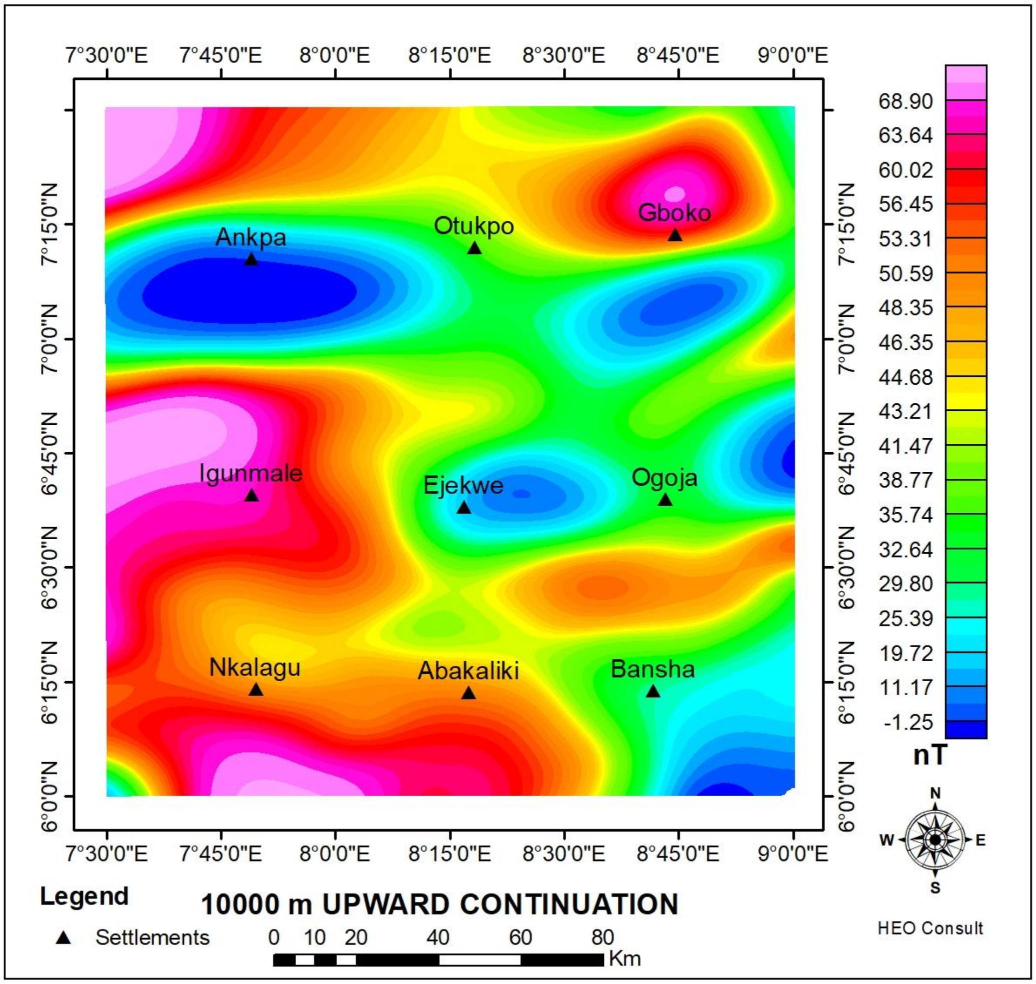

Figure 7b: Upward Continuation for 10,000 m Depth

Potential mineralisation zones are zones with persisting magnetic highs. The presence of these anomalies at both shallow (500 m) and deep (10,000 m) levels suggests large, deep-seated mineralised bodies. Areas like Gboko, Igumale, and Nkalagu show strong magnetic responses at both depths, making them promising targets for mineral exploration. The high magnetic anomalies could indicate the presence of iron ore deposits, mafic-ultramafic intrusions (potential for nickel, chromium, and platinum group elements), or hydrothermal alteration zones associated with gold and copper mineralisation.

Curie Point Depth (CPD)

The Curie point depth is the depth at which the rock begins to lose its magnetism due to extremely high temperatures. It has been estimated from the empirical relationship between the depth to the top of the magnetic source and the depth to the centroid as given by eq. 1, and presented in Table 1, alongside other parameters. Figure 8a is the 3D plot of the Curie depth which provides a volumetric perspective of the CPD distribution. The regions highlighted in red peaks correspond to deeper CPD, indicating lower geothermal gradients and potentially thicker crust in these zones. The blue troughs denote shallower CPD values, suggesting higher heat flow and thinner crust. Undulations in the 3D surface may reflect geological structures such as faults, sedimentary basins, or intrusive bodies.

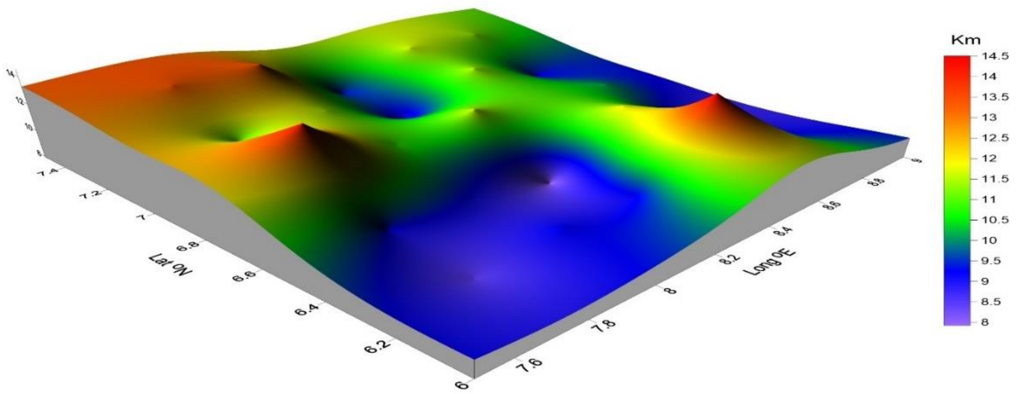

Figure 8a: The 3D surface plot of the Curie point depth of the study area

The Curie depth value for the area ranges from 7.923 km to a depth of 14.502 km, an average depth of 10.677 km as presented in Figure 8b. The southwest (comprising of Nkalagu and Abakaliki) and the eastern part (comprising parts of Gboko, Ogoja and Basha) have the lowest Curie depth of approximately 7.923 to 9.18 km, suggesting a thinner lithosphere. While Igumale, the north and the southeast (bounded by Basha and Abakaliki), have the highest Curie depth above 12.5 km, indicating the presence of a thicker crust. The study area centrally appears transitional with moderate CPD values.

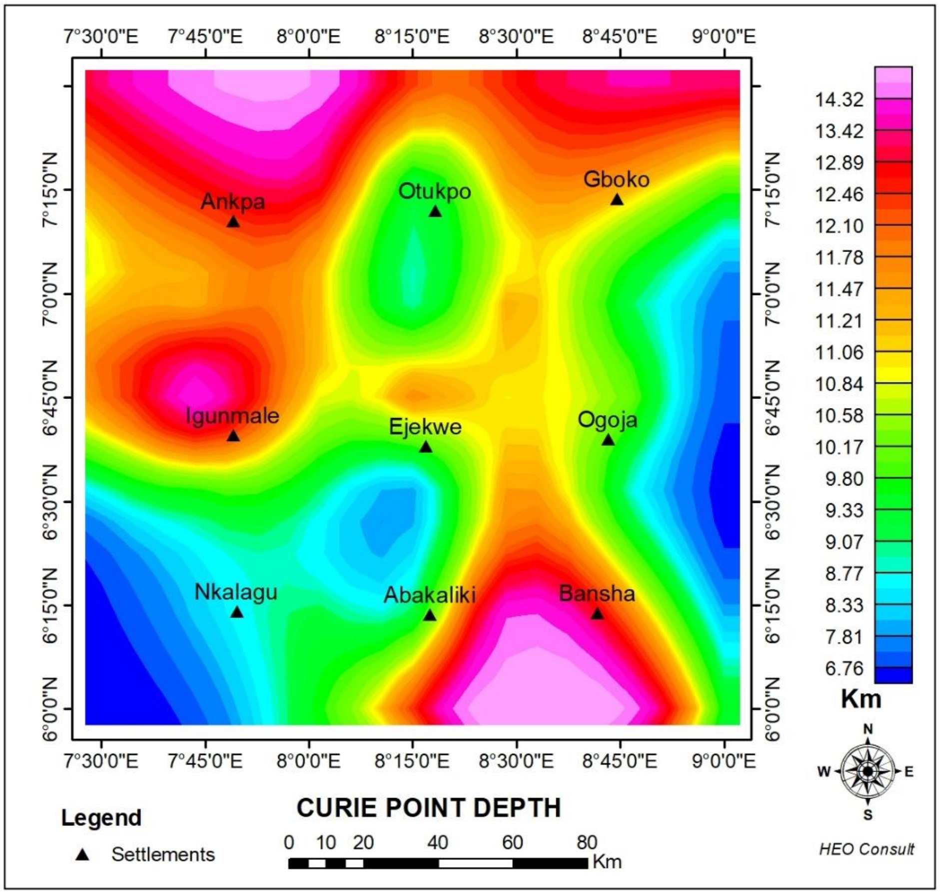

Figure 8b: The 2D contour map of Curie point depth of the study area

Geothermal gradient (GTG)

The geothermal gradient (GTG) indicates the rate of depth-dependent temperature changes in °C/km. Calculated values for the study area vary between 39.993 and 73.206 °C/km, with an average of 55.805 °C/km, and are presented in Figures 9a and 9b.

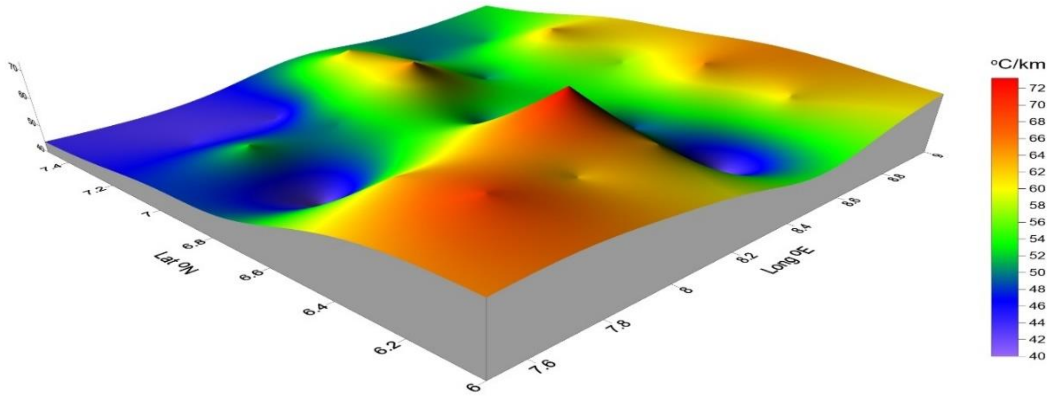

Figure 9a: The 3D surface plot of the geothermal gradient of the study area

The 3D plot in Figure 9a shows the spatial variations in the GTG across the study area. Peaks in the surface correspond to areas with high GTG (red/orange regions), suggesting higher subsurface heat flow, while valleys or depressions (blue/green regions) indicate lower GTG and associated lower heat production.

The 2D contour map of the GTG (Figure 9b) shows the distinct zones of high GTG (>68 °C/km) in the SW comprising Nkalagu and Abakaliki and in the eastern region of the study area. Intermediate values (~58 °C/km) are widespread in the central region, while low values (<48 °C/km) dominate the northern part of the study area.

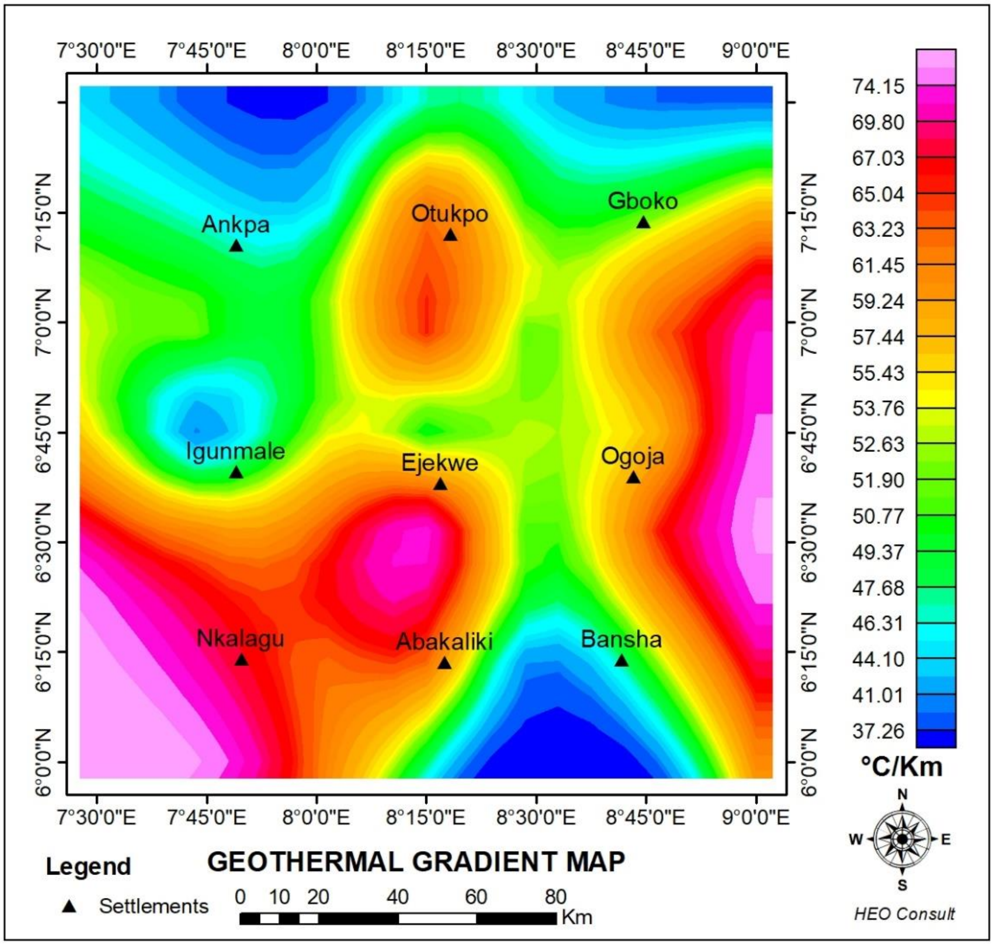

Figure 9b: The 2D contour map of the geothermal gradient over the study area shows the rate of temperature variation with depth

Heat flow

The 3D surface plot in Figure 10a showcases the spatial variation in heat flow intensity across the study area, with distinct peaks and troughs represented by varying colour gradients. High heat flow zones (red to orange shades, ~170–180 mW/m²), are around Nkalagu, Abakaliki and Otukpo. These regions exhibit pronounced heat flow peaks, indicating potential geothermal anomalies. The sharp, isolated peaks could signify the presence of intrusive dykes or magmatic bodies at shallow depths. Such structures are efficient heat conductors, transferring heat from deeper crustal levels to the surface. Geologically, the steep gradients suggest rapid heat transfer, typical of regions with igneous intrusions, which might be remnants of past volcanic activity or active geothermal systems.

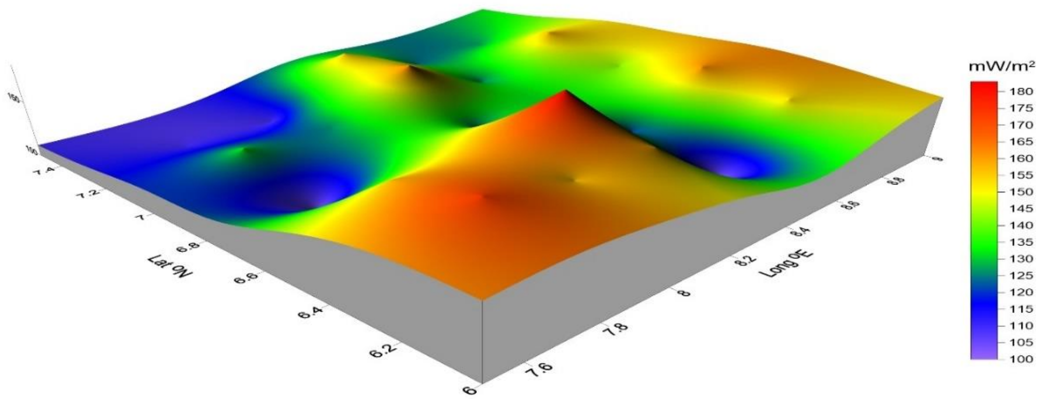

Figure 10a: The 3D surface plot of heat flow in the study area

Ogoja, Gboko, and Ejekwe are moderate heat flow zones (green to yellow shades, ~130–160 mW/m²). These areas show moderate heat flow, possibly influenced by regional geothermal gradients and fracture networks that facilitate heat conduction without significant magmatic influence.

Ankpa, Igumale, and Basha are low heat flow zones (blue to violet shades, ~100–120 mW/m²). These depressions suggest regions with thick sedimentary cover, high thermal resistance, or limited tectonic activity, where heat dissipates less efficiently, indicating a lack of intrusive bodies or effective thermal conduits.

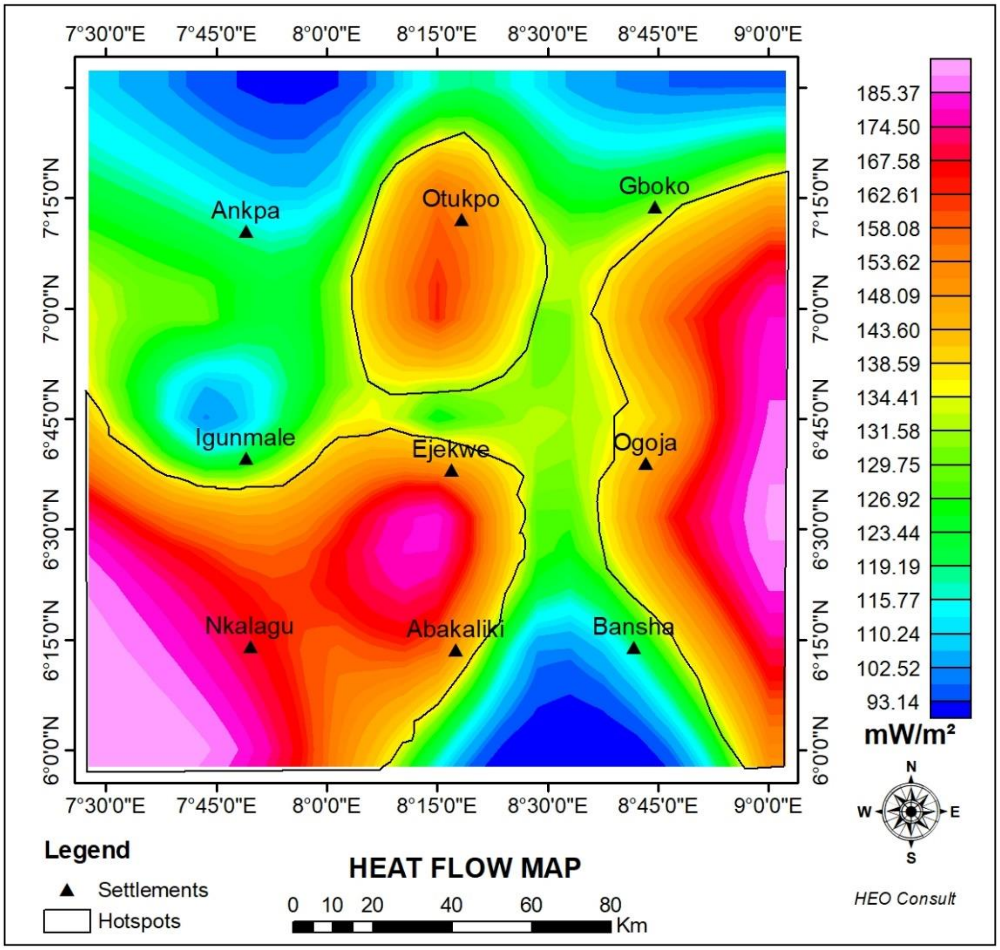

Figure 10b: The 2D contour map of heat flow in the study area

The 2D contour map (Figure 10b) complements the 3D surface plot, offering a more detailed spatial distribution of heat flow. Concentric heat flow patterns are observed around Abakaliki and Otukpo. Both display concentric contours, indicative of localised geothermal highs. These could be associated with buried intrusive dykes, sills, or batholiths. The tight contour spacing reflects steep heat flow gradients, further supporting the presence of magmatic intrusions.

There are linear trends between Ejekwe and Ogoja. The elongated heat flow patterns suggest the influence of faults or fracture zones acting as heat conduits. These linear features align with possible tectonic lineaments, facilitating upward heat migration.

Areas like Igumale and Ankpa have broad, low-gradient contours, indicating cooler, stable crustal regions. These zones might be underlain by thicker sedimentary basins or highly resistive basement rocks, limiting heat transfer.

Geological Structures and their Implications

The sharp heat flow peaks at Abakaliki and Otukpo in Figure 10a imply the presence of shallow igneous intrusions such as dykes and sills. These structures act as thermal anomalies, providing potential targets for geothermal exploration.

Linear anomalies suggest fault zones (e.g., between Ejekwe and Ogoja), which can enhance geothermal potential by increasing rock permeability and facilitating fluid flow. Areas with low heat flow (Igumale, Ankpa) are likely overlain by thick sedimentary layers (basins), which act as insulators, reducing geothermal potential.

Corroboration with Heat Flow Vector Map

The heat flow vector map (Figure 11) adds significant value by illustrating both the magnitude and direction of heat transfer within the study area. By analysing the orientation and density of these vectors, we can better understand subsurface thermal dynamics, supporting the observations from the 3D surface plot and 2D contour map in Figures 10a and 10b, respectively.

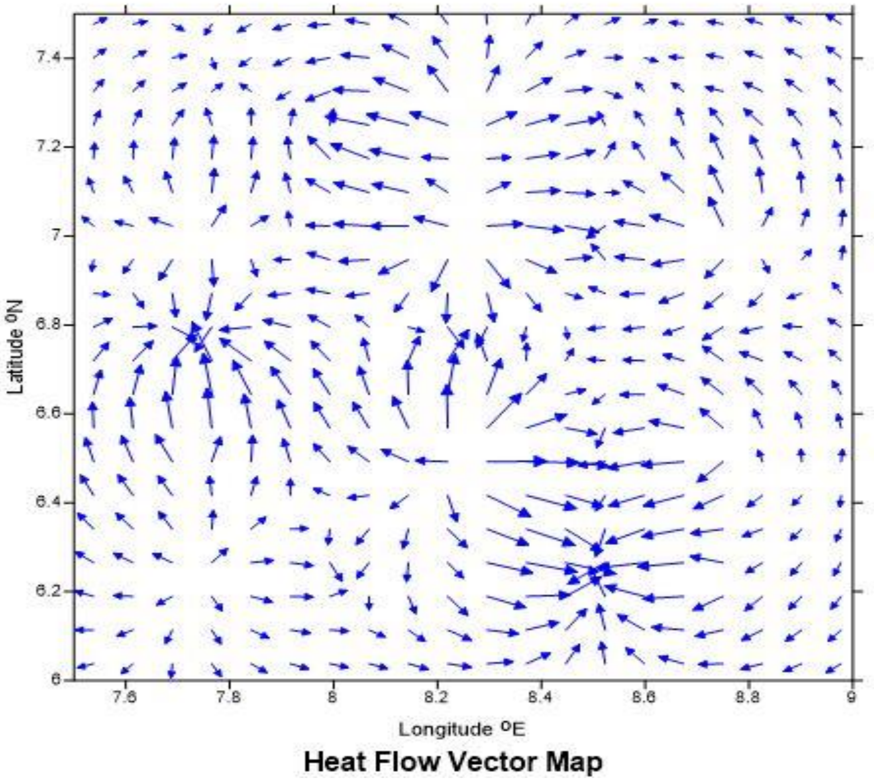

Figure 11: Heat flow vector map of the study area illustrating the magnitude and direction of heat transfers

Abakaliki (around 6.4°N, 8.2°E) is associated with high-density diverging/upward vectors, making the location a potential geothermal hotspot. Strong, densely packed vectors radiate outward from a central point, indicating intense upward heat flow, typical of shallow magmatic intrusions or active geothermal systems. This corroborates the high heat flow observed in the 3D and contour maps.

Otukpo (around 7°N, 8°E) has vectors that are also strongly directed upward and outward, suggesting an active geothermal anomaly. The heat flow concentration aligns with previously identified heat peaks.

Linear vector alignments (structural controls) are observed around the Ejekwe–Ogoja axis (near 6.6°N to 7.0°N, along ~8.3°E). Vectors are elongated and aligned, possibly along fault lines or fracture zones. These structures enhance permeability, allowing geothermal fluids to rise efficiently. This matches the linear heat anomalies from the contour map, suggesting the influence of tectonic features.

Low heat flow zones (convergent or weak vectors) are seen around Igumale and Ankpa. Sparse, weak vectors or convergent flow patterns indicate poor heat concentration. This suggests thick sedimentary cover or stable basement rocks, reducing geothermal potential.

Best Drilling Targets for Geothermal Exploration

Considering the vector intensity, direction, and previous heat flow analyses, the most promising drilling sites are categorized into primary and secondary targets. The primary target (high-priority) sites are Abakaliki (6.4°N, 8.2°E) and Otukpo (7°N, 8°E). The reasons are the strong upward heat flow, high heat flux, and potential magmatic intrusion here. The concentrated heat flow vectors indicate strong thermal anomalies and potential for high-temperature geothermal resources and active hydrothermal circulation, implying a likely shallow heat source; minimal drilling depth needed to access geothermal fluids ensures a cost-effective exploration effort on the site.

The secondary target (moderate priority) is the Ejekwe–Ogoja structural zone (~6.6°N to 7.0°N, 8.3°E). The reason is the tectonic influence with linear heat flow vectors, suggesting deep-seated fractures enhancing fluid movement. Cost-effective drilling in this area may require targeting fault intersections for optimal fluid flow.

CONCLUSION

This study investigated sustainable heat flow indicators, including geothermal gradient, Curie depth, and sedimentary thickness, within the Benue Trough using high-resolution aeromagnetic data to identify potential geothermal energy sources. Aeromagnetic data obtained from the Nigerian Geological Survey Agency (NGSA) were processed through reduction to the magnetic equator, upward continuation, regional-residual separation, and spectral analysis using Geosoft Oasis Montaj, ArcGIS, QGIS, Golden Software Surfer, and Microsoft Excel. Results revealed significant geological structures and magnetic anomalies associated with geothermal and mineral resource zones, with high magnetic intensity observed around Ankpa, Gboko, and Igumale. Spectral analysis estimated shallow magnetic source depths of 0.3–3 km and deeper sources between 4–8 km, averaging 5.8 km, representing sedimentary thickness, while Curie Point Depths ranged from 8–15 km. Geothermal gradients of 40–73°C/km and heat flux values of 100–183 mW/m² suggested strong geothermal prospects, particularly around Abakaliki, Otukpo, and the Ejekwe–Ogoja structural zone. Extensive faults, fractures, lithological boundaries, and intrusive bodies such as dykes, sills, and batholiths were identified as possible heat transfer pathways and heat sources, while vector mapping showed magnetic anomaly alignments consistent with active geothermal reservoirs. These findings agree with previous studies by Ofoegbu and Onuoha, Onwubuariri *et al*. 2023 and Abraham and Itumoh, 2019, supporting the geothermal and mineral exploration potential of the Lower Benue Trough for sustainable green energy development.

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