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Integrated Geophysical Study of Geothermal and Mineralization Potential for Energy and Strategic Resources in the Lower Benue Trough, Nigeria

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Abstract: *This study investigates the geothermal and mineral resource potential of the Lower Benue Trough (LBT), Nigeria, using high-resolution aeromagnetic and radiometric data – an integrated geophysical approach. The study area spans ~27,225 km² between latitudes 6.0°–7.5° N and longitudes 7.5°–9.0° E, covering Ankpa, Otukpo, Gboko, Igumale, Ejekwe, Ogoja, Nkalagu, Abakaliki, and Basha. Few studies have jointly evaluated geothermal and mineralization prospects in the LBT using such integration, making this work novel in bridging that gap. Spectral analysis of aeromagnetic anomalies was used to estimate Curie Point Depth (CPD), geothermal gradient (GTG), and heat flow (HF), while radiometric data validated crustal heat production and delineated mineralization zones. Results show CPD values from 7.923–14.502 km, with shallower depths concentrated in Nkalagu and Otukpo, indicating elevated subsurface temperatures. These correspond to GTG > 70 °C/km and HF > 170 mW/m². Radiometric analysis reveals significant Uranium (eU), Thorium (eTh), and Potassium (K) anomalies, supporting high radiogenic heat production and highlighting uranium–thorium mineralization potential at Otukpo, Igumale, and Nkalagu, and REE prospects at Ejekwe and Abakaliki. The findings indicate strong potential for renewable geothermal energy and critical mineral exploration, directly supporting Nigeria's energy transition and strategic mineral policies.*

Keywords*: Curie point depth, geothermal gradient, heat flow, aeromagnetic, radiometric, mineralization*

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1.0 Introduction

Knowledge of the Earth's subsurface thermal regime is vital for geothermal resource development, mineral exploration, and lithospheric studies. In Nigeria, where energy diversification and strategic mineral sourcing are policy priorities, geophysical methods such as aeromagnetic and radiometric surveys provide valuable insights.

Globally, geothermal indicators (CPD, GTG, HF) are widely used (Limberger *et al*., 2018; Li *et al*., 2020), and radiometric data provide geochemical markers of mineralization

(Mogren *et al*., 2019; Ebong *et al*., 2022). Previous Nigerian studies (Obaje, 2009; Ijeh *et al*., 2023) have noted geothermal anomalies and mineralized belts, but none have combined them comprehensively.

Despite the proven utility of aeromagnetic and radiometric methods in geothermal and mineral studies globally, the Lower Benue Trough has not been comprehensively investigated using an integrated geophysical approach. The knowledge gap is that most previous works in the region have focused either on structural geology or on isolated mineral/thermal features, leaving a knowledge gap in understanding the combined geothermal and mineralization framework. This study aims to bridge this gap by employing an integrated analysis of high-resolution aeromagnetic and radiometric data to delineate Curie Point Depth, geothermal gradient, heat flow, and radiogenic element distribution in the Lower Benue Trough. This holistic approach provides a clearer picture of the geothermal resource potential while simultaneously identifying zones of possible mineral enrichment.

The significance of this study extends beyond academic contribution. By identifying high-heat-flow zones and radiogenically enriched terrains, the findings offer practical benefits for Nigeria's energy diversification policies, particularly in advancing geothermal energy as a renewable alternative. Furthermore, mapping prospective uranium, thorium, and REE-bearing zones provides critical guidance for mineral resource development, with implications for industrial growth, strategic resource security, and sustainable economic planning.

This integrated approach is therefore novel and significant, offering practical guidance for Nigeria's renewable energy diversification and critical mineral development strategies.

1.1 Geological Setting

The study area lies within the Lower segment of the Benue Trough (LBT) in Nigeria, spanning latitudes 6.0°–7.5° N and longitudes 7.5°–9.0° E, and covering an estimated landmass of about 27,225 km². It occupies a transitional corridor between Nigeria's north-central and southeastern provinces and includes towns such as Ankpa, Otukpo, Gboko, Igumale, Ejekwe, Ogoja, Nkalagu, Abakaliki, and Basha (Fig. 1).

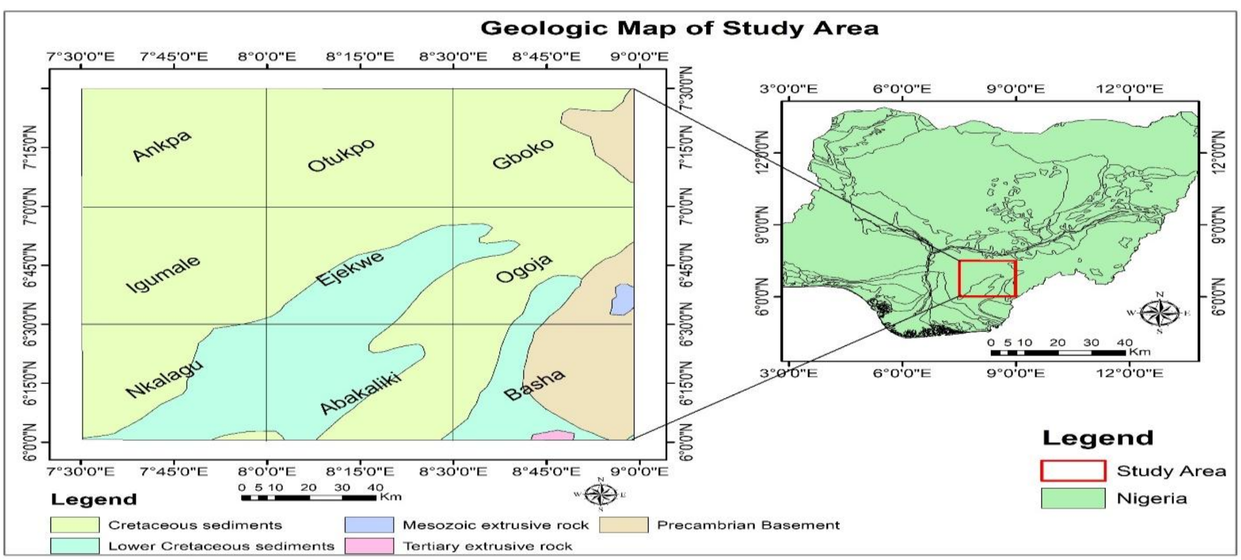

Fig. 1 shows the geologic framework of Nigeria, with emphasis on the study domain

From a geological perspective, the LBT constitutes the southern extension of the Benue Trough, a northeast–southwest oriented intracontinental rift system that originated during the Cretaceous following the rifting of the African and South American plates. The basin contains a thick Cretaceous succession of sedimentary deposits resting unconformably on the Precambrian crystalline basement. Regionally, the trough extends from the northernmost boundary of the Niger Delta in the south to the southern margin of the Chad Basin in the north (Obaje, 2009; Aigbogun *et al*., 2021).

The sedimentary infill of the LBT is dominated by fluvial, deltaic, and shallow-marine formations, including shale, sandstone, siltstone, limestone, and marl. These successions are locally intruded by felsic to intermediate magmatic bodies, such as dolerites, basalts, rhyolites, and granitic plutons, which are commonly linked to hydrothermal alteration and metallogenic activity. Such intrusions are associated with the Cretaceous rifting and magmatic phases that shaped the basin and are frequently connected to anomalously high geothermal gradients and enhanced crustal radiogenic heat production.

Structurally, the LBT displays a network of fault-bounded sub-basins and horst–graben architectures produced by extensional tectonics in the Early Cretaceous. These features govern sedimentation trends, facilitate the emplacement of igneous intrusions, and act as fluid migration pathway**s**. In particular, fault intersections and basement uplifts serve as conduits for hydrothermal fluids, thereby increasing the likelihood of geothermal manifestations and mineral accumulation, especially in U–Th–REE-enriched zones (Yakubu *et al*., 2023).

In summary, the geological framework of the Lower Benue Trough, defined by a dynamic interplay of rifting, magmatism, sedimentary deposition, and tectonic modification—provides a geologically favorable environment for the dual exploration of geothermal energy resources and strategic mineral commodities (Abraham *et al*., 2015; Fatoye and Gideon, 2013). This complexity justifies the integrated aeromagnetic and radiometric methodology employed in this research to unravel the region's geothermal and mineral potential.

2.0 Materials and Methods

This study utilized high-resolution aeromagnetic and radiometric datasets to estimate geothermal parameters—Curie Point Depth (CPD), geothermal gradient (GTG), and heat flow (HF)—as well as to validate thermal anomalies and identify mineral prospects in the Lower Benue Trough (LBT). High-resolution aeromagnetic and radiometric datasets (flight-line spacing 500 m, mean terrain clearance 80 m) were sourced from the Nigerian Geological Survey Agency (NGSA). Radiometric channels included U (ppm), Th (ppm), and K (%). Standard leveling and noise corrections were applied to minimize acquisition errors.

2.1 Aeromagnetic Data Acquisition and Processing

A total of nine aeromagnetic maps were sourced from NGSA. These maps cover the following sheets and corresponding towns: Ankpa (Sheet 269), Otukpo (270), Gboko (271), Igumale (288), Ejekwe (289), Ogoja (290), Nkalagu (302), Abakaliki (303), Basha (304).

These datasets were merged to produce a composite Total Magnetic Intensity (TMI) map of the study area. The TMI data were subjected to a series of geophysical processing techniques using Oasis Montaj™, Surfer® and ArcGIS environments to enhance signal quality and isolate relevant anomalies.

The key preprocessing steps included Reduction to the Equator (RTE) - applied to correct for the inclination and declination of the geomagnetic field, ensuring that magnetic anomalies appear directly above their sources, which is crucial near the magnetic equator.

Regional–Residual Separation - performed to isolate shallow crustal sources from deeper background trends. The residual magnetic anomalies emphasize short-wavelength features often associated with near-surface geological structures and mineralization zones.

2.2 Spectral Analysis and Estimation of Geothermal Parameters

The residual magnetic grid was subdivided into 25 overlapping spectral blocks. Each block underwent spectral analysis using the Fast Fourier Transform (FFT) method. This technique converts spatial domain data into the frequency domain, facilitating the estimation of magnetic source depths.

Following the method of Tanaka *et al*. (1999), the depth to the top of magnetic sources (Z_t), and the centroid depth (Z_0) were computed from the slopes of the high and low-frequency portions of the radially averaged power spectrum, respectively.

The Curie Point Depth (Z_b) was then estimated using the empirical relation:

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

Subsequently, the geothermal gradient ($\frac{dT}{dZ}$) between the surface and the Curie depth was calculated using:

$$\frac{dT}{dZ} = \frac{T_C}{Z_b} \qquad (2)$$

where T_C is the Curie temperature, assumed to be 580 °C for magnetite-bearing rocks.

The heat flow (q) was estimated using Fourier's law:

$$q = \lambda \cdot \frac{dT}{dZ} \qquad (3)$$

with thermal conductivity λ = 2.5 W/m·K (typical of Nigerian granitoids; Reiter *et al*., 2020).

2.3 Radiometric Data Processing and Mineral Analysis

Radiometric data comprising Uranium (U in ppm), Thorium (Th in ppm), and Potassium (K in %) were obtained from NGSA for the same region. These data were processed and gridded to generate distribution maps for each element using Oasis Montaj™ and ArcGIS software. Thresholds defined as: high U > 5 ppm, high Th > 18 ppm, high K > 3%.

These elements were analyzed for (i) Crustal heat production potential, based on their radiogenic decay contributions (ii) Geological mapping and lithological discrimination, especially for identifying felsic rocks and alteration zones (iii) Mineralization zoning, especially in areas with high U–Th–K concentrations, which are commonly associated with hydrothermal systems, pegmatitic intrusions, and REE-bearing phases. Derived elemental maps were compared with heat flow and CPD distributions to identify zones where elevated heat signatures coincided with high radiogenic content—an indication of geothermal and mineral resource potential.

3.0 Results and Discussion

Fig. 2 shows the composite magnetic intensity map depicting the magnetic intensities of the distinct rocks domiciled in the study area. The measured magnetic intensity ranges from low -90 nT to high 118 nT. The study area is generally characterized by high magnetic intensities indicated by widespread red/pink colors, and attributed to crystalline basement or intrusive rocks.

The residual anomaly map presented in Fig. 3, with magnetic intensities ranging from about -143 nT to 68 nT represents the spatial distribution of short-wavelength magnetic anomalies that constitute localized mineralization in the study area. The residual filter enhances the localized remanent magnetic signatures in the area by separating the magnetic effects due to the Earth's core from those due to the crust. The regions of high magnetic susceptibility in low observed magnetic intensities (blue) and regions of low magnetic susceptibility in high observed magnetic intensities (red/pink) are clearly shown in the residual magnetic map (Figure 3) of the study area. The observed prominent positive magnetic intensities are attributed to sedimentary rocks such as shale, sandstone, and limestone.

Both Figs. 2 and 3 show that the study area is generally characterized by short-wavelength magnetic signatures. These are suspected to be due to some near-surface basement activities within the area, indicative of some form of mineralization zones or magmatism, but with considerable thick sedimentary cover.

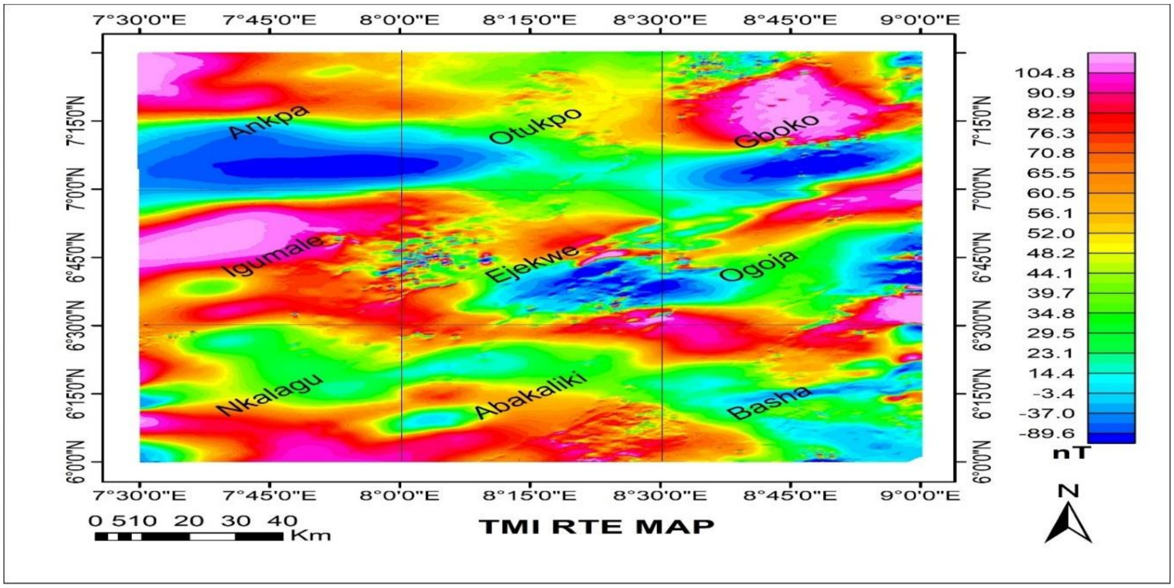

Fig. 2 : Composite Total Magnetic Intensity map of the study area reduced to the equator

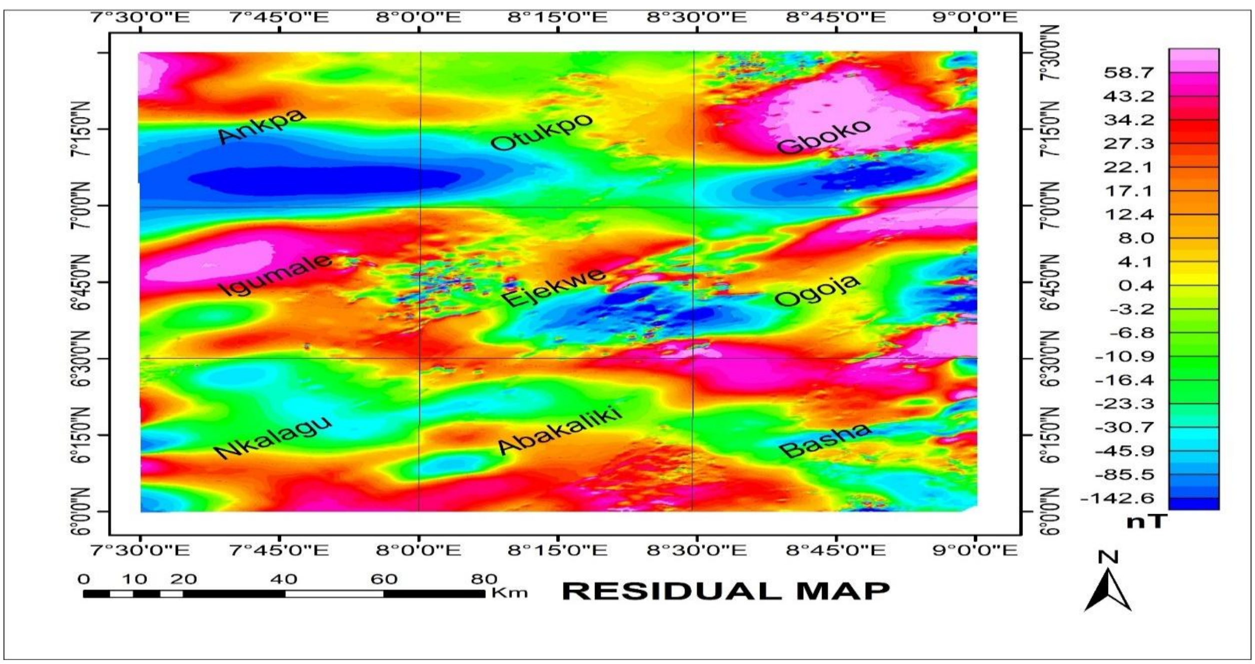

Fig. 3. Residual Magnetic Intensity map of the study area

Figure 4 is the spectral plot for block 1, representing a sample of the results of the analyzed spectrum of the residual magnetic anomalies from where the depths to the top, Z_t and centroid Z_0, respectively, have been obtained. The results for the rest of the blocks have been extracted and tabulated in Table 1. The Curie depth Z_b, the GTG, and the heat flow were calculated using equations 1, 2, and 3, respectively, and tabulated in Table 1. These estimated parameters were then harnessed and used to generate the plots of the CPD, GTG, and HF presented in Figs.5, 6, and 7, respectively.

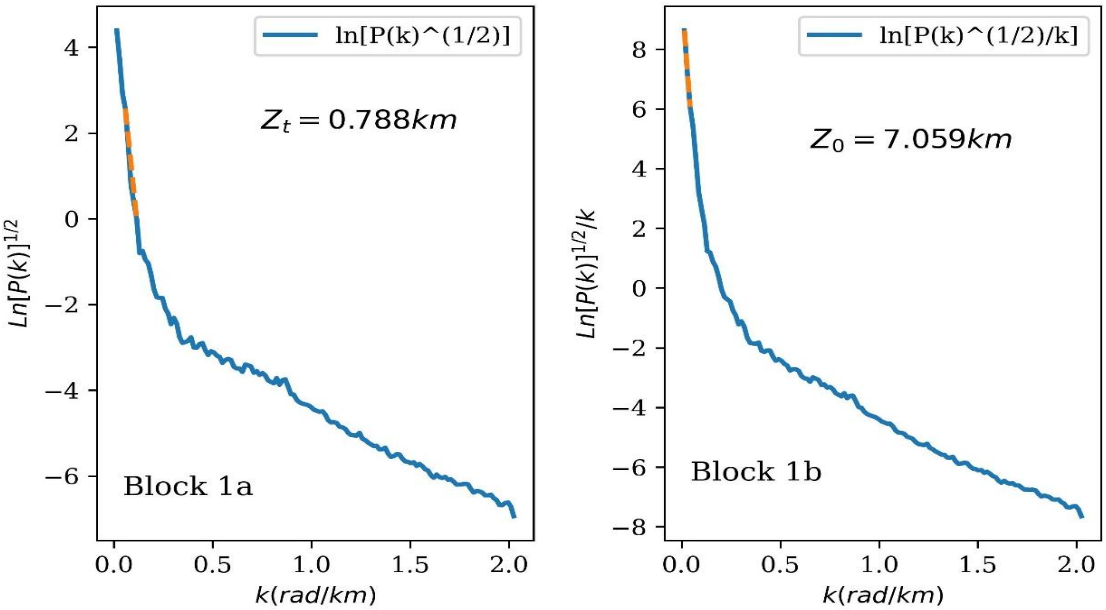

Fig. 4: Sample plot of the spectral blocks

Table 1. Estimated values of geothermal parameters for the study area

Block Number	LONG (Degree)	LAT (Degree)	Depth to Centroid, Z_0 (Km)	Depth to Top, Z_t (Km)	Curie Point Depth, Z_b (Km)	Geothermal Gradient, dT/dZ (°C/km)	Heat Flow, q (mW/m^2)
1	7.75	7.25	7.059	0.788	13.331	43.507	108.767
2	8.00	7.25	6.964	0.569	13.360	43.413	108.533
3	8.25	7.25	4.830	0.321	9.339	62.103	155.258
4	8.5	7.25	5.988	0.303	11.674	49.684	124.211
5	8.75	7.25	6.152	0.929	11.375	50.988	127.469
6	7.75	7.00	5.889	0.781	10.998	52.737	131.842
7	8.00	7.00	6.935	2.360	11.509	50.394	125.984
8	8.25	7.00	5.858	2.829	8.887	65.261	163.151
9	8.50	7.00	6.574	1.654	11.494	50.460	126.149
10	8.75	7.00	5.039	0.878	9.199	63.049	157.623
11	7.75	6.75	7.326	0.396	14.255	40.687	101.717

12	8.00	6.75	5.829	0.813	10.844	53.486	133.716
13	8.25	6.75	5.973	0.319	11.627	49.886	124.714
14	8.5	6.75	6.314	1.653	10.974	52.851	132.128
15	8.75	6.75	5.522	0.877	10.167	57.049	142.622
16	7.75	6.50	4.811	0.416	9.206	63.005	157.513
17	8.00	6.50	5.060	1.036	9.084	63.852	159.630
18	8.25	6.50	4.208	0.494	7.923	73.206	183.016
19	8.50	6.50	6.216	0.547	11.885	48.800	121.999
20	8.75	6.50	4.619	0.272	8.967	64.683	161.708
21	7.75	6.25	4.701	1.023	8.379	69.218	173.046
22	8.00	6.25	4.945	0.637	9.253	62.679	156.698
23	8.25	6.25	4.879	0.561	9.196	63.070	157.674
24	8.50	6.25	8.029	1.556	14.502	39.993	99.983
25	8.75	6.25	5.150	0.801	9.499	61.061	152.653
	Min		**4.208**	**0.272**	**7.923**	**39.993**	**99.983**
	Max		**8.029**	**2.829**	**14.502**	**73.206**	**183.016**
	Mean		**5.795**	**0.912**	**10.677**	**55.805**	**139.512**

3.1 Curie Point Depth (CPD)

The contour map (Figure 5) shows CPD values between 7.9 and 14.5 km, averaging 10.7 km. Shallow CPDs (~7.5–9.5 km) occur in the southwest and southeast (Nkalagu, Otukpo), indicating a thinner lithosphere, while deeper CPDs (>12.5 km) are found in the northwest (Ankpa), central Igumale, and Abakaliki–Basha, suggesting thicker crust. These results are comparable to Ijeh *et al*. (2023), who reported CPD values of ~8–13 km in the LBT, but are shallower than values from northern Nigeria (~16–18 km; Aboud *et al*., 2011) and northeastern Wikki Warm Spring (~15–20 km; Abraham *et al*., 2015).

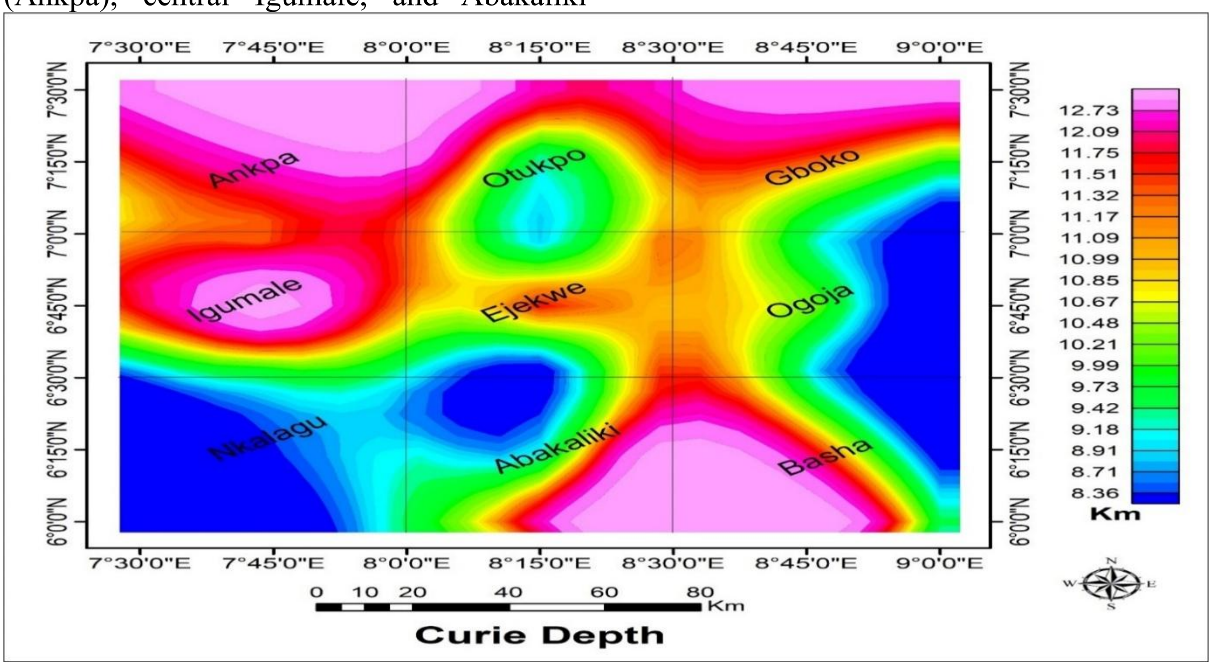

Fig. 5: Contour Map of Curie point depth for the study area

3.2 Geothermal Gradient (GTG)

Geothermal gradients (Figure 6) range from ~40 to 73 °C/km, with an average of 55.8 °C/km. High values (>68 °C/km) dominate the southwest, moderate gradients (~55–60 °C/km) are central, while lower gradients (<48 °C/km) occur in the northwest. These values exceed typical Nigerian averages of 25–45 °C/km reported in the Jos Plateau and Sokoto Basin (Onwubuariri & Ohaegbuchu, 2020; Ijeh *et al*., 2023), highlighting the elevated thermal regime of the LBT.

3.3 Heat Flow (HF)

Heat flow (Fig. 7) varies from ~100 to >170 mW/m², averaging 139.5 mW/m². The highest values (>170 mW/m²) are recorded at Nkalagu, Otukpo, and Abakaliki–Ejekwe, coinciding with shallow CPDs and high GTG. Lower values (~100–120 mW/m²) occur in Ankpa, Igumale, and Abakaliki–Basha, reflecting thicker crust or insulating layers. These results are higher than the national average of 60–120 mW/m² reported in other Nigerian basins (Reiter *et al*., 2020; Yakubu *et al*., 2023) and approach values from tectonically active geothermal provinces globally.

4.0 Validation of Aeromagnetic Data with Radiometric Data

Radiogenic elements—Uranium (U), Thorium (Th), and Potassium (K)—are the primary drivers of long-term crustal heat production, significantly influencing geothermal gradients. Their spatial distribution, controlled by crustal lithology and geochemistry, underpins the viability of geothermal energy resources. We have processed radiometric data from the study area under investigation to validate the results from aeromagnetic data. The maps of Potassium (K%), equivalent Thorium (eTh in ppm), and equivalent Uranium (eU in ppm) presented in Figures 8, 9, and 10 represent the concentrations of natural radiogenic heat-producing elements across a section of the study area, covering locations such as Ankpa, Otukpo, Igumale, Ejekwe, Nkalagu, and Abakaliki. Table 2 is a summary of the elemental distribution of radiogenic heat-producing materials in some regions of the study area, indicating their geological significance.

Fig. 8 shows the potassium (K) distribution in the study area. High K anomalies typically correlate with granitic or felsic rocks, K-feldspar, and hydrothermal alteration zones. This is observed in Ejekwe, Abakaliki, and southeastern Nkalagu, indicating significant crustal contribution and/or alteration zones.

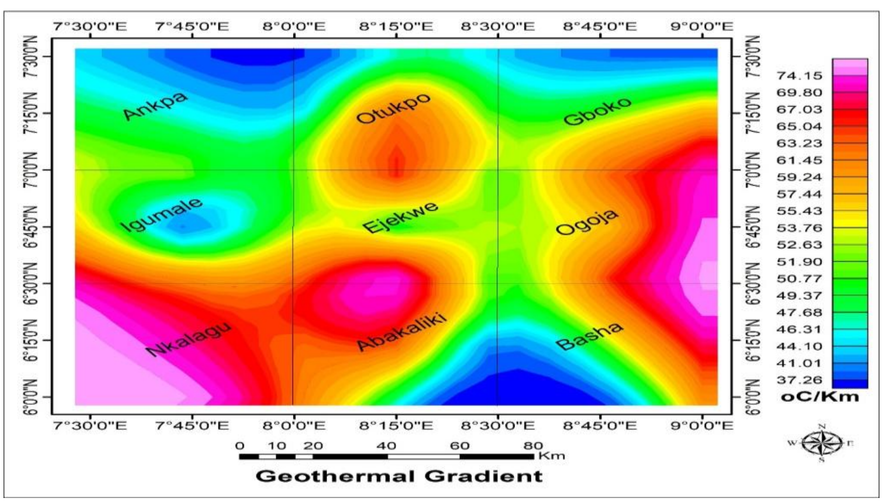

Fig. 6: Contour Map of geothermal gradient for the study area

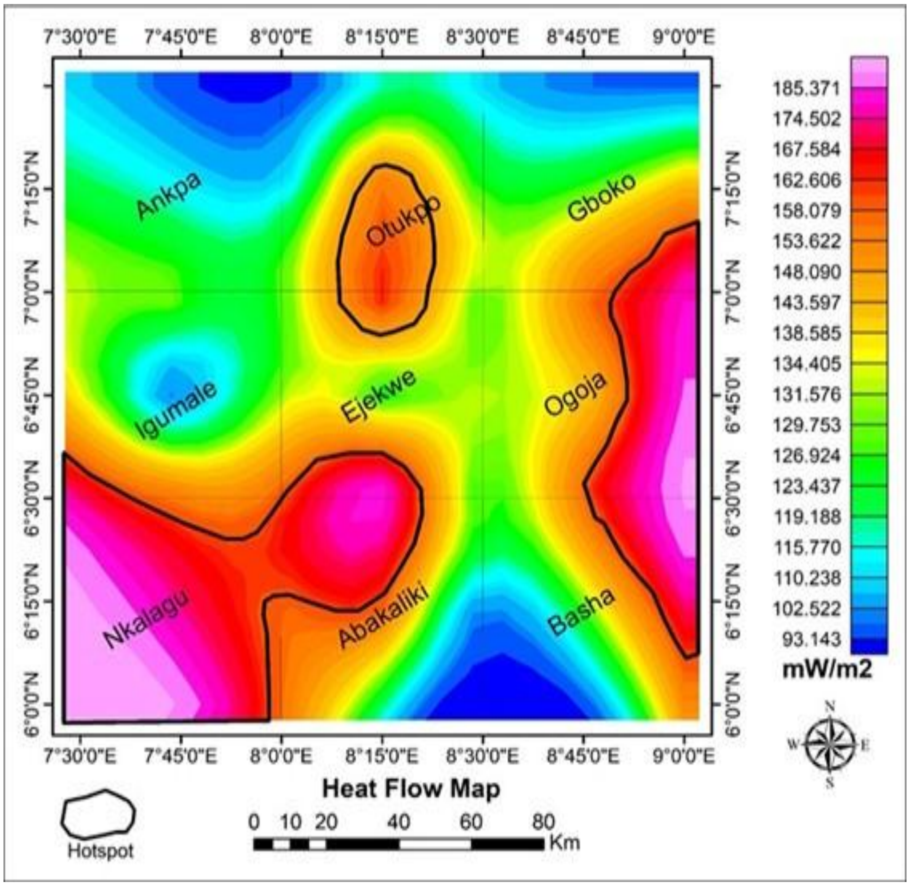

Fig. 7: Contour Map of Heat Flow for the Study Area

Table 2: Radiometric Elemental Distribution Summary

Location	K (%)	eTh (ppm)	eU (ppm)	Geological Significance
Ankpa	Low	moderate	High	Possible U mineralization; less heat production unless uranium is concentrated volumetrically.
Igumale	Low	High	High	Strong radiogenic heat potential despite low K; favorable for geothermal systems.
Nkalagu	Moderate	Moderate	High	High U suggests localized geothermal potential; mixed rock types are likely.
Otukpo	Low	High	High	Radiogenic heat mainly from Th and U, promising for deep geothermal targets.
Ejekwe	High	High	Moderate	Felsic rocks are likely; moderate heat generation from radiogenic sources.
Abakaliki	High	High	Low	Good Th and K support moderate heat output; less favorable due to low U.

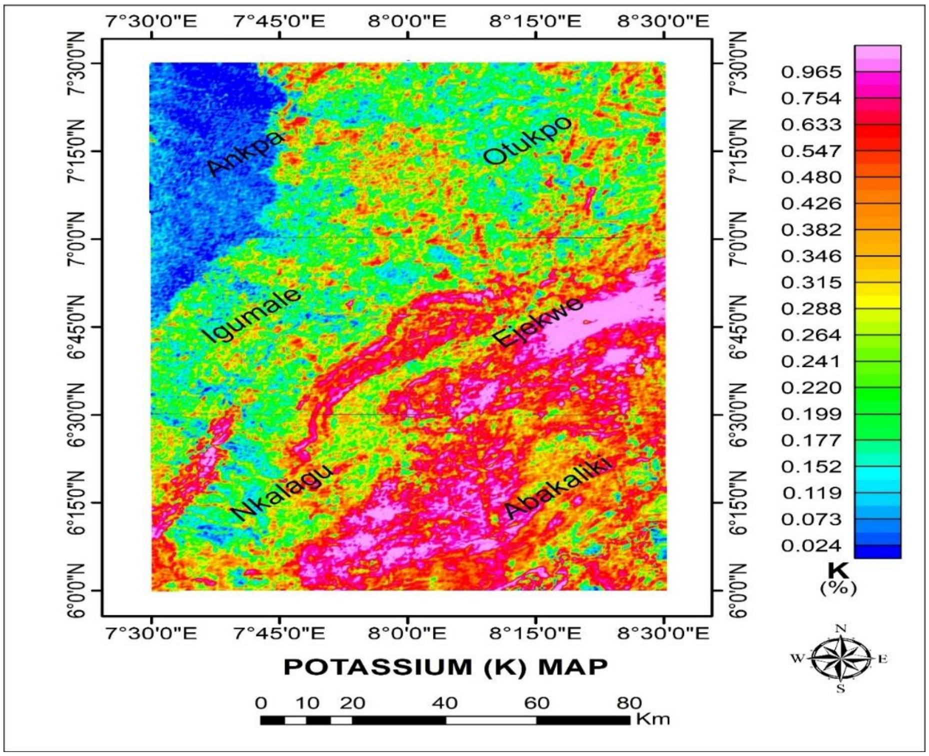

Fig. 8: Potassium Distribution in Subregions of the Study Area

High Th is characteristic of accessory minerals such as monazite, zircon, and allanite — common in felsic rocks and metamorphic terrains. Fig. 9 indicates that high Th concentrations (eTh > 18 ppm) are observed notably in Ejekwe, Igumale, Ankpa, Abakaliki, and Otukpo, correlating with felsic to intermediate igneous rocks and metasedimentary terrains that typically host Th-bearing minerals (e.g., monazite, allanite, thorite).

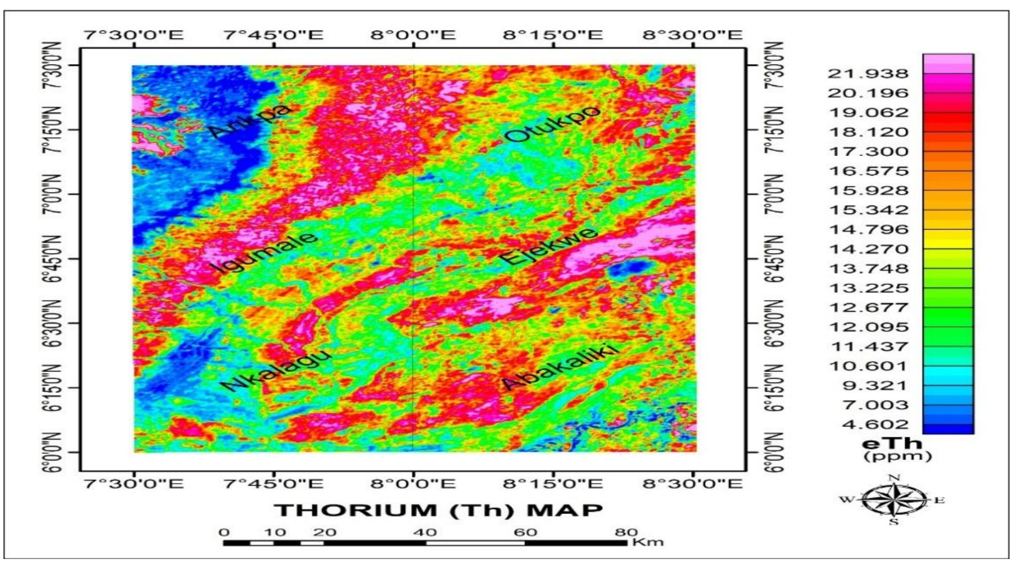

Fig. 9: Thorium Distribution in Subregion of the Study Area

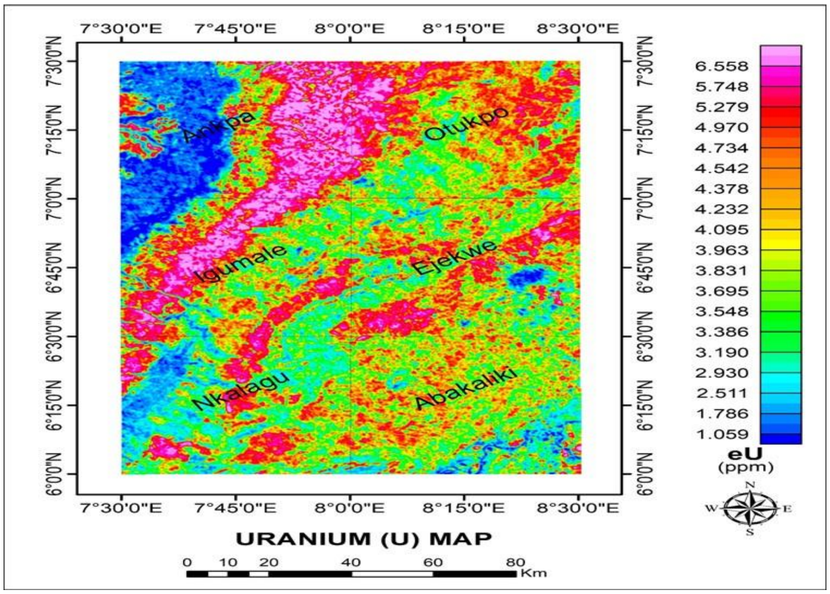

Fig. 10: Uranium Distribution in Subregions of the Study Area

Mobile under oxidizing conditions; high U values may point to hydrothermal enrichment, secondary mineralization, or reduced trapping environments. It is observable from Fig. 10 that Uranium (eU > 5 ppm) is elevated in Ankpa, Otukpo, Igumale, and parts of Ejekwe and Nkalagu, indicative of U-rich granitoids or pegmatitic intrusions.

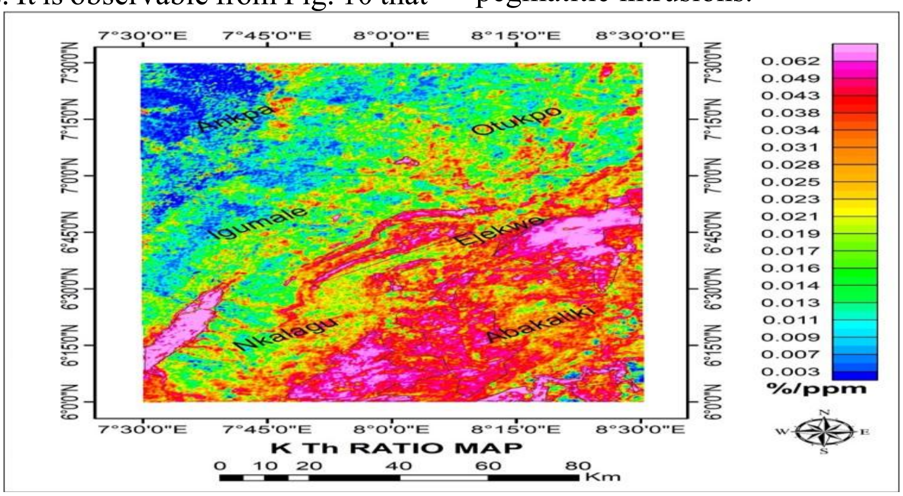

Fig.11: K Th Ratio for the Study Area

The K Th ratio serves as a lithologic and alteration discriminator, helping to identify hydrothermal systems and differentiation trends in igneous bodies. In Fig. 11, low K Th ratios are observed (<0.015 %/ppm), especially in Ankpa, Igumale, and Otukpo, pointing toward felsic or evolved rocks, where K is depleted relative to Th. These are potential hydrothermal alteration zones, where K is mobilized or lost.

High K Th ratios in some areas, such as Ejekwe, Abakaliki, and Nkalagu, may correspond to younger, more mafic units or sedimentary deposits and non-radiogenic K-enriched zones (e.g., clay minerals, K-feldspars).

Fig. 12 below is an integrated interpretation of the radiometric ternary map and the heat-flow map, showing how radiogenic heat production correlates with surface heat flow anomalies and what this implies for geothermal potential and mineralization.

Areas with concurrent radiometric highs (U/Th/K) and heat-flow hotspots (e.g., Nkalagu, Otukpo) confirm that crustal heat production from radioactive decay is a primary driver of elevated geothermal gradients.

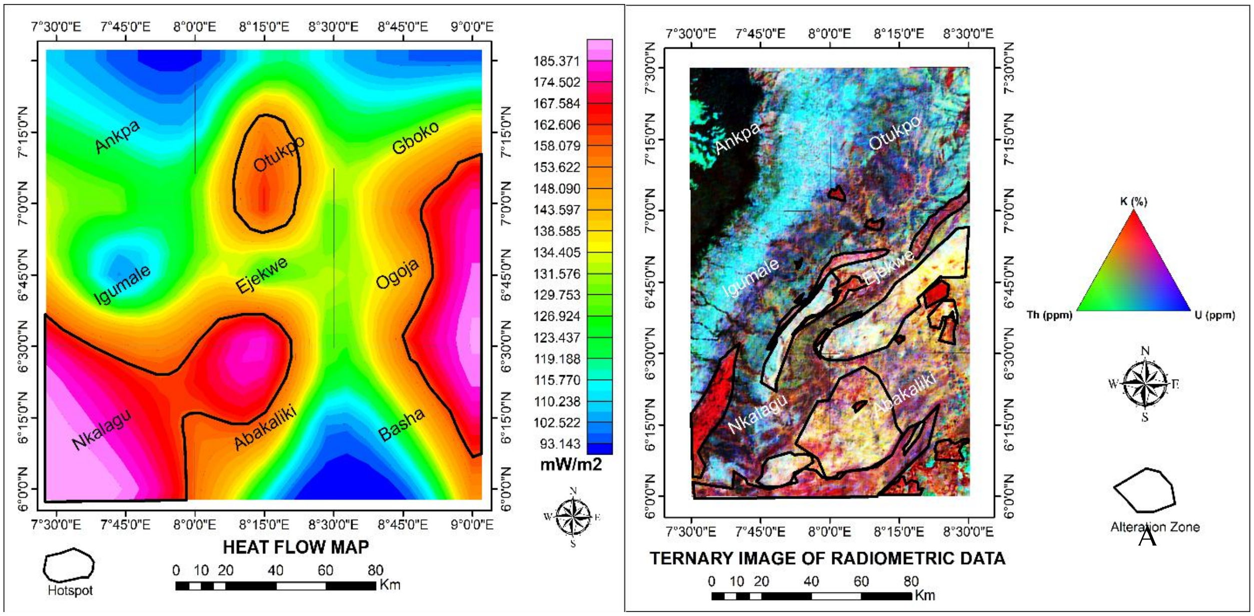

Fig. 12: (A) Heat Flow Map from Aeromagnetic Data. (B) Ternary Map from Radiometric Data

Ankpa and Igumale show radiogenic enrichment but muted heat-flow anomalies, suggesting either insulating cover (e.g., thick regolith) or lateral conductivity effects delaying heat transfer to the surface.

Felsic intrusives (high K and Th at Ejekwe, Abakaliki) produce moderate to high heat flows, but low U content can limit total radiogenic heat. Their high heat flow may also reflect structural conduit systems (faults/fractures) that facilitate upward heat transport. Mafic or metasedimentary units with high U (e.g., Nkalagu) concentrate heat production in narrow zones, giving rise to sharp heat-flow hotspots.

4.1 Mineral Prospects

Uranium-Thorium-Rich Zones (Nkalagu, Otukpo, Gboko–Ogoja) are prime targets for U/Th-bearing minerals (monazite, zircon, uraninite) and associated hydrothermal vein deposits. Elevated heat may drive convective fluid systems, enhancing ore deposition.

High-K Felsic Terrains (Ejekwe, Abakaliki) are favorable for rare-earth element (REE) Th-phosphates and potassic alteration halos, potentially hosting REE-Th pegmatites or greisen systems.

4.2 Geothermal Potentials

Optimal targets for Enhanced Geothermal Systems (EGS) are regions where high radiogenic heat overlaps with structural permeability, notably Otukpo and Nkalagu.

Abakaliki's anomalously high heat flow over a high-K/Th zone suggests possible deep-seated magmatic or fluid heat contributions, warranting detailed seismic and drill testing. The summary of the above characterization is presented in Table 3 below.

Table 3: Characterization for Energy & Exploration

Use Case	Target Zones	Rationale
Geothermal energy	Nkalagu, Ejekwe, Otukpo, Abakaliki	High radiogenic heat production
Uranium mining	Ankpa	High eU anomaly, oxidized environment
REE exploration	Ejekwe, Otukpo, Abakaliki	High Th suggests monazite/REE presence
Hydrothermal system studies	Ejekwe, Nkalagu	K anomalies + structural trends

5.0 Limitations and Future Work

This study is constrained by assumptions of uniform Curie temperature and average crustal thermal conductivity, which may vary with lithology. The resolution of aeromagnetic and radiometric surveys limits the detection of small-scale anomalies, while spectral methods provide depth-averaged estimates rather than detailed subsurface heterogeneity. Radiometric anomalies also reflect near-surface concentrations that may not extend to depth. The absence of borehole, seismic, and geochemical data restricts direct validation of the modeled geothermal and mineralization zones. Future work should integrate higher-resolution geophysical imaging, geochemical sampling, and exploratory drilling to refine and confirm these findings.

6.0 Conclusion

This study integrated high-resolution aeromagnetic and radiometric datasets to evaluate the geothermal framework and mineralization potential of the Lower Benue Trough, Nigeria. The analysis of Curie Point Depth (CPD), geothermal gradient (GTG), and heat flow (HF) revealed spatial variations in subsurface thermal regimes, with CPD values ranging from 7.923 km to 14.502 km. Shallow Curie depths in areas such as Nkalagu, Otukpo, and Ejekwe correspond to elevated geothermal gradients (>70 °C/km) and high heat flow (>170 mW/m^2), indicating significant geothermal energy prospects.

Radiometric data further validate these results by showing high concentrations of Uranium, Thorium, and Potassium—key radiogenic heat-producing elements. Zones enriched in U and Th (Otukpo, Igumale, and Nkalagu) demonstrate potential for uranium–thorium mineralization, while elevated K and Th signatures in Ejekwe and Abakaliki suggest felsic intrusions favorable for rare-earth element (REE) mineralization.

The integration of magnetic and radiometric evidence underscores the dual-resource potential of the Lower Benue Trough, positioning it as a promising region for both sustainable geothermal energy development and critical mineral exploration. These findings provide a scientific basis for advancing Nigeria's renewable energy goals and strategic resource management. Future work should focus on integrated geophysical imaging, targeted geochemical studies, and exploratory drilling to confirm these anomalies and guide policy and investment decisions in energy and mineral resource development.

7.0 References

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Not applicable

Data availability

The microcontroller source code and any other information can be obtained from the corresponding author via email.

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Authors' Contribution

Henry Ekene Ohaegbuchu conceptualized the study, developed the methodology, conducted spectral analysis, interpreted geothermal results, and drafted the manuscript. Boniface Ikechukwu Ijeh supervised data processing, validated interpretations, and reviewed the manuscript. Paul Igienekpeme Aigba analyzed radiometric data and supported mineralization interpretation. Obinna Christian Dinneya performed GIS mapping, assisted structural interpretation, prepared figures, and contributed to manuscript refinement and approval.