

Tectono-Thermal Framework of the Southern Benue Trough, Nigeria: Implications for Hydrothermal Mineralization and Geothermal Energy

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Tectono-Thermal Framework of the Southern Benue Trough, Nigeria: Implications for Hydrothermal Mineralization and Geothermal Energy

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ABSTRACT

The increasing global demand for clean and sustainable energy has intensified the search for geothermal resources and associated hydrothermal mineral systems. However, limited understanding of the thermal structure and tectonic controls of the Southern Benue Trough, Nigeria, has constrained effective geothermal and mineral exploration in the region. This study aims to investigate the thermal and tectonic framework of the basin using integrated high-resolution airborne magnetic and radiometric data. Aeromagnetic data were processed using reduction to the equator, First Vertical Derivative (FVD), Analytical Signal (AS), Source Parameter Imaging (SPI), and Spectral Analysis (SA) techniques to aid the delineation of subsurface structures and the estimation of depths to magnetic sources and Curie Point Depth for thermal analysis. Airborne radiometric data, including potassium (K), thorium (eTh), uranium (eU), and K/eTh ratio maps, were analyzed to identify lithological variations and hydrothermally altered zones. The results reveal dominant NE–SW and subordinate E–W trending lineaments linked to pre-Pan-African and Pan-African tectonic events, providing strong structural control for fluid migration pathways. Zones of high lineament density and radiometric anomalies correspond to areas of enhanced hydrothermal alteration. Spectral analysis indicates variable Curie point depths and elevated geothermal gradients and heat flow, while 2D forward modeling reveals a horst–graben basement architecture that facilitates heat transfer and fluid circulation. These findings provide new insights into the thermal–tectonic evolution of the Southern Benue Trough and highlight its potential for geothermal energy development and hydrothermal mineral exploration.

Keywords: Geothermal energy, Hydrothermal mineralization, Aeromagnetic data, Airborne radiometric data, Curie point depth, Tectonic framework.

Introduction

Energy resources remain a fundamental driver of economic development worldwide, particularly in the context of the ongoing transition toward low-carbon and sustainable energy systems. The increasing global demand for sustainable energy sources and critical minerals has accelerated the development and application of integrated geophysical approaches for resource exploration (Abraham et al., 2024). In Nigeria, despite its status as a major oil and gas producer, recent economic pressures and the global transition toward low-carbon energy systems have intensified efforts to diversify into solid minerals and geothermal resources (Obaje, 2009; Ekwok, 2020; International Energy Agency, 2023). Mineral resources form through diverse geological processes, including magmatic differentiation, hydrothermal activity, sedimentation, and metamorphism. Among these, hydrothermal systems are particularly significant because they host economically viable ore deposits such as porphyry copper, epithermal gold, and volcanogenic massive sulphides (Groves et al., 2023; Sillitoe, 2010). These systems are closely linked to geothermal processes, as both are controlled by crustal heat flow, tectonic deformation, and fluid circulation within permeable lithospheric structures. Consequently, the interaction between heat sources, structural pathways, and fluid movement plays a fundamental role in the formation of hydrothermal mineralization and geothermal systems.

The Benue Trough, a Cretaceous intracontinental rift basin in Nigeria, represents one of the most prominent geological features associated with the separation of the African and South American plates. It is characterized by complex tectonic evolution, intrusive magmatic activities, and widespread hydrothermal alteration. The Southern Benue Trough, in particular, hosts polymetallic mineralization (Pb–Zn–Ba), thermal springs, and radiogenic minerals, indicating strong coupling between tectonic processes and thermal evolution (Olade & Morton, 1985; Ekwok, 2020). These geological characteristics suggest significant potential for both hydrothermal mineral resources and geothermal energy development. Despite these prospects, the region remains relatively underexplored, particularly with respect to integrated studies that simultaneously address structural controls, crustal thermal regimes, and hydrothermal processes.

Previous investigations in the Benue Trough have largely focused on either structural interpretation, mineral exploration, or geothermal assessment independently, with limited efforts directed toward understanding the genetic relationship between these processes. This lack of integration has hindered the ability to determine whether geothermal anomalies and hydrothermal mineralization are linked through common tectono-thermal mechanisms or represent independent geological phenomena.

Recent studies emphasize that tectonic architecture and structural permeability exert fundamental control on fluid flow, heat distribution, and mineral deposition in rift-related basins (Richards, 2011; Sillitoe, 2010). In such environments, faults, fractures, and lineaments act as conduits for the migration of hydrothermal fluids, while elevated heat flow associated with crustal thinning and magmatic intrusions drives hydrothermal circulation. Therefore, a comprehensive understanding of the spatial relationship between structural features, thermal anomalies, and geochemical signatures is essential for identifying zones of mineralization and geothermal potential. Geophysical methods provide a reliable means of investigating concealed subsurface systems. Aeromagnetic data enable the delineation of structural features such as faults, fractures, and intrusive bodies, while also allowing quantitative estimation of subsurface thermal conditions through Curie Point Depth (CPD) analysis. From CPD, geothermal gradient and heat flow can be derived, providing critical insights into the thermal state of the lithosphere. Airborne radiometric data, on the other hand, offer valuable information on lithological variations and hydrothermal alteration through the spatial distribution of potassium (K), thorium (eTh), and uranium (eU) concentrations (Nabighian et al., 2005; IAEA, 2003).

The integration of aeromagnetic and radiometric datasets has proven effective in mapping mineral systems and geothermal prospects in structurally complex terrains (Dentith & Mudge, 2014; Nabighian et al., 2005). However, the application of integrated aeromagnetic and radiometric approaches to simultaneously evaluate tectonic structures, geothermal conditions, and hydrothermal mineralization within the Southern Benue Trough remains limited. In addition, the absence of comprehensive datasets that combine structural, thermal, and geochemical indicators has constrained the identification of zones where mineralization and geothermal systems are genetically linked.

This study addresses these gaps by integrating high-resolution aeromagnetic and airborne radiometric data to investigate the thermal structure and tectonic framework of the Southern Benue Trough. Specifically, the study aims to delineate structural corridors and their control on fluid migration, estimate Curie point depth, geothermal gradient, and heat flow, identify radiometric anomalies and hydrothermal alteration zones, and establish the relationship between tectonic structures, geothermal conditions, and hydrothermal mineralization. This integrated approach provides a more comprehensive understanding of the coupled tectono-thermal processes controlling resource potential in the region and offers a geophysical basis for future geothermal and mineral exploration.

DATA AND METHODOLOGY

STUDY AREA

The study area is located within the Southern Benue Trough, Nigeria, and lies approximately between longitudes 7°00'E and 9°00'E, and latitudes 5°00'N and 7°00'N, covering an aerial extent of about 27,225 km² (Fig. 1). The terrain exhibits variable topography, with elevations ranging from approximately 19.1 m in the low-lying sedimentary plains to over 415.31 m above sea level within the Oban Massif and adjacent highlands, as derived from Digital Elevation Model (DEM) data (Fig. 2). This variation in elevation reflects lithological contrasts and structural controls that influence hydrothermal fluid migration and mineralization processes.

Geologically, the study area comprises parts of the Southern Benue Trough and the adjoining Precambrian Basement Complex, represented by the Oban Massif. The Benue Trough is a Cretaceous intracontinental rift basin formed during the separation of the African and South American plates and is characterized by thick sedimentary successions deposited from the Albian to Maastrichtian (Benkhelil, 1989; Obaje, 2009). The principal lithostratigraphic units of the Southern Benue Trough include the Asu River Group, Eze-Aku Formation, Awgu Formation, and Nkporo Group, which consist predominantly of shales, sandstones, limestones, and minor volcanic and intrusive rocks (Nwajide, 2013; Obaje, 2009). The Oban Massif, which forms part of the Nigerian Basement Complex, consists predominantly of migmatites, gneisses, schists, and granitoids that were extensively reworked during the Pan-African orogeny (~600 Ma) (Rahaman, 1988). The contact between the basement complex and the sedimentary basin is structurally controlled and marked by major fault systems and intrusive activities. Structurally, the region is characterized by complex faulting, folding, and fracture systems with dominant orientations in the NE–SW, NW–SE, and E–W directions, reflecting the tectonic evolution of the Benue Trough, including Santonian compression and subsequent reactivation (Benkhelil 1989; Nwajide 2013).

The area hosts significant hydrothermal mineralization, particularly Pb–Zn–Ba deposits, along with thermal springs and radiogenic anomalies, indicating strong tectono-thermal interactions (Olade & Morton 1985; Ekwok 2020). These geological and structural characteristics make the Southern Benue Trough a favorable setting for investigating tectonic controls on hydrothermal mineralization and associated geothermal resources.

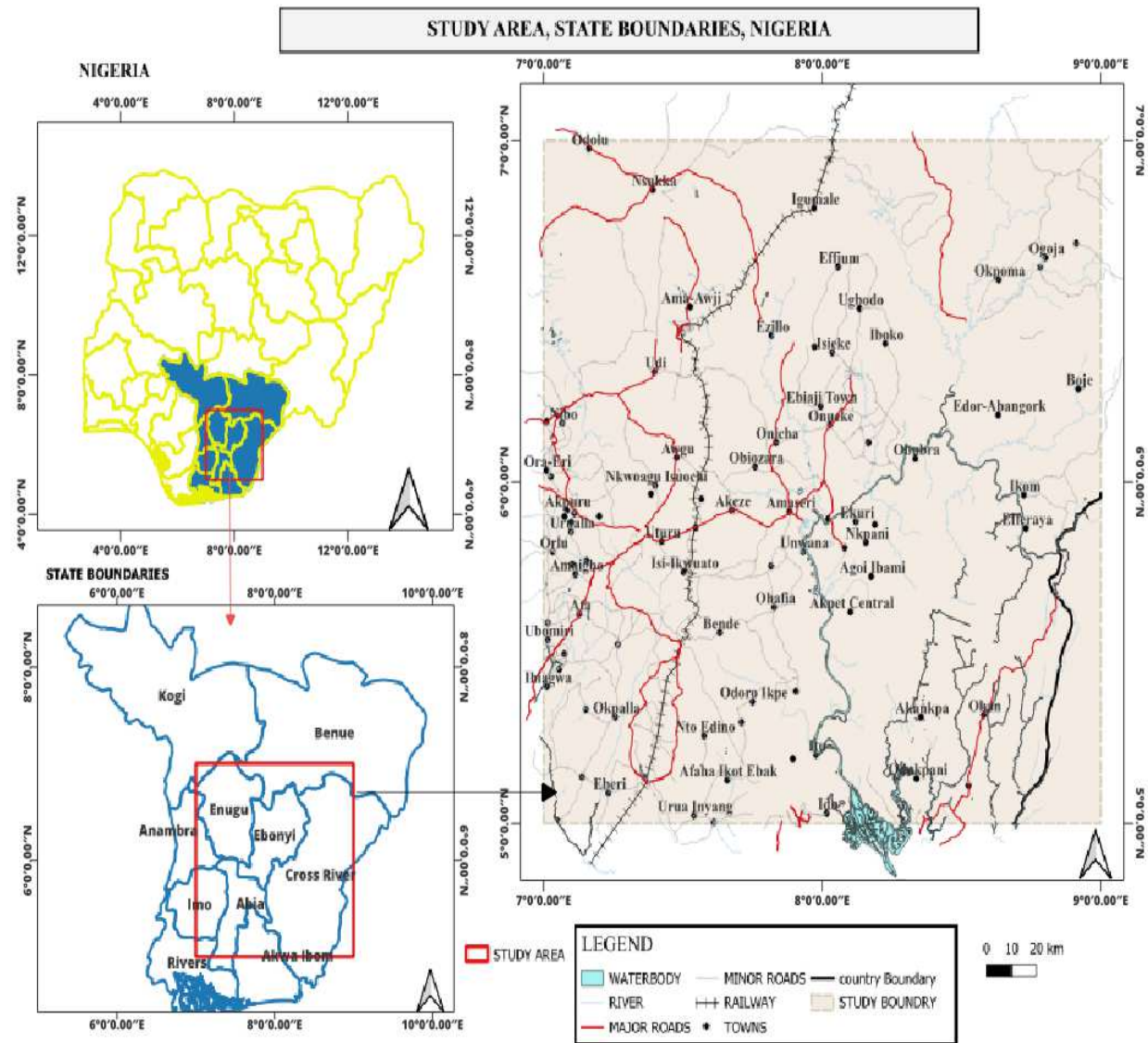


Fig. 1 Location Map of the Study Area

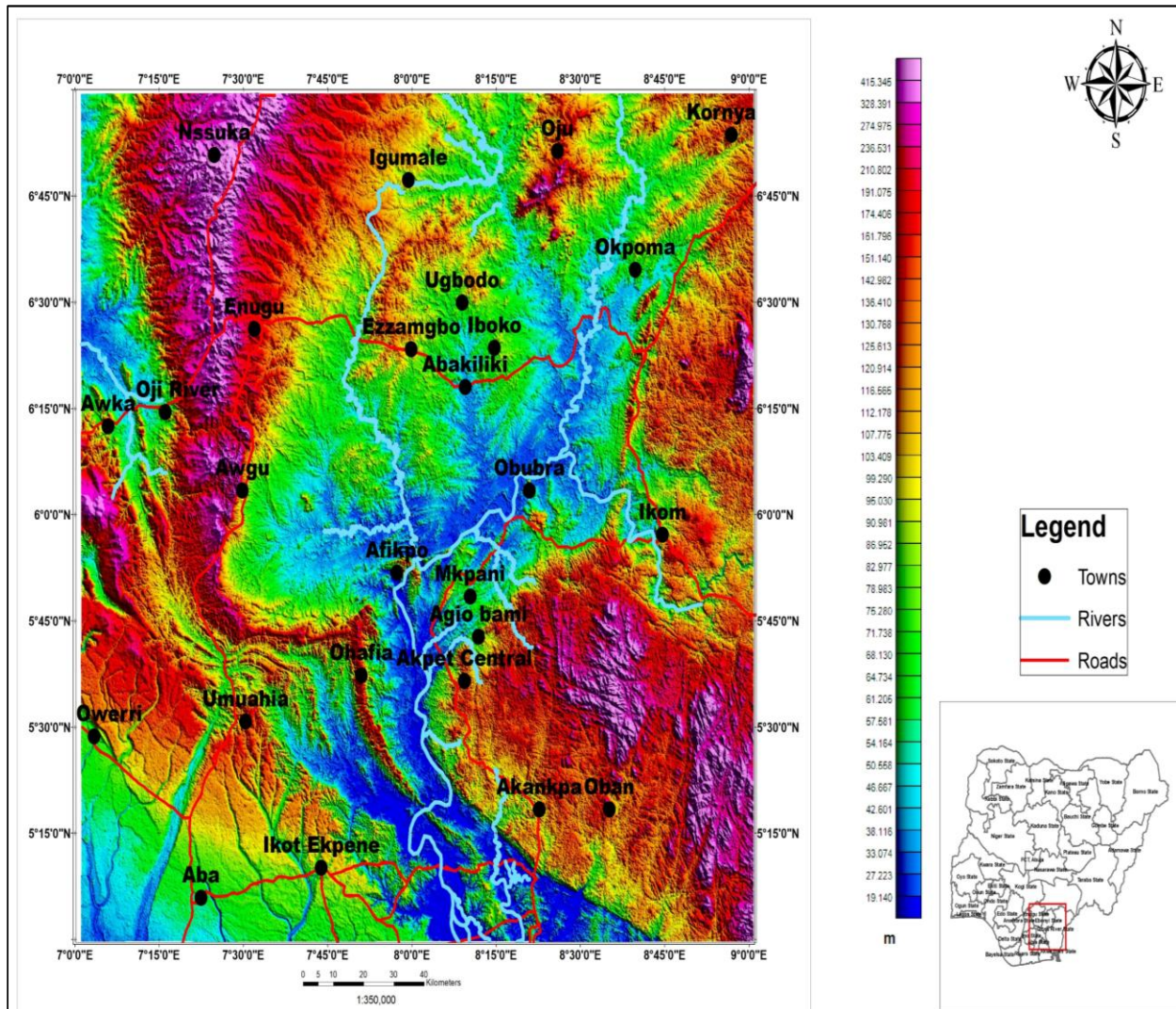


Fig. 2 Digital elevation model (DEM) of the study area (courtesy of USGS)

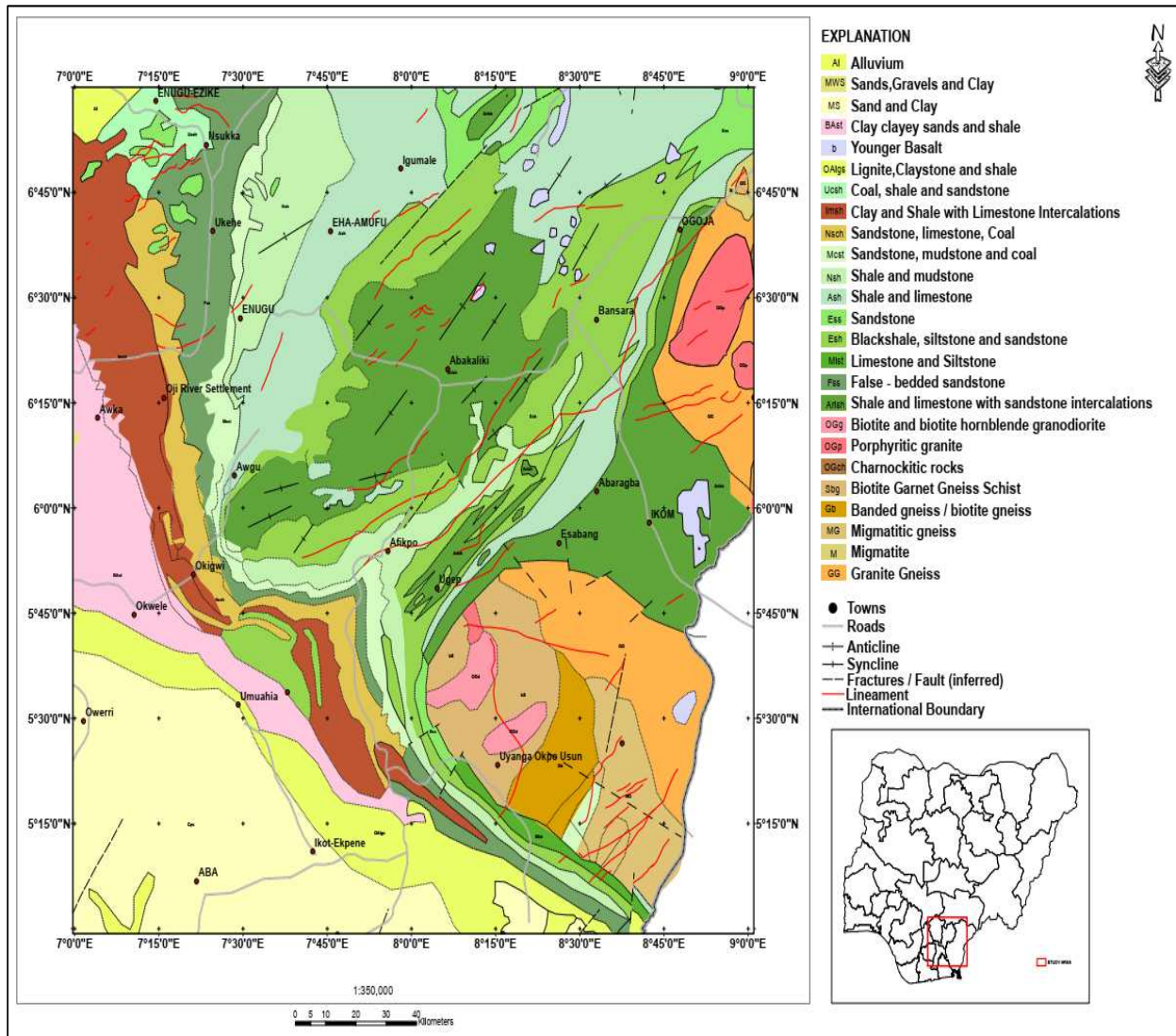


Fig. 3 Geologic map of the study area (modified after NGSA, 2011)

DATA

This study utilized high-resolution airborne geophysical datasets comprising aeromagnetic and radiometric data covering the Southern Benue Trough and adjoining basement terrains. The datasets were acquired by Fugro Airborne Surveys for the Nigerian Geological Survey Agency (NGSA) as part of a nationwide airborne geophysical survey program conducted between 2004 and 2008, aimed at enhancing mineral exploration and geological mapping across Nigeria.

The aeromagnetic dataset consists of sixteen (16) sheets (287, 288, 289, 290, 301, 302, 303, 304, 312, 313, 314, 315, 321, 322, 323, and 324), while the airborne radiometric dataset covers thirteen (13) sheets within the study area (Fig. 1). To ensure uniformity and regional consistency, all individual datasets were merged to produce continuous composite grids prior to further processing and interpretation using the Oasis Montaj 8.3 software. This merging process minimizes edge effects and enhances the continuity of geological features across sheet boundaries.

Data acquisition was carried out using a high-precision magnetometer along NW–SE oriented flight lines with an average spacing of approximately 500 m, while tie lines were spaced at about 2 km. The survey was flown at a nominal altitude of approximately 80 m above ground level. The aeromagnetic data were pre-processed to remove diurnal

127 variations, heading errors, and other noise components before being compiled into a Total Magnetic Intensity (TMI)
128 grid. These data provide valuable information on variations in the magnetic susceptibility of subsurface rocks, enabling
129 the delineation of structural features such as faults, fractures, dykes, and lithological contacts (Nabighian et al., 2005;
130 Salem et al., 2022).

131 The airborne radiometric data comprise gamma-ray spectrometric measurements of naturally occurring radioelements,
132 namely potassium (K), thorium (eTh), and uranium (eU). These data were processed to generate grids of individual
133 radioelement concentrations, as well as derived ratio maps. Radiometric datasets are particularly effective for lithological
134 discrimination and the identification of hydrothermal alteration zones due to spatial variations in radioelement
135 concentrations (IAEA, 2003; McCay et al., 2014).

136 Both datasets, after merging and gridding, were subjected to further processing using standard geophysical techniques.
137 The integration of aeromagnetic and radiometric datasets provides complementary insights into subsurface structural
138 architecture and surface geochemical variations. This combined approach enhances the delineation of hydrothermal
139 mineralization zones and potential geothermal anomalies within the study area.

140 Figure 4 summarizes the integrated workflow adopted in this study. Magnetic data processing yields structural features
141 and thermal parameters such as Curie point depth (CPD), geothermal gradient, and heat flow, while radiometric analysis
142 highlights radiogenic anomalies and hydrothermal alteration zones. These thematic layers are subsequently integrated
143 using a multi-criteria approach to generate mineralization potential maps for exploration targeting.

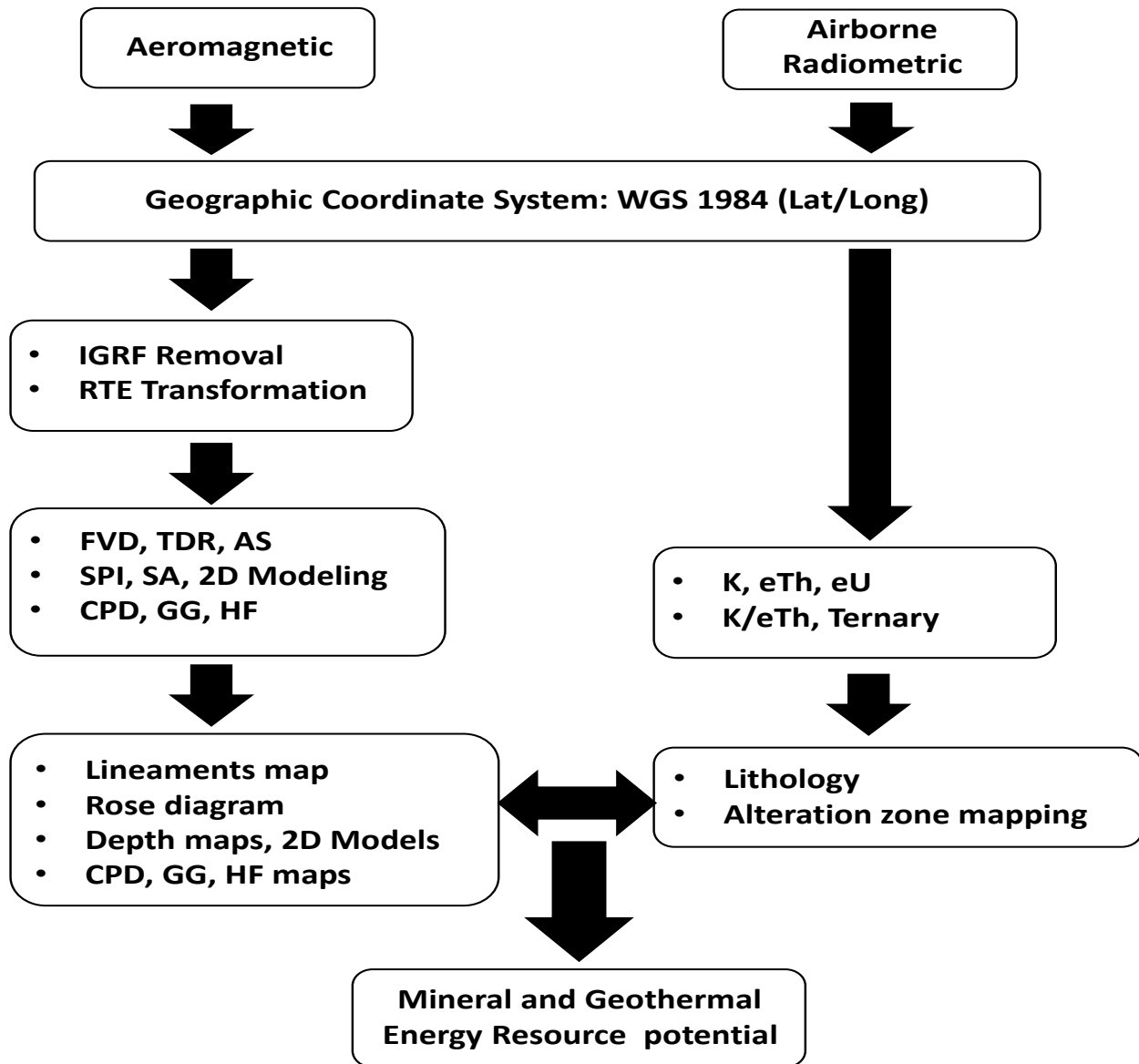


Fig. 4 Flowchart of Research Data Processing and Analysis

METHODOLOGY

Aeromagnetic Data Processing

To delineate subsurface structures, identify hydrothermal alteration zones, and establish the relationship between tectonic and thermal features, a combination of enhancement, transformation, and analytical techniques was applied to the aeromagnetic and airborne radiometric datasets.

Aeromagnetic Data Processing and Structural Enhancement

The Total Magnetic Intensity (TMI) data were first transformed using the reduction to the equator (RTE) technique to correct for the asymmetry and positional displacement of magnetic anomalies caused by low magnetic inclination in the study area. This transformation ensures that magnetic anomalies are centered over their causative bodies, thereby improving the reliability of structural and lithological interpretation (Blakely, 1995; Nabighian et al., 2005).

To enhance shallow subsurface features, the First Vertical Derivative (FVD) was applied to the RTE data. This filter emphasizes short-wavelength anomalies associated with near-surface sources and sharpens magnetic gradients, enabling the delineation of faults, fractures, and lithological contacts that may serve as pathways for hydrothermal fluids (Salem et al., 2007).

The Analytical Signal (AS) was subsequently computed to locate the edges of magnetic sources independent of magnetization direction. This is particularly effective in low magnetic latitude regions such as the Southern Benue Trough. The amplitude of the analytical signal is expressed as:

$$AS_{(x,y)} = \sqrt{\left(\frac{\partial J}{\partial x}\right)^2 + \left(\frac{\partial J}{\partial y}\right)^2 + \left(\frac{\partial J}{\partial z}\right)^2} \quad (1)$$

where $\left(\frac{\partial J}{\partial z}\right)$ is the vertical derivative.

These enhancement techniques collectively enabled the extraction of structural lineaments representing faults, fractures, and intrusive bodies that define the tectonic framework of the study area (Roest et al., 1992).

Depth Estimation and Basement Configuration

Depth to magnetic sources was estimated using Source Parameter Imaging (SPI) and spectral analysis to improve reliability and spatial resolution. The SPI method computes depth based on the local wave number of the magnetic field and operates on the complex analytic signal principle, providing rapid and spatially distributed depth estimates (Thurston & Smith, 1997; Nabighian et al., 2005).

Spectral analysis was applied following the method of Spector and Grant (1970) to estimate the depths to both shallow and deep magnetic sources. This approach involves analyzing the radially averaged power spectrum of magnetic anomalies to separate contributions from shallow and deep source ensembles. To constrain basement morphology, selected profiles across the SPI-derived depth map were modeled using two-dimensional (2D) forward modeling techniques. These profiles were oriented perpendicular to dominant structural trends, and SPI-derived depths were used as constraints to generate geologically plausible subsurface models. This approach provides insight into basement geometry, including horst–graben architecture (Blakely, 1995; Talwani, 1965).

Lineament Extraction and Structural Analysis

Structural lineaments were extracted from the enhanced magnetic datasets, particularly the FVD and AS maps, using the Centre for Exploration Targeting (CET) grid analysis technique. This automated extraction was complemented by manual digitization and geological validation to ensure consistency with regional tectonic trends (Holden et al., 2012; Grose et al., 2012).

Lineament orientation analysis was performed using rose diagrams to determine dominant structural trends, while lineament density mapping was used to identify structurally complex zones. Areas characterized by high lineament density are interpreted as zones of enhanced permeability, which are favorable for hydrothermal fluid migration and mineralization (Bonham-Carter, 1994; Sibson, 1996).

Curie Point Depth and Geothermal Modelling

To investigate the thermal structure of the crust and evaluate geothermal energy potential, Curie Point Depth (CPD) was estimated from the aeromagnetic data using spectral analysis. The dataset was divided into twenty-five overlapping blocks (110 × 110 km) to ensure adequate spatial coverage and spectral stability. The radially averaged power spectrum for each block was computed using Fast Fourier Transform (FFT) techniques (Blakely, 1988; Tanaka et al., 1999). Depth to the top of magnetic sources (Z_t) was derived from the high-frequency component, while the centroid depth (Z_c) was obtained from the low-frequency component. The Curie point depth (Z_b) was then calculated as:

$$Z_b = 2Z_c - Z_t \quad (2)$$

Geothermal gradient (GTG) and heat flow (HF) were calculated using:

$$GTG = \frac{T_c}{Z_b} \quad (3)$$

where $T_c = 580^\circ\text{C}$, the Curie temperature of magnetite, and

$$HF = GTG \times k \quad (4)$$

where $k = 2.5 \text{ W m}^{-1}\text{K}^{-1}$, represents the average thermal conductivity of crustal rocks (Turcotte & Schubert, 2014).

In this framework, the Curie point depth represents the depth at which magnetic minerals lose their magnetization ($\sim 580^\circ\text{C}$), thereby providing a proxy for subsurface thermal conditions. This transition from magnetic depth estimation to thermal modelling establishes the link between structural framework and geothermal processes.

Airborne Radiometric Data Processing

Airborne radiometric data comprising potassium (K), thorium (eTh), and uranium (eU) were processed to generate colour composite, ternary, and ratio maps for lithological discrimination and the identification of hydrothermal alteration zones. The K/eTh ratio was computed to delineate zones of potassium enrichment associated with hydrothermal alteration. Potassium is highly mobile during hydrothermal processes, whereas thorium is relatively immobile; therefore, elevated K/eTh ratios are indicative of alteration zones (Hoover et al., 1992; Elkhateeb & Abdellatif, 2018). A ternary map was generated using a red–green–blue (RGB) color scheme, where red represents K, green represents eTh, and blue represents eU. This visualization enhances the discrimination of lithological units and alteration patterns across the study area.

Result

Aeromagnetic Characteristics of the Study Area

The Total Magnetic Intensity (TMI) map (Fig. 5) shows variations in high (red) and low (blue) magnetic signatures, reflecting differences in the magnetic susceptibilities of subsurface rock units within the study area. After removal of the International Geomagnetic Reference Field (IGRF) value of 34,000 nT, the magnetic anomaly values range from -69.4 nT to 158.9 nT . The peak amplitude signatures observed in the central part of the map exhibit dominant trends in the NE–SW and E–W directions.

Intermediate magnetic anomalies (green) dominate the northern, northeastern, eastern, and southeastern parts of the region, while the southern portion is characterized by relatively low magnetic signatures. These variations reflect lithological contrasts, basement configuration, and possible intrusive activities within the subsurface.

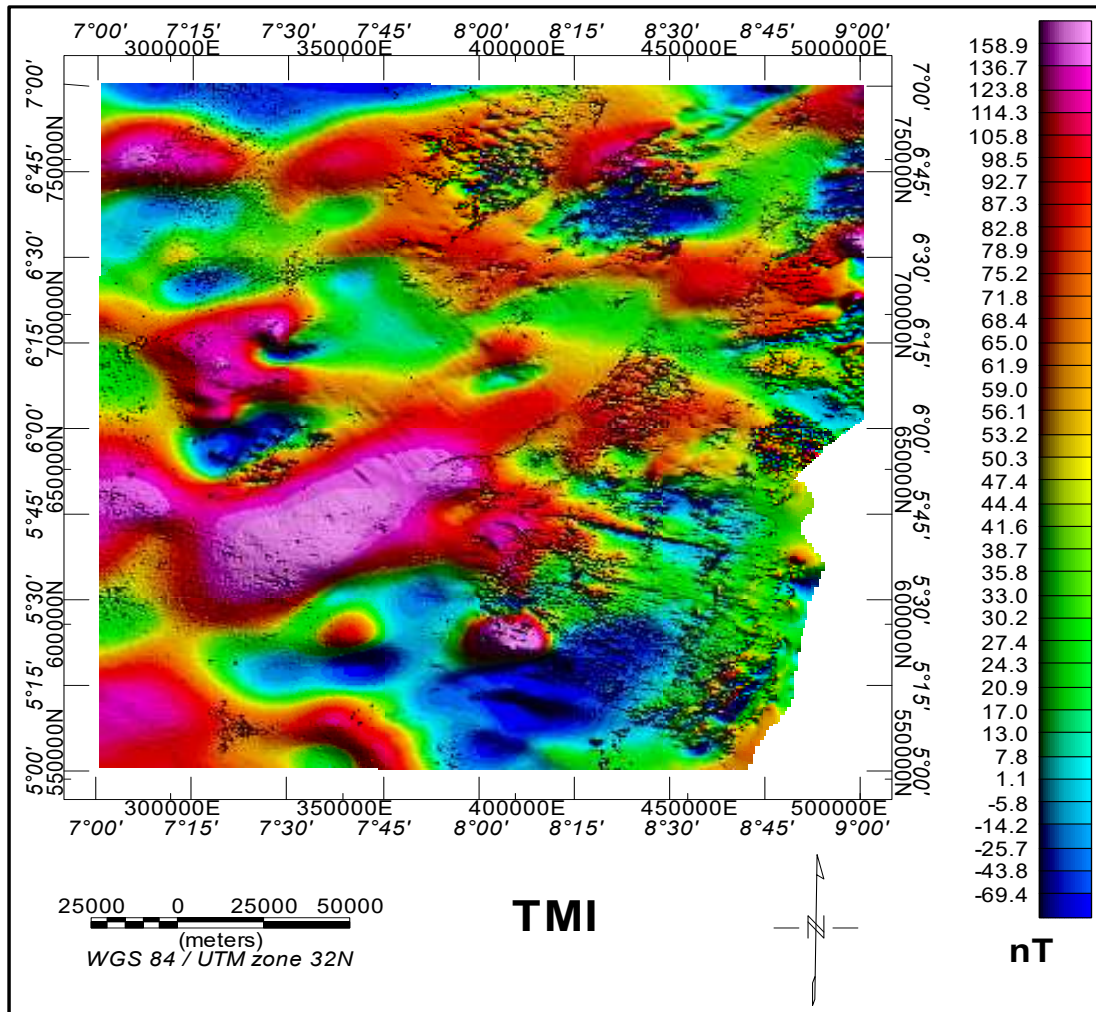


Fig.5 TMI map of the study area

The reduction to the equator (RTE) map (Fig. 6) was generated to correct for the positional displacement and asymmetry of magnetic anomalies caused by low magnetic inclination in the study area. The RTE magnetic intensity values range from approximately -57.8 nT to 138.9 nT, indicating significant heterogeneity in subsurface magnetic properties. The anomalies exhibit a heterogeneous distribution characterized by alternating magnetic highs and lows. The magnetic highs, trending predominantly in the NE-SW and E-W directions, correspond to zones of high magnetic susceptibility, while the magnetic lows reflect zones of relatively low magnetic susceptibility. Intermediate values indicate transitional lithological units or moderately magnetized rocks.

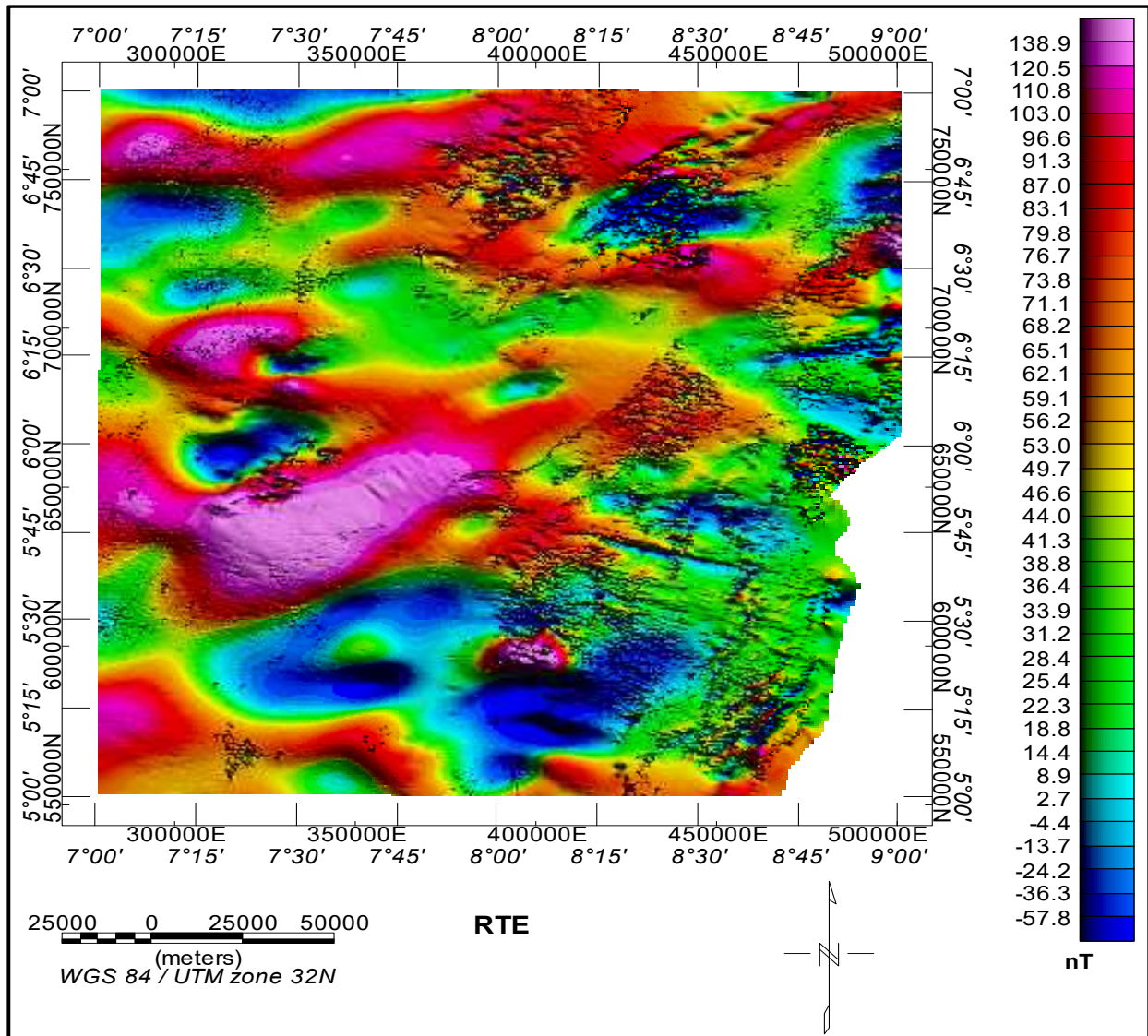


Fig. 6 RTE map of the study area

Structural Interpretation (FVD, Analytical Signal, and Lineaments)

The First Vertical Derivative (FVD) map (Fig. 7) enhances the resolution of shallow subsurface magnetic sources by emphasizing high-frequency anomalies and suppressing deeper regional effects. The FVD values range from approximately -0.0511 nT/m to 0.0497 nT/m and reveal sharp magnetic gradients corresponding to near-surface structural features such as faults, fractures, lithological contacts, and intrusive bodies.

These features exhibit dominant orientations in the NE–SW and NW–SE directions, consistent with the regional tectonic framework of the Southern Benue Trough.

The Analytical Signal (AS) map (Fig. 8) provides a robust representation of the amplitude of magnetic gradients independent of magnetization direction. The amplitude values range from approximately 0.0023 nT/m to 0.1342 nT/m, reflecting variations in magnetic susceptibility and structural configuration. The AS map clearly delineates linear and curvilinear features corresponding to structural discontinuities, which trend predominantly in the NE–SW and NW–SE directions.

Lineament extraction using the Centre for Exploration Targeting (CET) technique further defines the structural framework of the region. Orientation analysis from the rose diagram indicates dominant NE–SW trends, with subordinate NW–SE and E–W orientations. These structural trends reflect regional tectonic controls and are consistent with the evolution of the Benue Trough under extensional and reactivation tectonic regimes. The lineament density map reveals values ranging from approximately 0.0061 to 96.4104, indicating significant variation in structural intensity. Zones of high lineament density correspond to structurally complex areas that may serve as conduits for fluid migration.

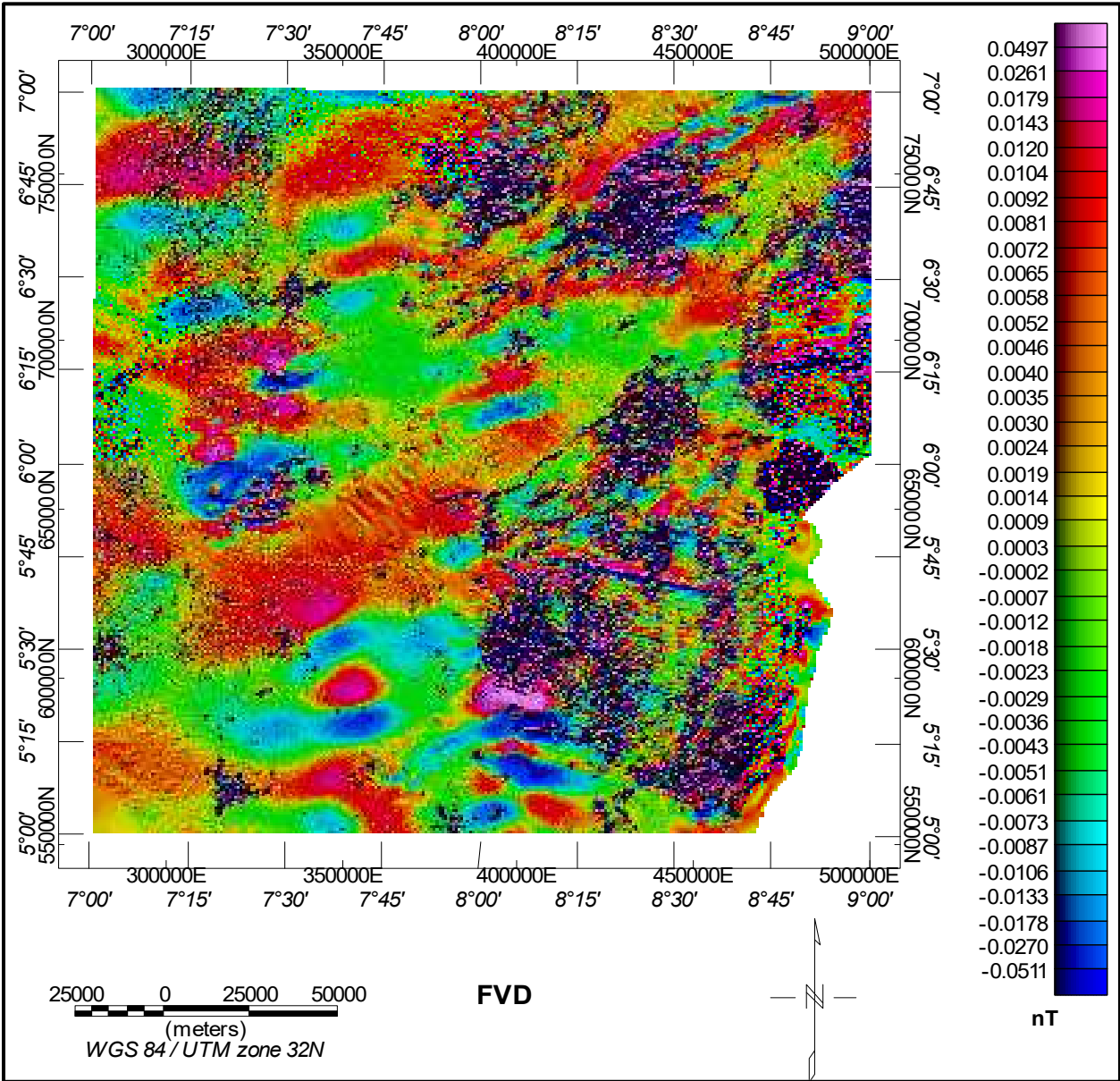


Fig. 7 First Vertical Derivative map of the Study area

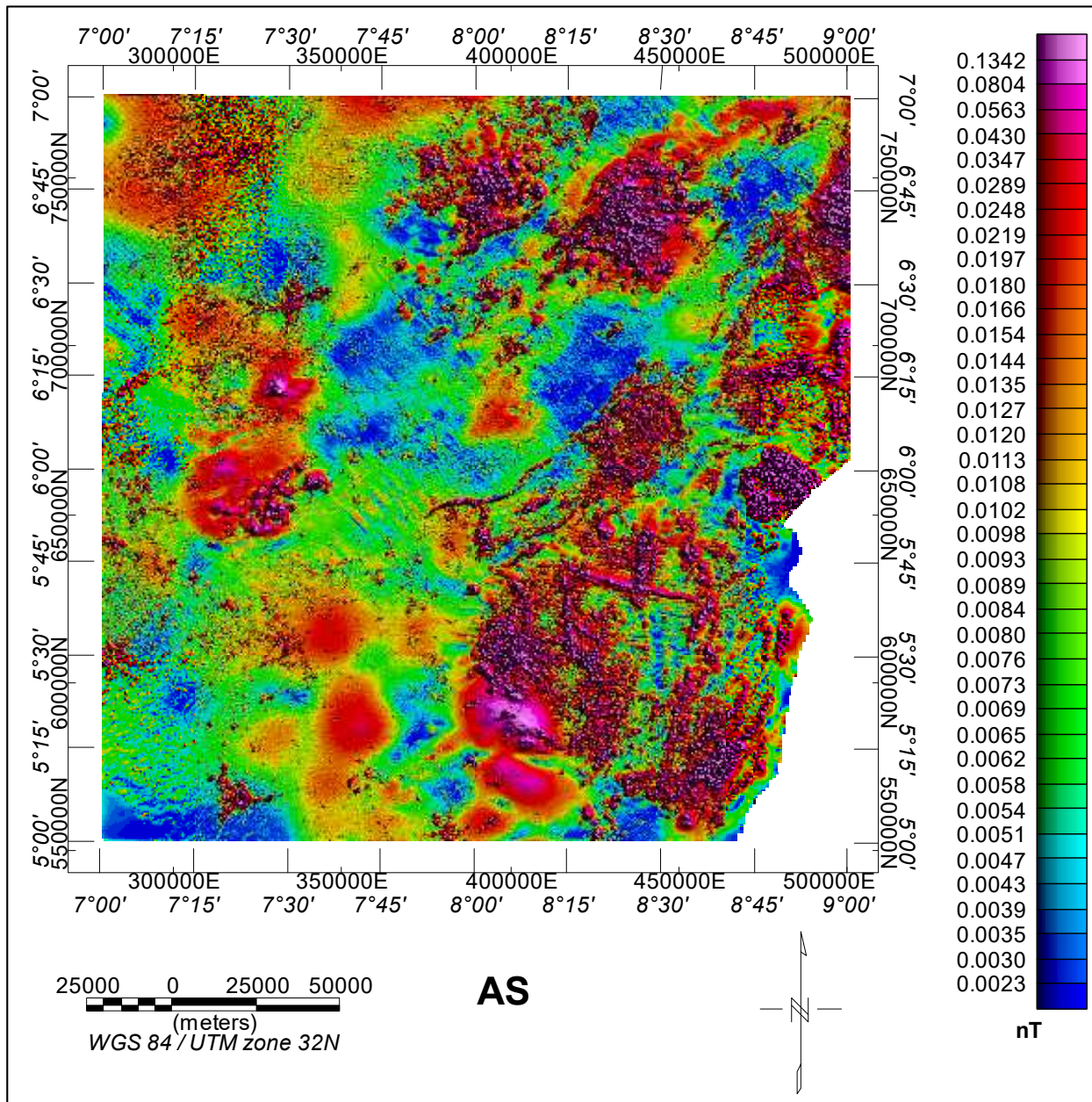


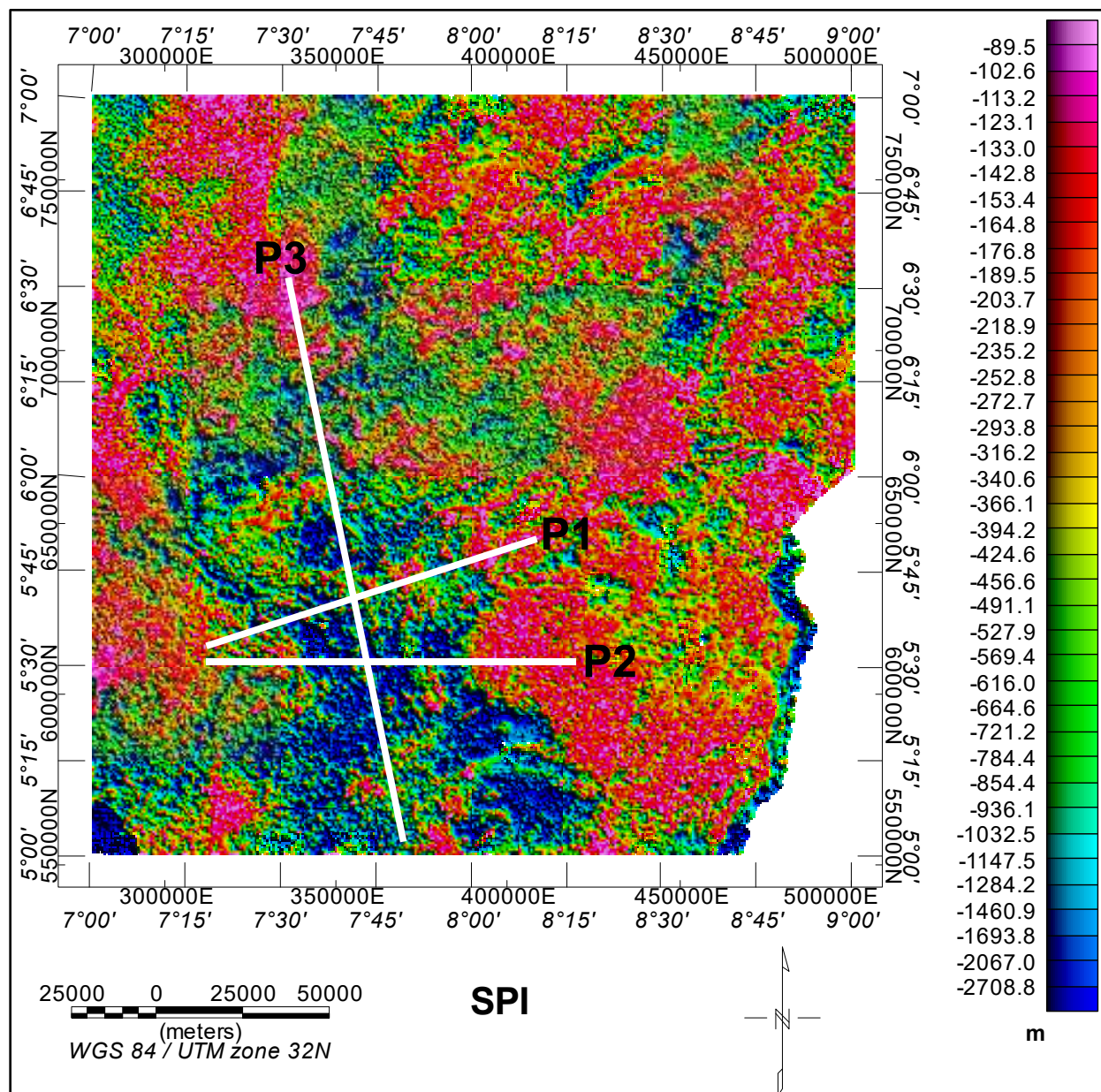
Fig. 8 Analytical Signal (AS) Map of the Study area

Basement Depth and Structural Architecture (SPI and Spectral Analysis)

Depth estimation using Source Parameter Imaging (SPI) indicates that basement depths range from less than 0.10 km to more than 2.7 km (Fig. 9). Shallow basement depths dominate the northern, eastern, western, and southeastern portions of the study area, suggesting the presence of basement rocks and magmatic intrusions close to the surface. In contrast, deeper basement regions occur within the central and southern parts, indicating thicker sedimentary sequences.

Spectral analysis of the 2D power spectra (Fig. 10) reveals depths to deeper magnetic sources ranging from 2.08 km to 9.02 km, with an average of 5.01 km, while shallow source depths range from 0.15 km to 0.846 km, with an average of 0.32 km (Table 1). The corresponding basement depth maps (Figs. 11 and 12) further illustrate this variation. The 3D representation of the deeper source depth map (Figs. 13 and 14) reveals an undulating basement morphology

269 characterized by horsts and grabens. These basement depressions act as depocenters that accommodated up to 7 km of
 270 sedimentary sequences.



271 Fig. 9 SPI depth map of the study area. Lines P1, P2, and P3 are the modeled 2D profiles in fig. 14
 272
 273

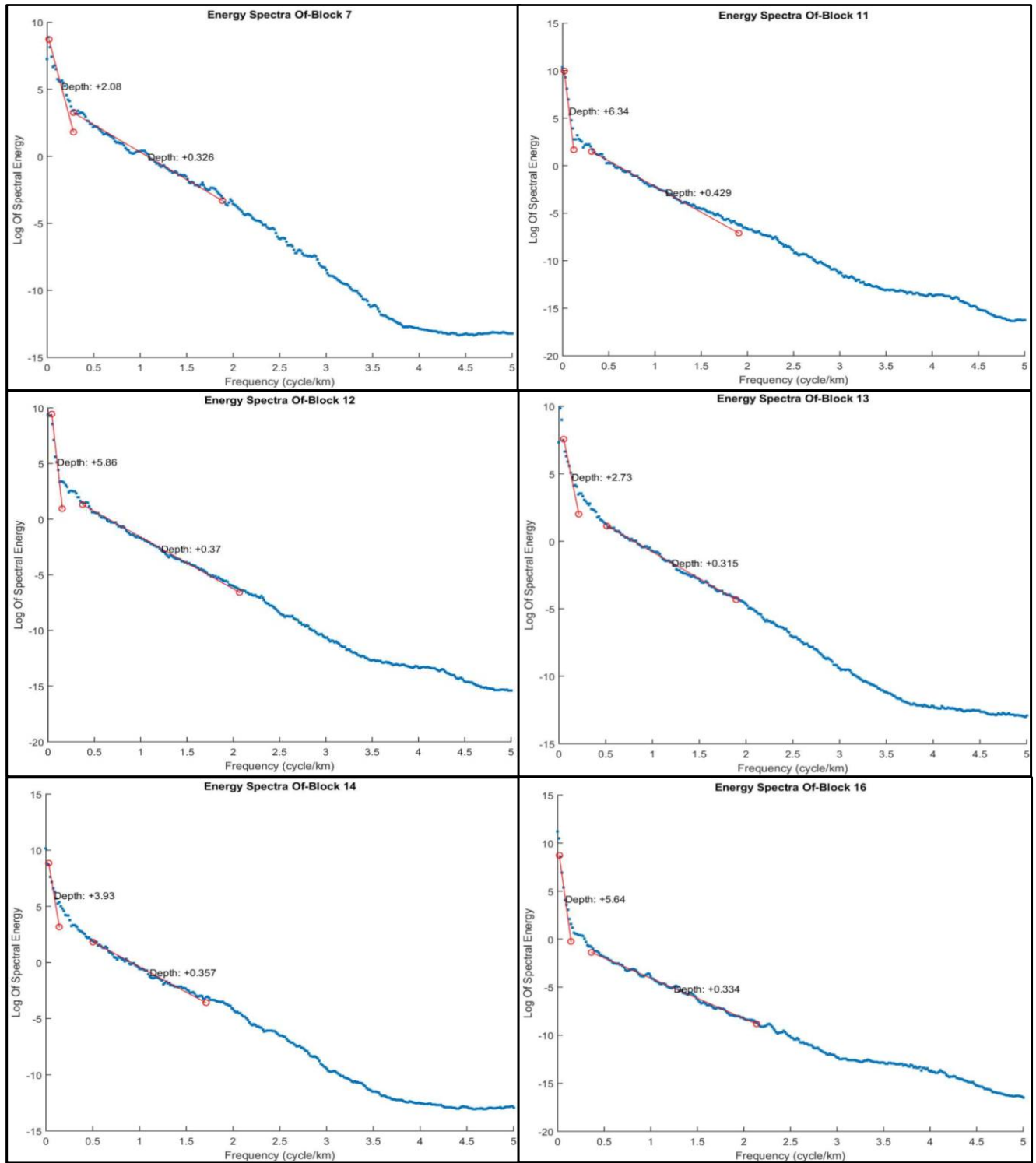


Fig. 10 Illustration of depth determination for shallow and deep-seated source bodies from 2D power spectrum curves of some of the analyzed blocks

281 **Table 1 Estimated depth to magnetic basement in the study area**

Block	X	Y	Deeper Source Depths (km)	Shallower Source Depths (km)
1	306150	580750	5.18	0.244
2	334000	580950	7.99	0.223
3	361300	580550	4.98	0.292
4	389800	581400	5.78	0.503
5	417000	580950	6.27	0.319
6	445300	580750	7.08	0.292
7	471950	580750	2.08	0.326
8	306150	608850	4.23	0.195
9	333800	609050	6.77	0.198
10	361300	608650	5.22	0.329
11	389150	608400	6.34	0.429
12	416800	608000	5.86	0.37
13	444700	608050	2.73	0.315
14	471950	608650	3.93	0.357
15	306350	636100	4.58	0.343
16	334400	636100	5.64	0.334
17	361700	636100	7.19	0.294
18	389200	635900	9.02	0.783
19	416600	635700	3.67	0.332
20	444700	636500	3.58	0.348
21	471950	635900	3.84	0.304
22	306700	663800	4.18	0.846
23	334000	663600	5.07	0.362
24	361900	663800	5.16	0.288
25	389350	526550	5.58	0.28
26	417000	663200	5.56	0.277
27	444900	664200	2.37	0.308
28	472200	663600	3.93	0.308
29	306350	691300	3.07	0.196
30	334200	691300	4.85	0.15
31	361700	691300	4.35	0.199
32	389400	691300	4.83	0.308
33	417000	691500	5.17	0.321
34	444700	691300	3.5	0.279
35	471950	691500	1.94	0.307
36	306450	719000	6.09	0.133
37	334350	719150	4.13	0.158
38	361700	718650	4.95	0.256
39	389450	719000	5.01	0.296
40	416950	718750	5.14	0.319
41	444700	718800	5	0.377
42	472050	718900	4.5	0.336
43	306450	746400	5.69	0.216
44	334200	746350	5.84	0.155
45	362050	746550	6.02	0.311
46	389850	746400	5.14	0.317
47	417250	746750	5.3	0.345
48	444850	746400	6.75	0.39
49	472150	746650	4.35	0.34
Average			5.01	0.32

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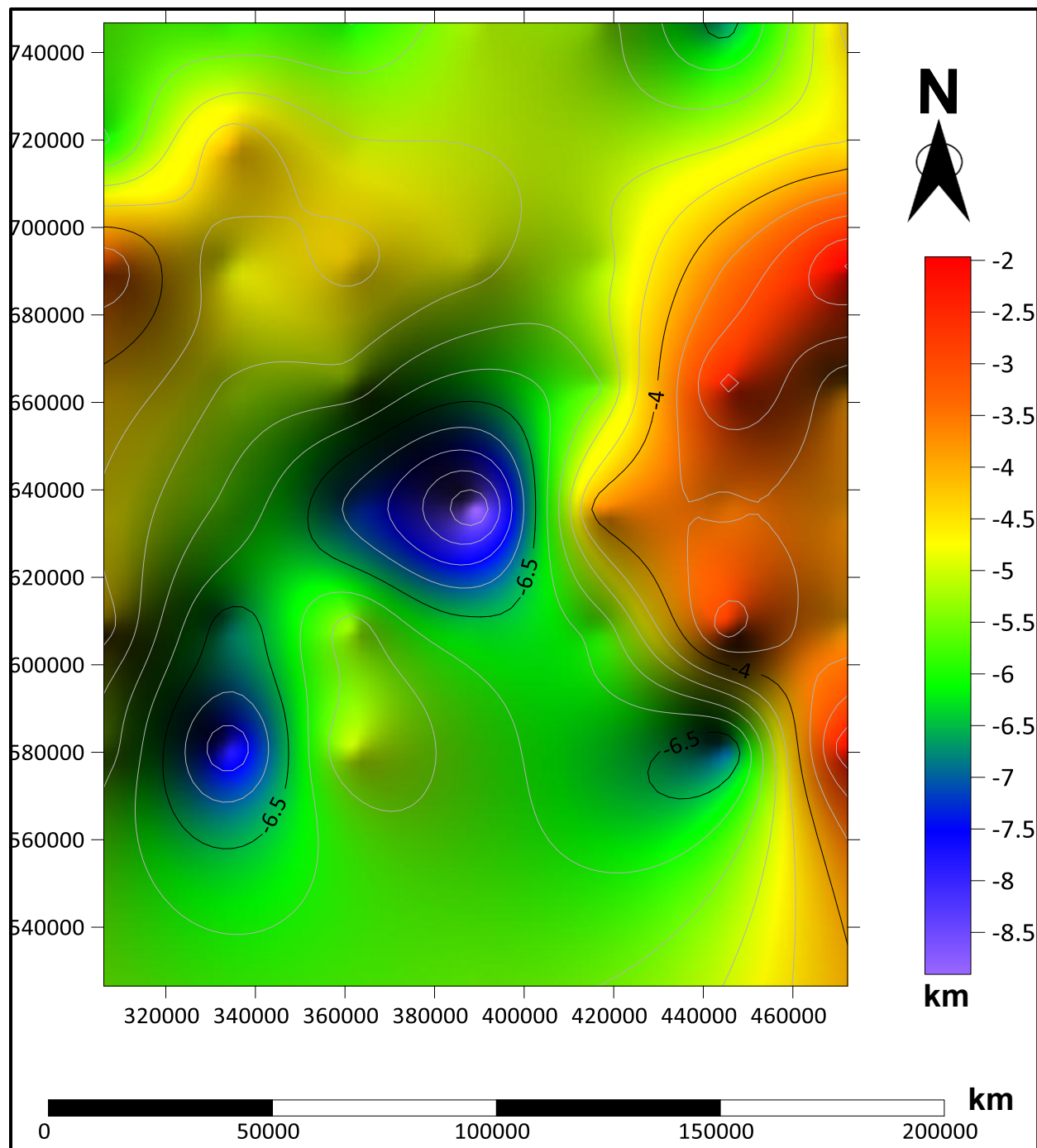


Fig. 11 Depth basement map of deeper magnetic sources in study area computed from analysis of the power spectrum

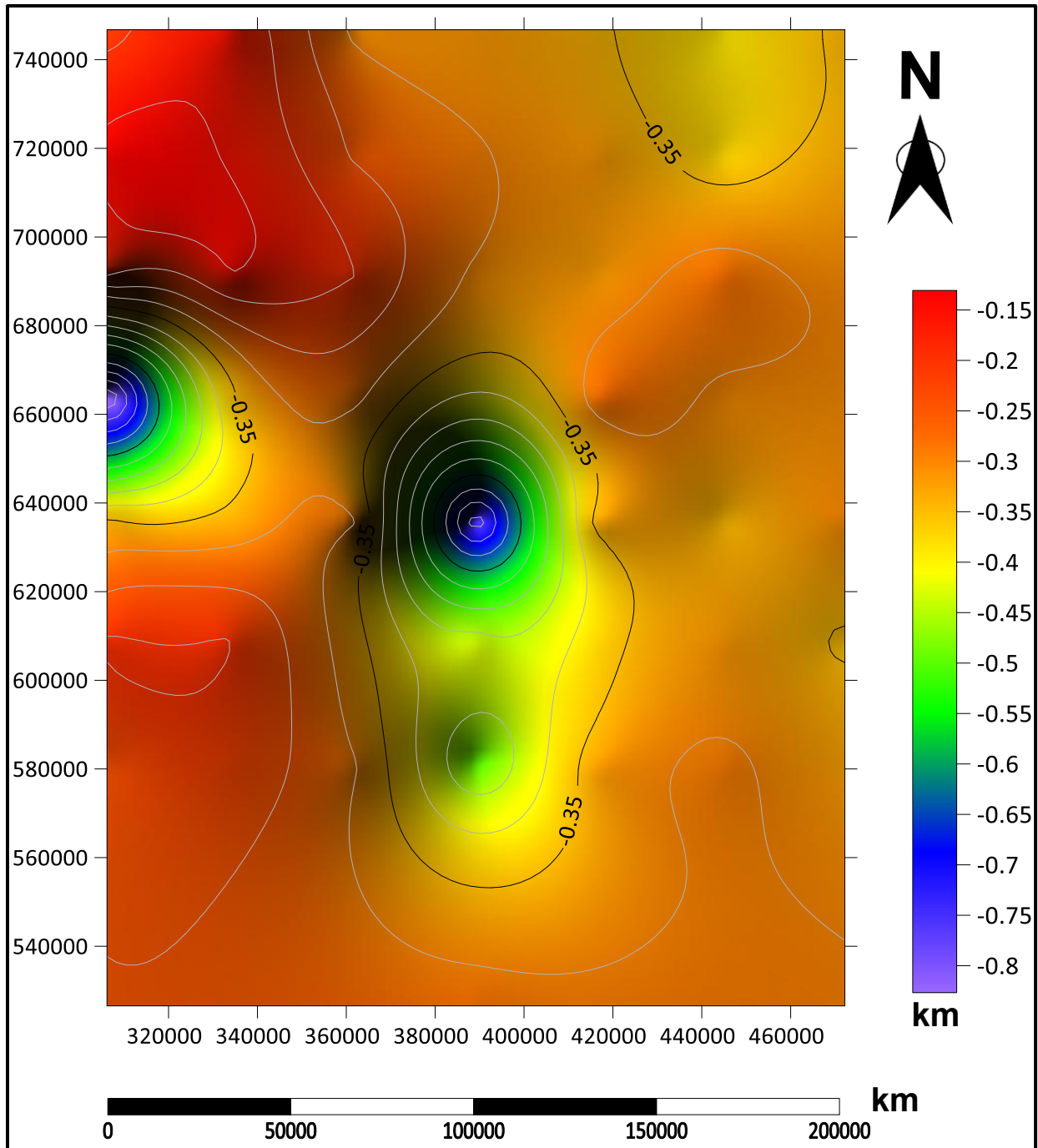


Fig. 12 Depth basement map of shallower magnetic sources in study area computed from analysis of the power spectrum

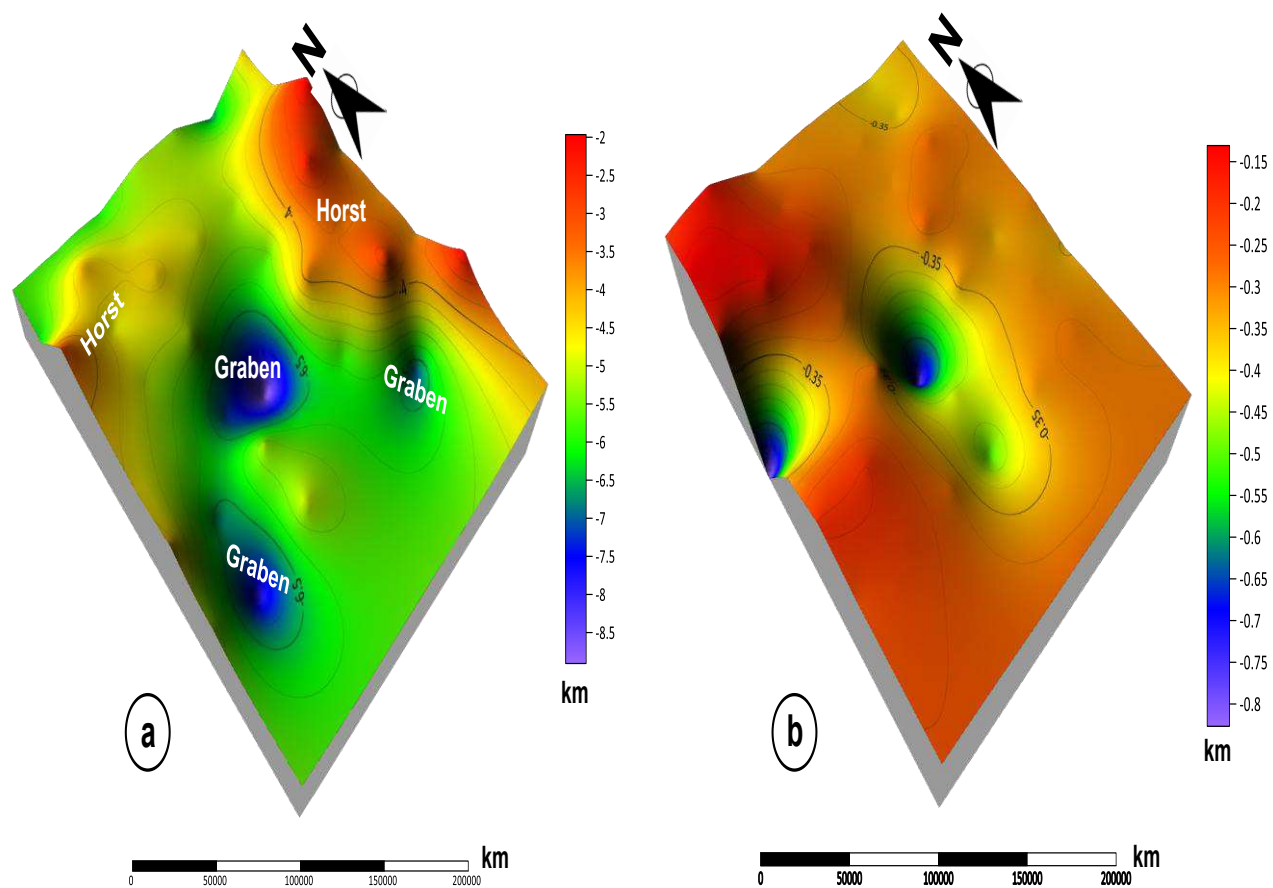


Fig. 13 3D display of the depth to basement for (a) deeper and (b) shallow magnetic sources

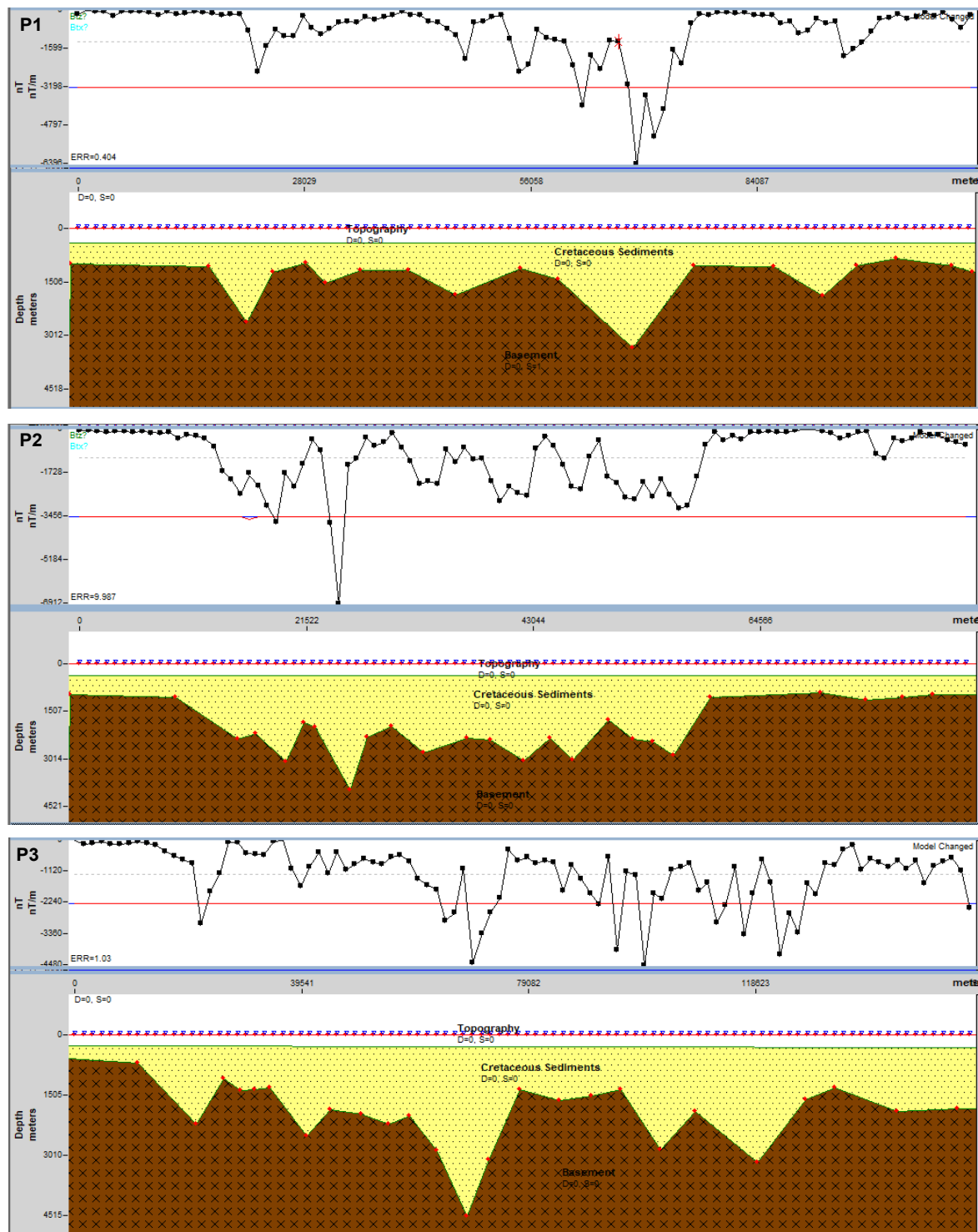


Fig. 14 2D modeled profiles (P1, P2, and P3) showing the morphology of the basement

Thermal Structure (Curie Point Depth, Geothermal Gradient, and Heat Flow)

To further quantify the thermal structure, Curie Point Depth (CPD), geothermal gradient, and heat flow were estimated from the aeromagnetic data. Analysis of the 2D power spectrum curves provides insight into the distribution of CPD beneath the region. Spectral analysis of twenty-five overlapping aeromagnetic blocks (110 km × 110 km) (Fig. 15) Curie Point Depth (CPD) estimation shows values ranging from 3.73 km to 15.56 km, with an average of 10.99 km. Shallow CPD values are observed in the northeastern, northwestern, and southeastern parts of the study area, while deeper values dominate the southwestern and southern regions.

The geothermal gradient values range from 37.28 °C/km to 155.50 °C/km, with an average of 58.35 °C/km. Heat flow values range from 93.19 mW/m² to 388.74 mW/m², with an average of 145.85 mW/m². The geothermal gradient and heat flow maps (Figs. 18 and 19) reveal anomalously high values in the northeastern and southeastern parts of the study area, with a gradual decrease toward other regions. The calculated geothermal gradients range from 42.37 °C/km to 155.50 °C/km, with a mean of 58.34 °C/km. Corresponding heat flow values vary from 39.19 mW/m² to 388.74 mW/m², with an average of 145.85 mW/m², which is significantly higher than the global continental mean of approximately 65 mW/m². A clear relationship is observed between CPD, geothermal gradient, and heat flow, such that shallow CPD zones correspond to high geothermal gradients and heat flow values, while deeper CPD zones correspond to lower thermal values (Tanaka et al., 1999; Li et al., 2017).

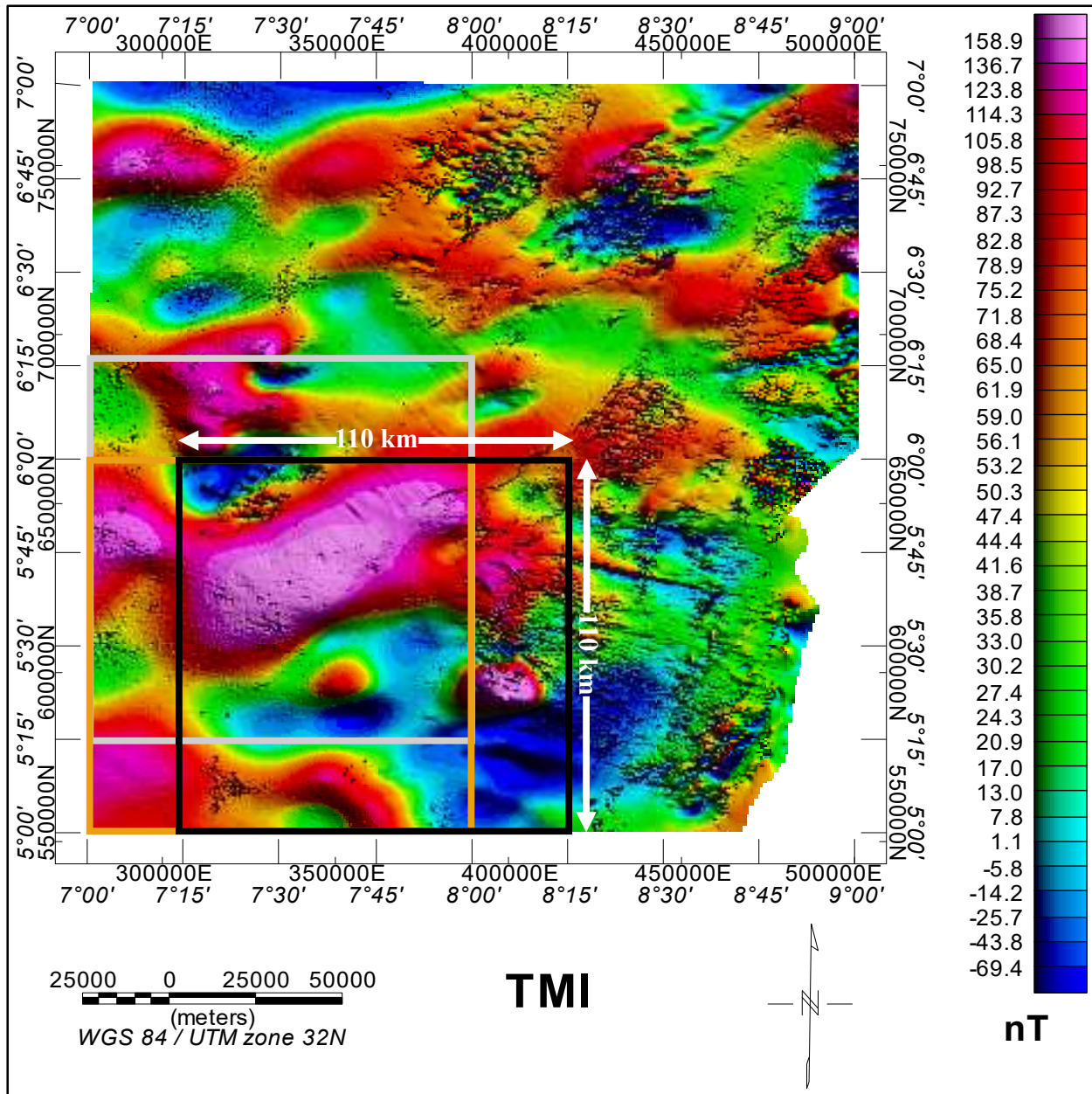


Fig. 15 Total magnetic intensity (TMI) map of the study area illustrating sections of 110 km × 110 km overlapping blocks analyzed for CPD determination

Table 2 Estimated Curie Point depths, heat flow and geothermal gradients values

Block	X	Y	Zo (km)	2Zo (km)	Zt (km)	Zb (CPD) (km)	GG (°C)	HF (W/m ²)
1	333900	608100	8	16	2.31	13.69	42.37	105.92
2	361950	608800	8.87	17.74	5.95	11.79	49.19	122.99
3	389200	608300	8.2	16.4	1.64	14.76	39.30	98.24
4	416800	608300	6.77	13.54	1.76	11.78	49.24	123.09
5	444400	608450	6.74	13.48	7.11	6.37	91.05	227.63
6	334300	636050	8.37	16.74	1.18	15.56	37.28	93.19
7	361950	636050	9.34	18.68	5.37	13.31	43.58	108.94
8	389600	635850	8.28	16.56	5.88	10.68	54.31	135.77
9	417050	636050	9.4	18.8	5.84	12.96	44.75	111.88
10	444400	635900	7.73	15.46	6.19	9.27	62.57	156.42
11	333950	663700	8	16	3.31	12.69	45.71	114.26
12	361950	663900	8.37	16.74	1.28	15.46	37.52	93.79
13	389400	663500	8.35	16.7	5.97	10.73	54.05	135.14
14	417000	663300	8.62	17.24	6.16	11.08	52.35	130.87
15	444200	663700	9.54	19.08	5.99	13.09	44.31	110.77
16	334250	691250	6.47	12.94	3.99	8.95	64.80	162.01
17	361550	691250	6.34	12.68	2.1	10.58	54.82	137.05
18	389900	691250	5.88	11.76	5.62	6.14	94.46	236.16
19	417050	691250	5.05	10.1	6.37	3.73	155.50	388.74
20	444750	691050	7.09	14.18	5.89	8.29	69.96	174.91
21	334050	718950	6.52	13.04	2.09	10.95	52.97	132.42
22	362150	718600	6.7	13.4	2.06	11.34	51.15	127.87
23	389100	718550	6.83	13.66	1.88	11.78	49.24	123.09
24	417450	718150	5.92	11.84	0.895	10.945	52.99	132.48
25	444150	718800	5.46	10.92	2	8.92	65.02	162.56
Average				14.95		10.99	58.34	145.85

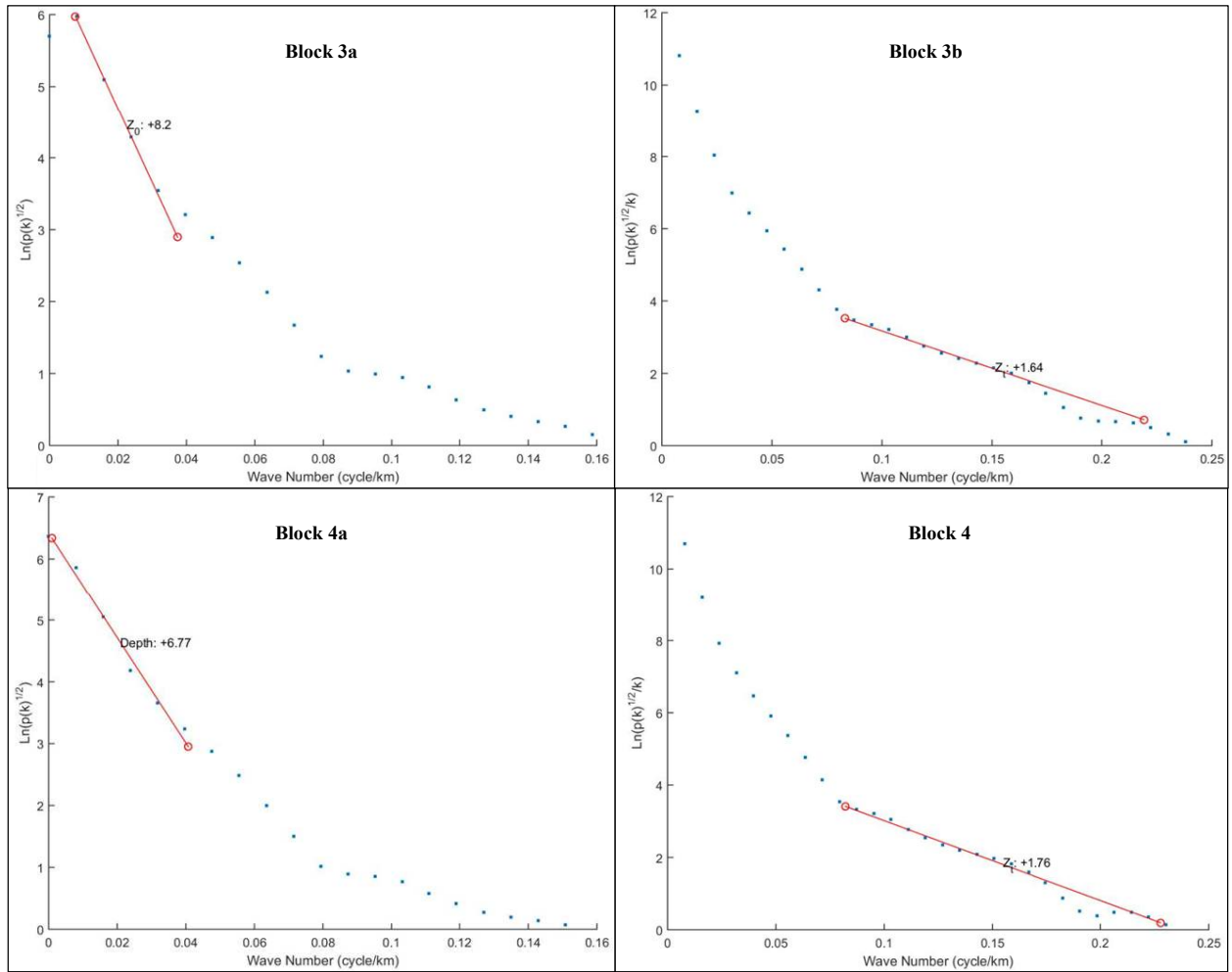


Fig. 16 2D power spectrum curves of Block 3 and Block 4 showing the estimated depths to top (Z_t) and centroid (Z_0) in the study area

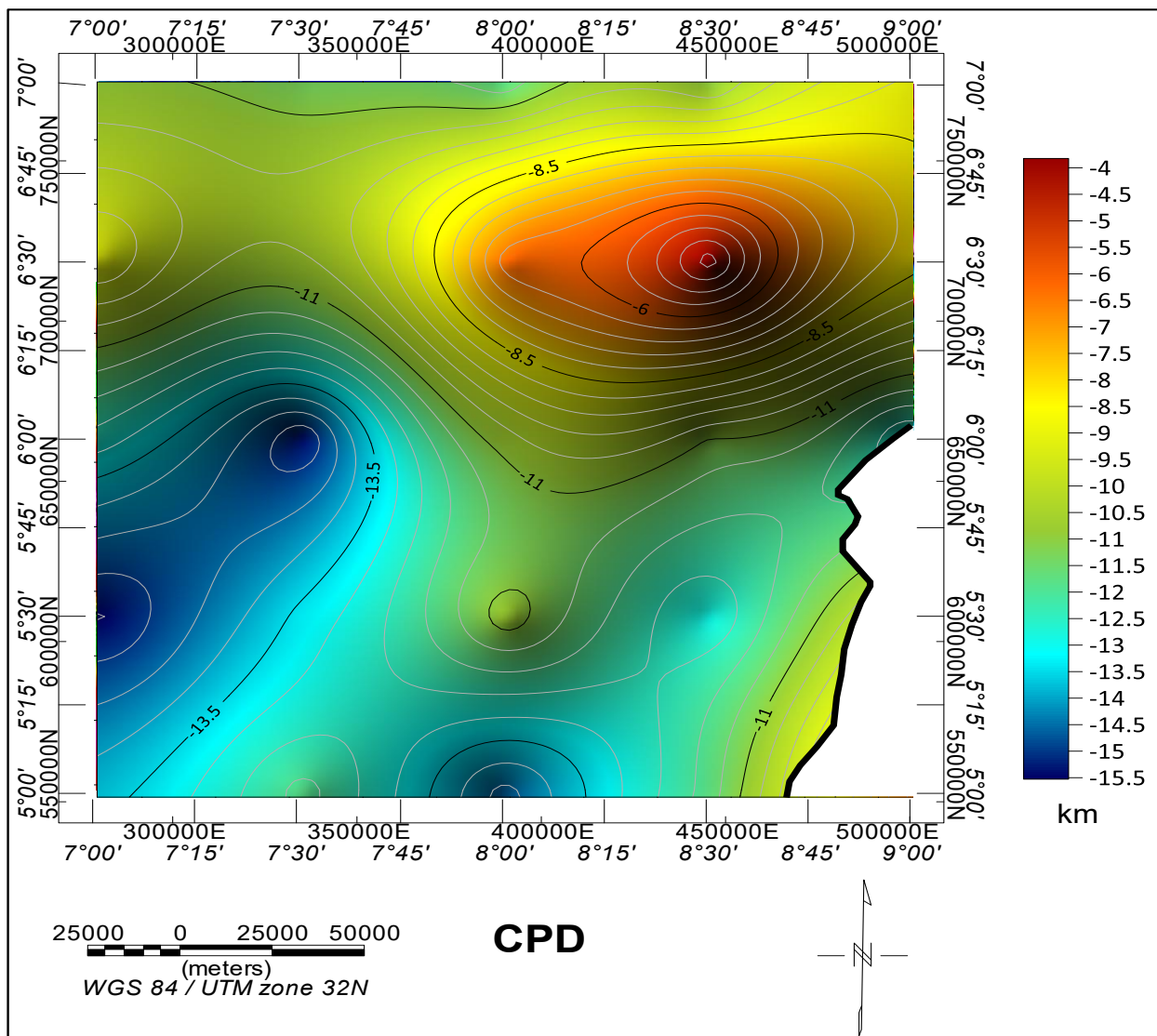


Fig. 17 Curie point depth map of the study area

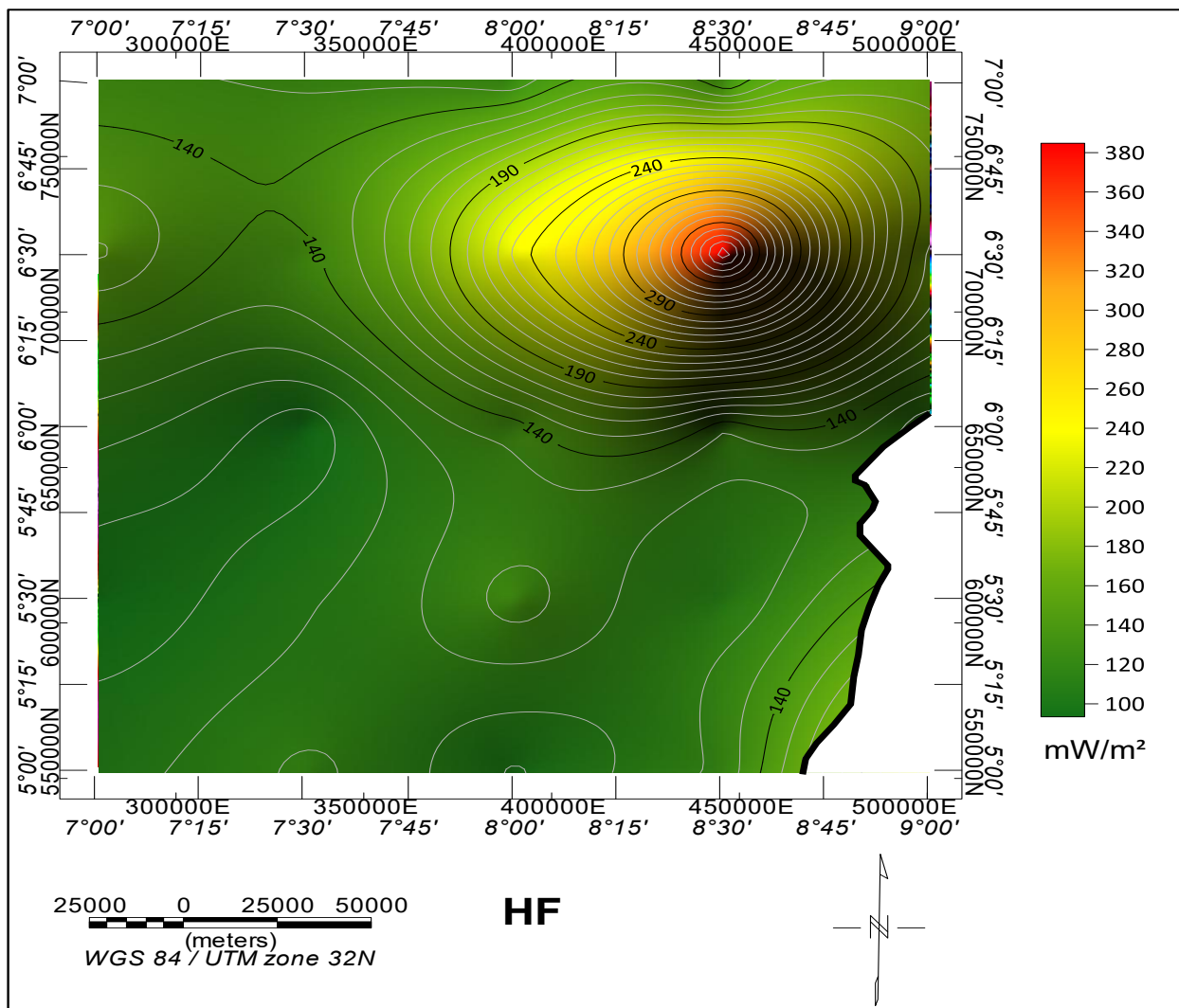


Fig. 18 Heat flow (HF) map of the study area

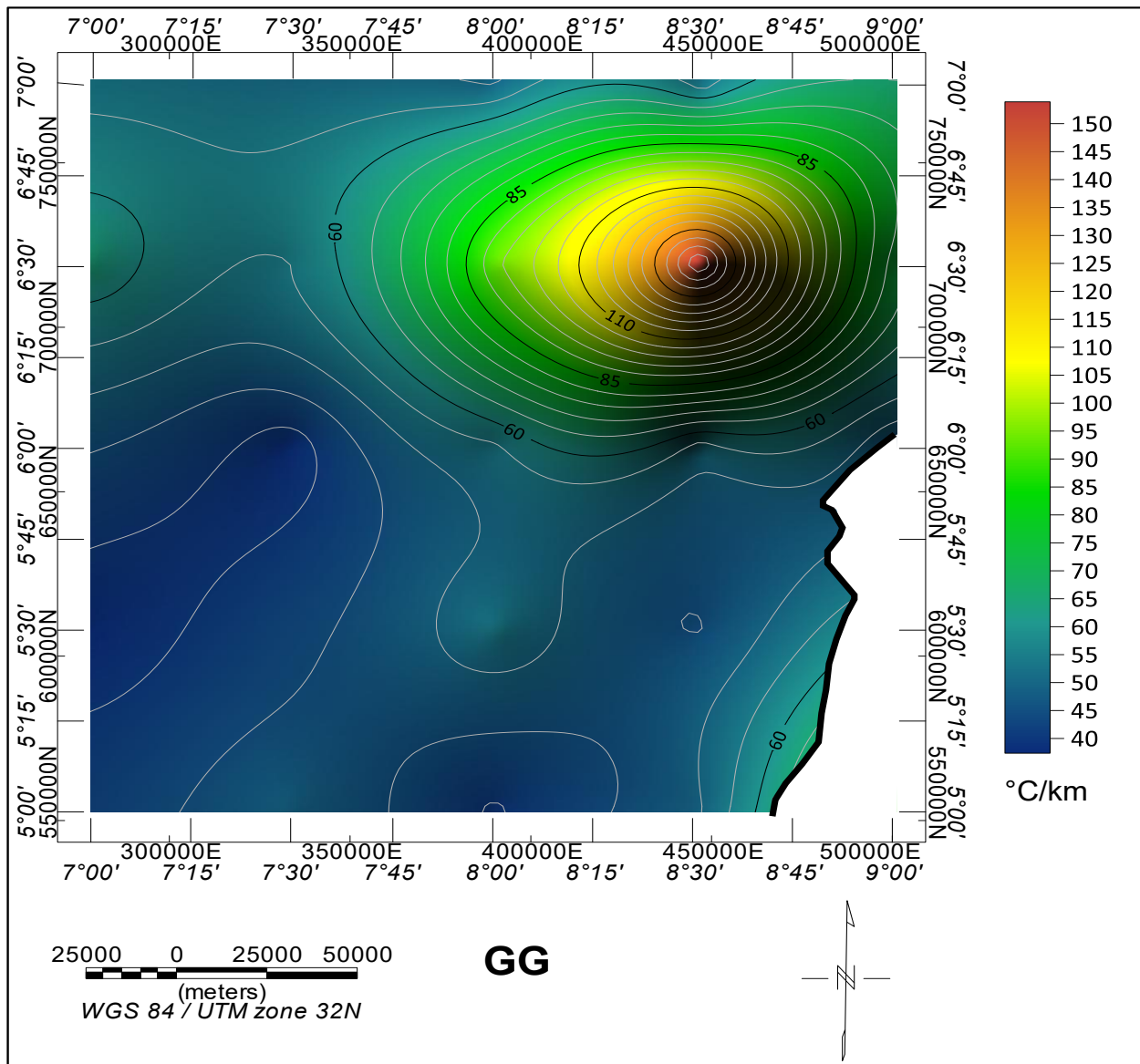


Fig. 18 Geothermal gradients (GG) map of the study area

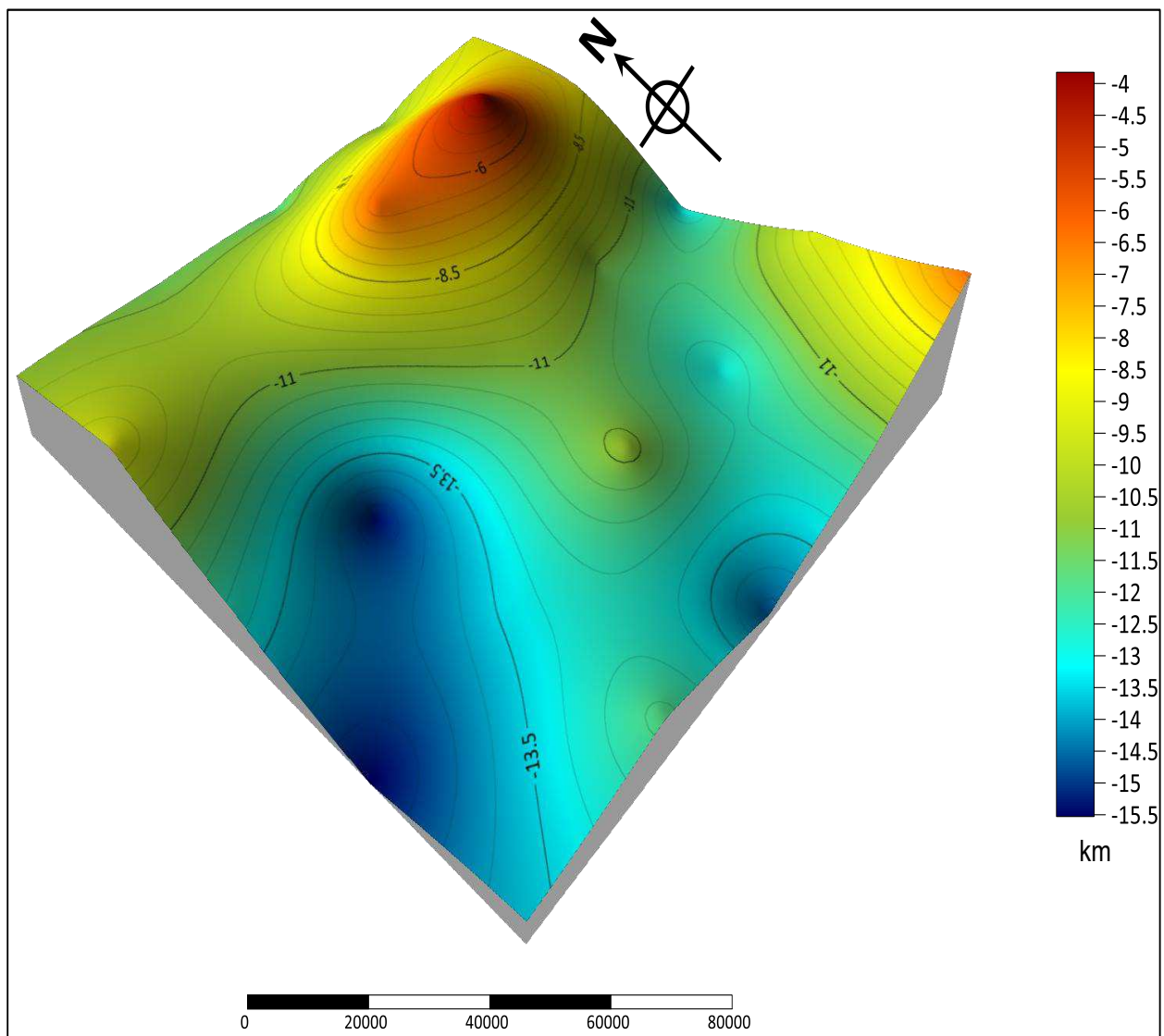


Fig. 19 3D display of the Curie Point depth map of the study area

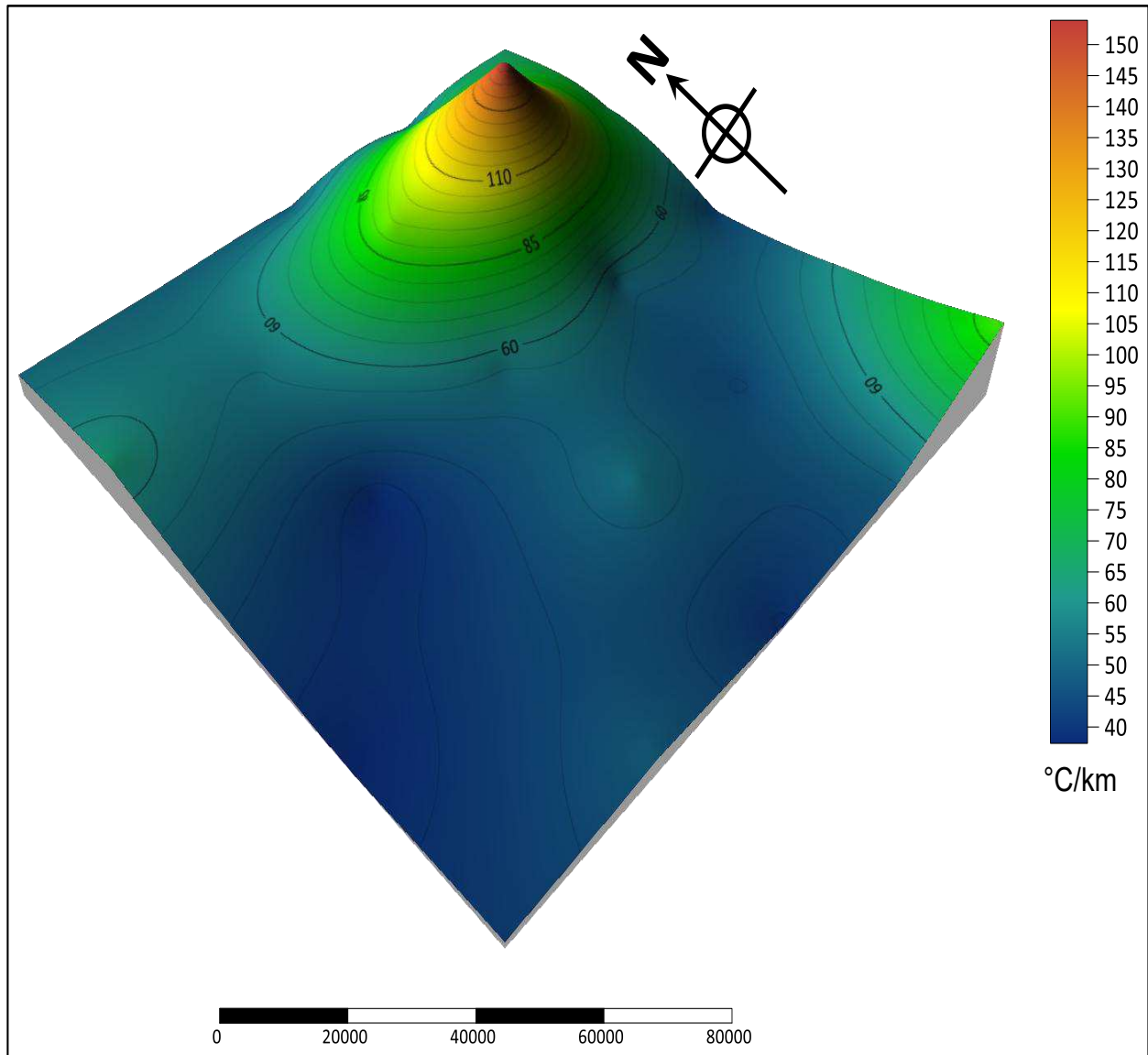


Fig. 20 3D display of the geothermal gradient map of the study area

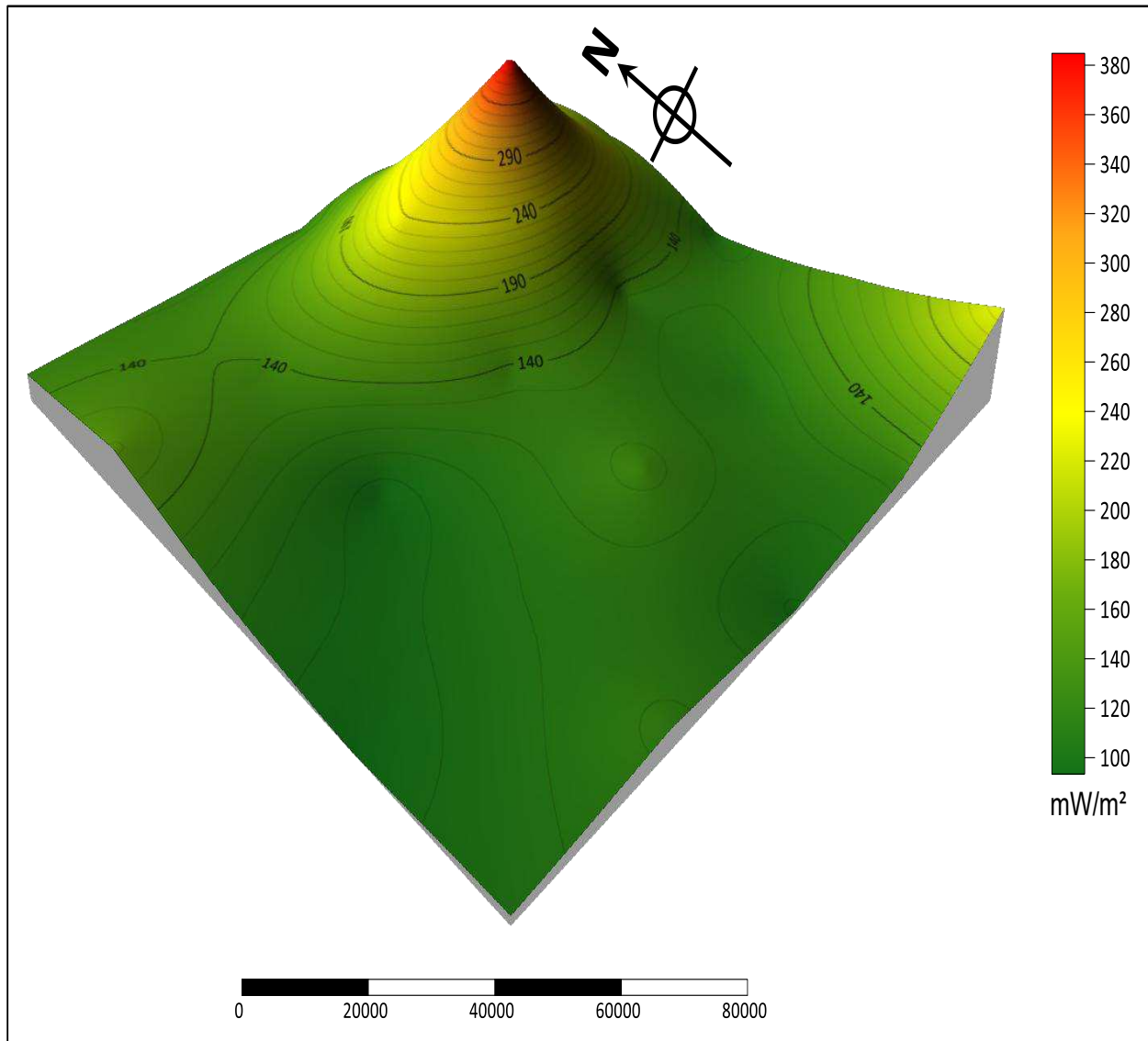


Fig. 21 3D display of the heat flow map of the study area

Airborne Radiometric Data

Airborne radiometric data provide information on the spatial distribution and concentration of naturally occurring radioactive elements, primarily potassium (K), uranium (U), and thorium (Th), within the near-surface geological environment. These elements emit gamma radiation during radioactive decay, which can be measured using airborne gamma-ray spectrometry. Their distribution reflects lithological variations, hydrothermal alteration processes, structural controls, and geothermal heat generation potential.

Potassium (K), Thorium (eTh), and Uranium (eU) Concentration Maps

The potassium (K) distribution map provides information on lithological variation, hydrothermal alteration, and structural control within the Southern Benue Trough. Potassium concentration values range from approximately 0.0269% to 1.8665%, indicating significant spatial variation across different geological formations. Areas of high potassium concentration (up to 1.8665%), represented by pink, red, and purple colors, are predominantly located in the central, southeastern, and northeastern portions of the study area. Moderate potassium concentrations, ranging from 0.630% to 1.005%, occur in parts of the northwestern, central, and southeastern regions. Low potassium concentrations,

368 represented by blue and dark blue colors, are mainly observed in the northwestern and localized southwestern portions
369 toward the Anambra Basin.

370 Thorium (eTh) concentration values range from approximately 3.7018 ppm to 27.1055 ppm, indicating considerable
371 variation across the region. Since thorium is relatively immobile during hydrothermal processes, its distribution reflects
372 the original lithological composition and serves as an indicator of primary rock types and geological boundaries. High
373 thorium values, represented by pink, red, and purple colors, occur predominantly in the central, northeastern, and
374 northwestern portions of the study area. Low thorium values (around 3.7018 ppm), shown in blue and dark blue, are
375 mainly observed in the southern and southwestern regions, while moderate concentrations are widely distributed.

376 Uranium (eU) concentration values range from approximately 0.3002 ppm to 6.3304 ppm, indicating significant spatial
377 variation in uranium enrichment. Uranium is highly mobile under oxidizing hydrothermal conditions, and its distribution
378 is influenced by structural pathways, fluid migration, and lithological composition. High uranium values (4.789 ppm to
379 6.3304 ppm), represented by pink, red, and purple colors, and are concentrated in the central, northeastern, and
380 southeastern portions of the study area. Moderate concentrations are widely distributed, whereas low values, shown in
381 blue and dark blue, are predominantly observed in the northwestern and southern regions.

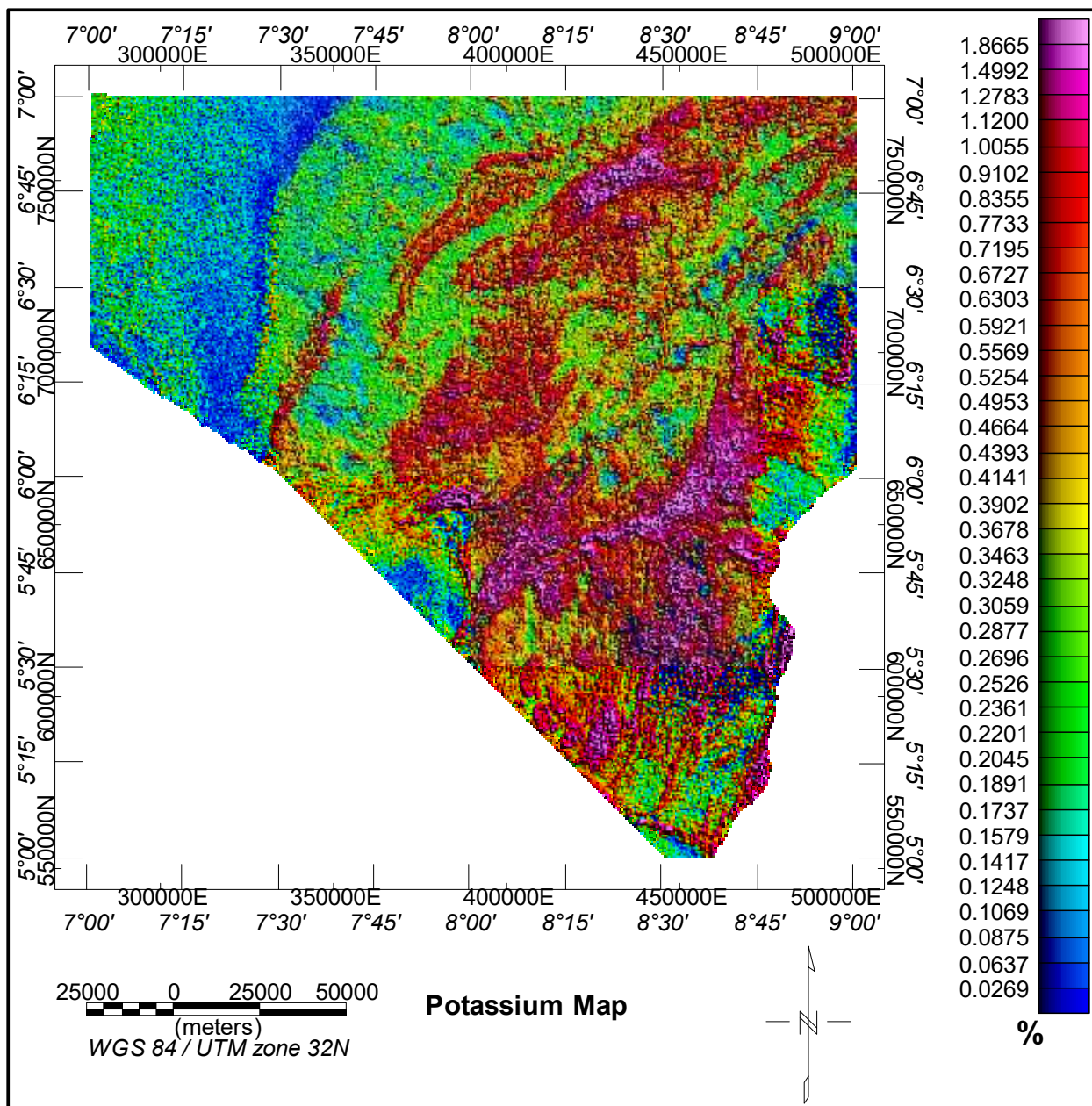


Fig. 22 Potassium Alteration Map of the study area

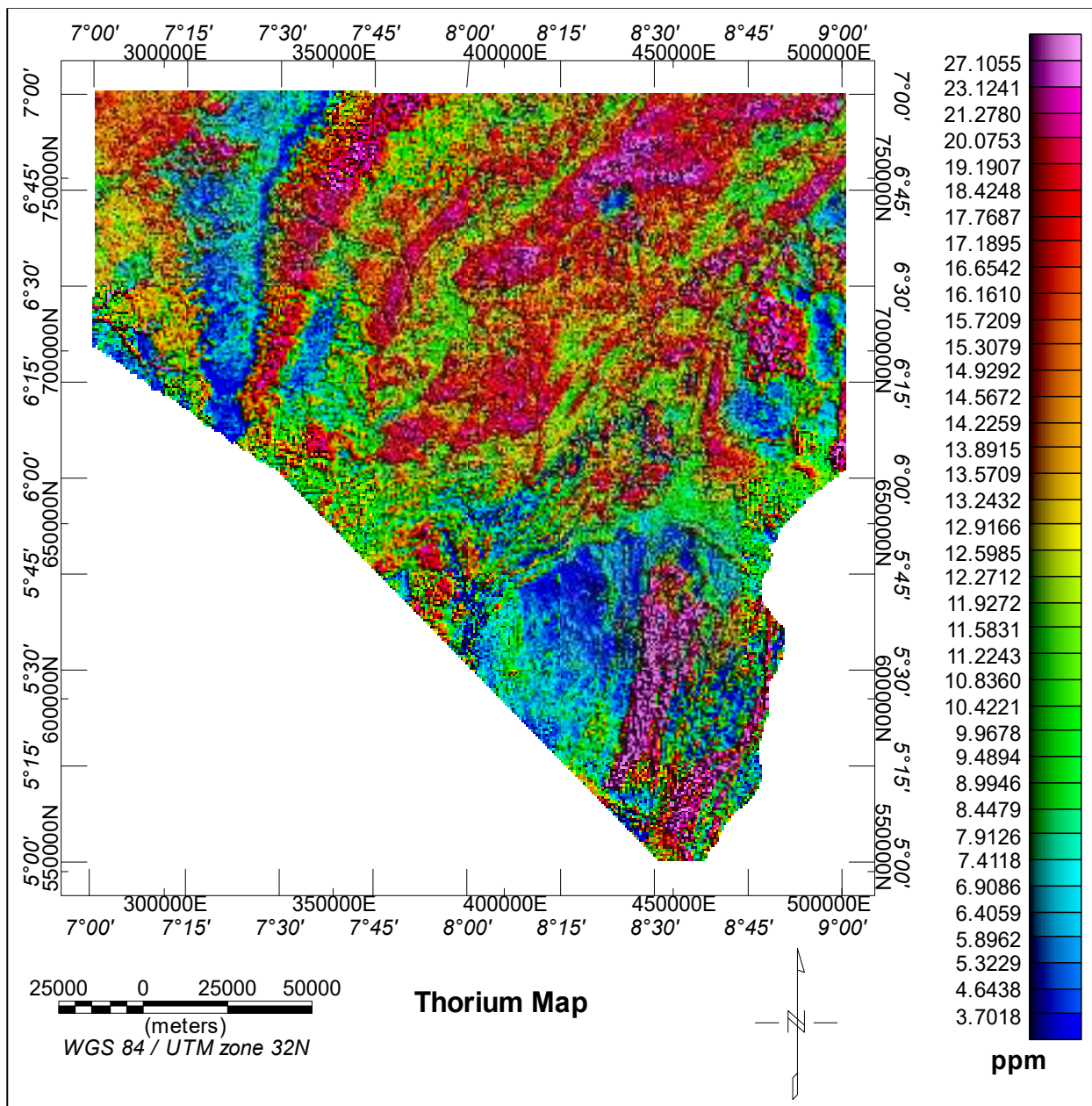


Fig. 23 Thorium Concentration Map of the study area

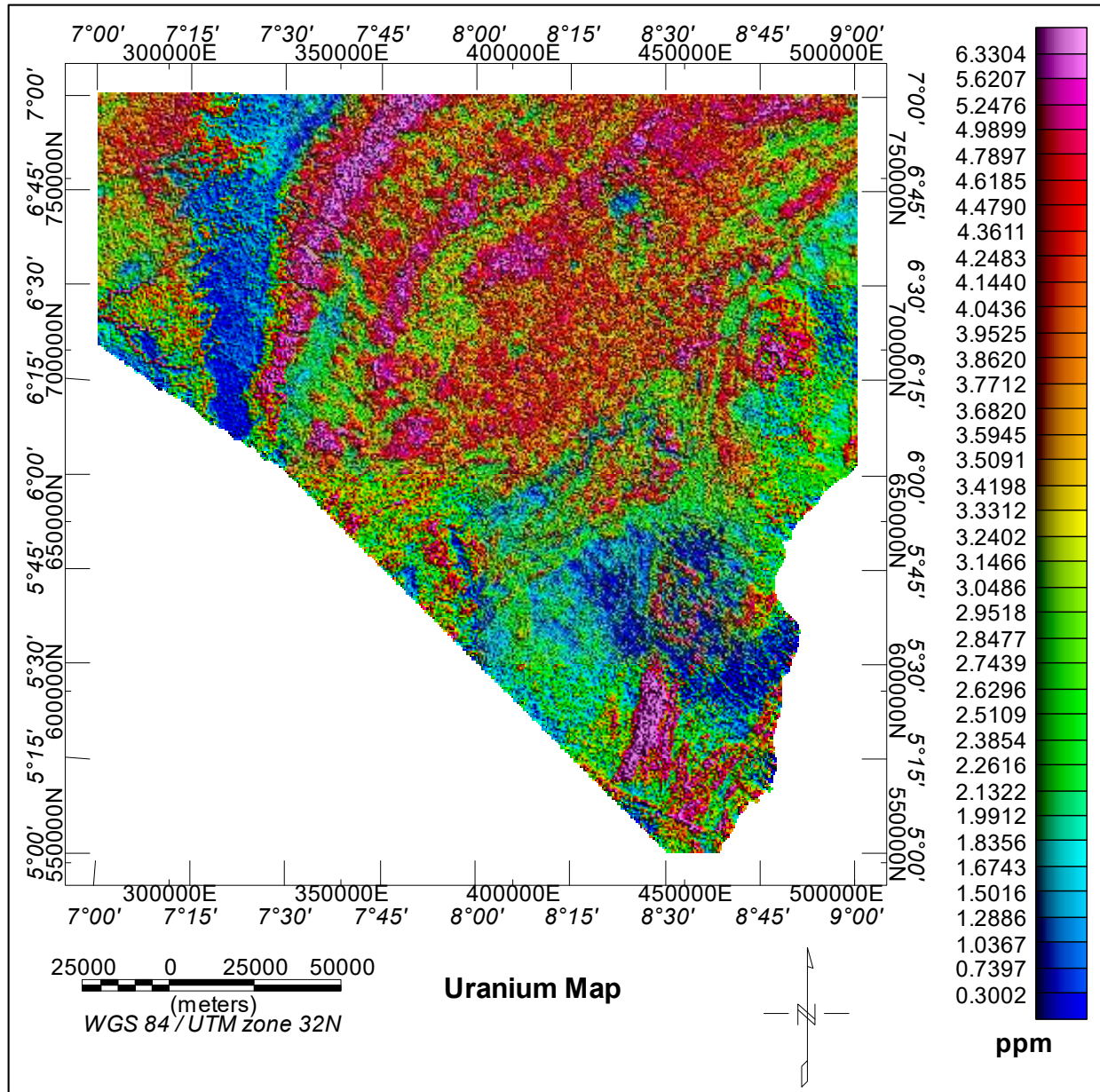


Fig. 24 Uranium Concentration Map of the study area

K/eTh Ratio Map

The K/eTh ratio map of the study area shows values ranging from 0.0024 to 0.2233 %/ppm (Fig. 4.18), which is higher than the stability range and suggests the presence of hydrothermal mineralization within the region. High anomalous zones dominate the eastern and southeastern parts of the study area and coincide with the basement rocks of the Oban Massif. These high K/eTh ratio anomalies are interpreted to represent hydrothermally altered zones or mineralized environments.

The highest K/eTh ratio values (0.2233 %/ppm) are associated with Pan-African granites, migmatites, migmatitic gneiss, porphyritic granite, and undifferentiated schist, including gneiss, fine-grained flaggy quartzites, muscovite schist, and biotite granite. In contrast, low K/eTh ratio values are concentrated in the northwestern and parts of the eastern and southeastern margins of the region, which are predominantly underlain by Cretaceous sedimentary rocks.

Ternary Map

The composite ternary map of the radioelements (K, eTh, and eU) displayed in red, green, and blue (RGB), respectively (Fig. 4.19), shows variations in the concentration and natural radioactivity of the elements, reflecting the response of different lithological units beneath the study area. Potassium (K) is represented by red, thorium (eTh) by green, and uranium (eU) by blue.

Areas with bright red coloration indicate high potassium concentration, while bright green colors represent high thorium concentration. White zones indicate strong concentration of the three radioelements, whereas black zones indicate low concentrations associated with weakly radioactive rocks.

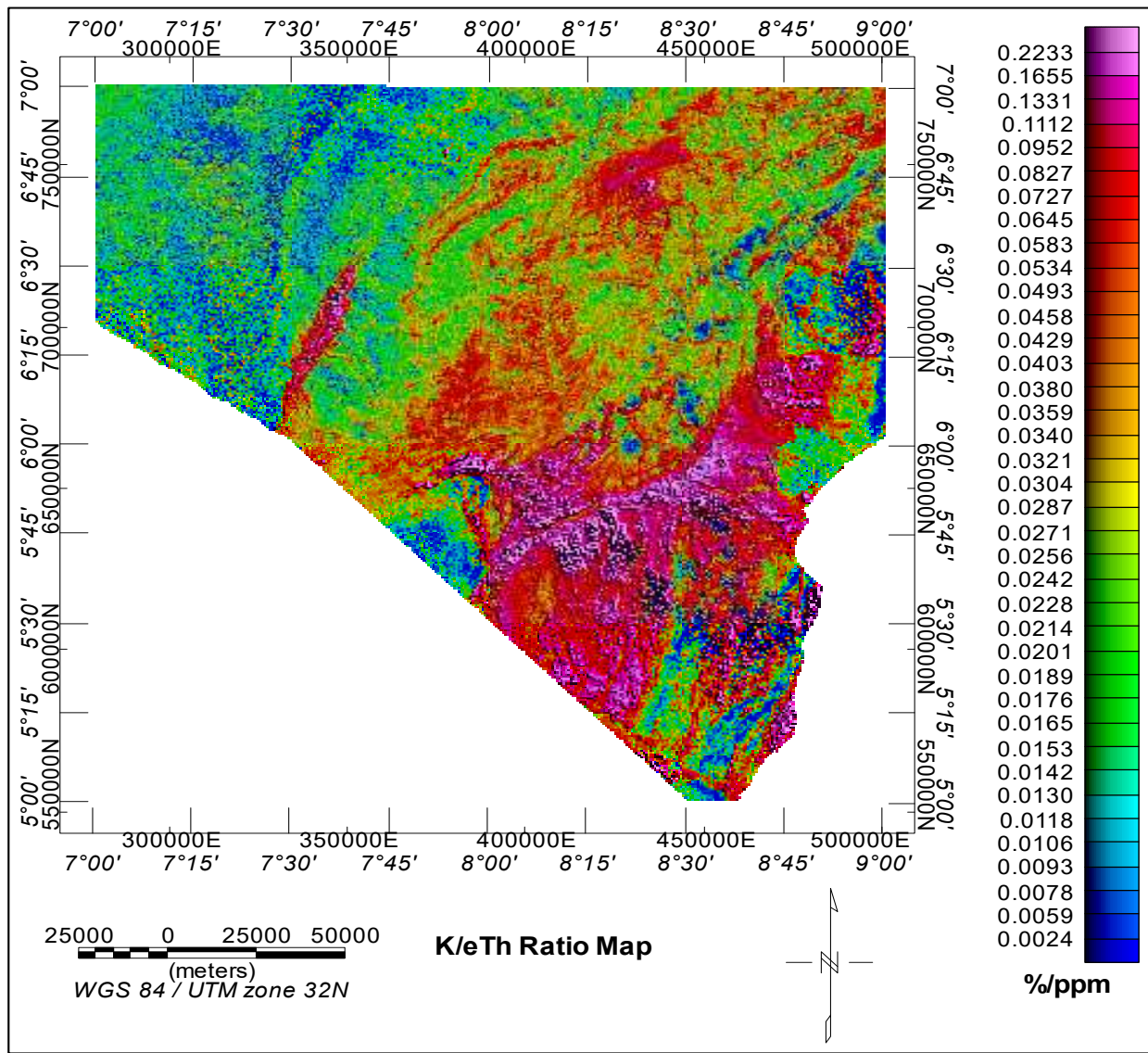


Fig. 25 K/eTh ratio map of the study area

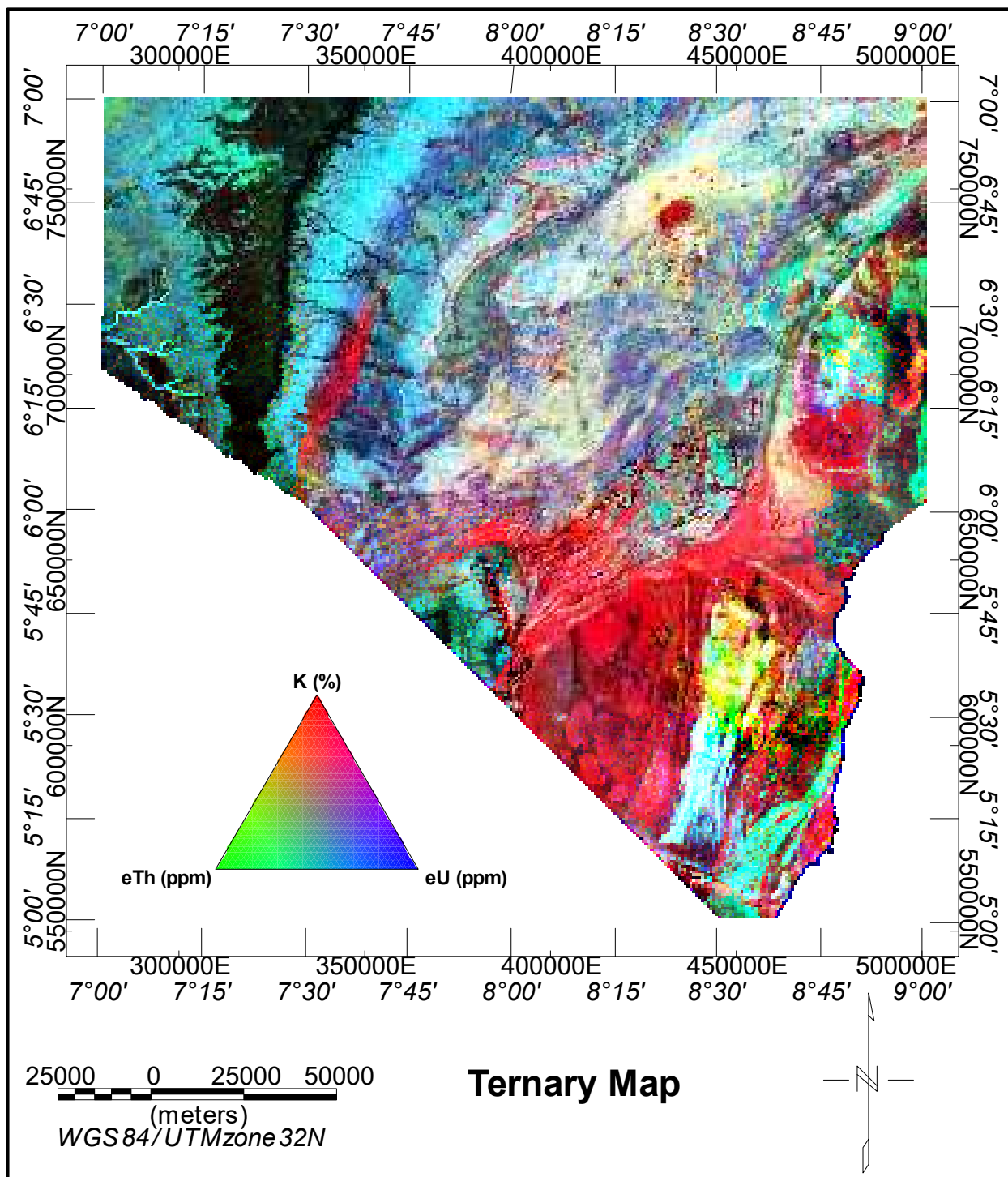


Fig.26 Ternary image of the study area

Discussion

Airborne Magnetic Characteristics of the Southern Benue Trough

The TMI (Fig. 5) and RTE (Fig. 6) maps show variations in high (red) and low (blue) magnetic signatures that reflect differences in the magnetic susceptibilities of subsurface rock units within the study area. The peak amplitude signatures observed in the central part of the TMI map trend predominantly in the NE–SW and E–W directions, while the RTE map further resolves these anomalies into NW–SE, NE–SW, and E–W orientations. These patterns indicate the presence of both shallow and deep-seated magnetic sources, suggesting a complex subsurface composed of heterogeneous lithologies and structurally controlled features.

The occurrence of relatively high magnetic intensities within areas underlain by sedimentary rocks is particularly significant. Rather than representing purely sedimentary responses, these anomalies are interpreted to result from igneous intrusions emplaced within the Cretaceous sedimentary sequences. This interpretation is consistent with the known tectono-magmatic evolution of the Benue Trough, where intrusive activities are closely associated with rifting and subsequent tectonic reactivation. Thus, the magnetic signatures not only reflect lithological contrasts but also provide evidence of magmatic contributions to the subsurface architecture.

Tectonic Features of the Southern Benue Trough

Structural enhancement techniques, including FVD (Fig. 7) and Analytical Signal (Fig. 8), clearly delineate magnetic anomalies corresponding to the edges and contacts of lineaments, faults, fractures, dykes, and veins. These features follow dominant NE–SW, NW–SE, and E–W orientations, which correspond to major tectonic trends within the Benue Trough.

Their geometric characteristics suggest that they originate from deep-seated structural deformations associated with Pan-African and earlier tectonic events that impacted the Nigerian Basement Complex (Obaje, 2009). However, beyond simply reflecting inherited structures, the present results indicate that these tectonic features have been repeatedly reactivated, thereby maintaining their significance in controlling subsurface processes.

The segmentation of the basement into distinct structural blocks, as revealed by the magnetic data, explains the rugged basement topography observed across the study area. The Analytical Signal map further enhances this interpretation by revealing rounded and subrounded anomalies interpreted as magmatic intrusions emplaced into the sedimentary sequences. These intrusions are more prominent within the southeastern and eastern parts of the study area, corresponding to the Oban Massif, where high-amplitude signatures dominate. In contrast, intermediate to low magnetic anomalies correspond to sedimentary terrains such as the Afikpo Syncline and the Anambra Basin. This contrast highlights the transition between basement-dominated and sedimentary domains and reinforces the interpretation that the magnetic field is strongly controlled by both lithology and tectonic structure. Importantly, the spatial association between intrusive bodies and structural discontinuities suggests that magmatic emplacement was structurally controlled. This implies that tectonic features not only influenced deformation but also governed the localization of magmatic and thermal processes within the basin.

Lineament Interpretation and Tectono-Thermal Evolution

Lineaments interpreted from the First Vertical Derivative (FVD) map indicate that structural elements are concentrated in areas underlain by crystalline basement rocks and are expressed as both long and short linear magnetic anomalies. Orientation analysis using rose diagrams reveals a dominant NE–SW trend, with subordinate E–W and NW–SE orientations. These structural trends are consistent with known tectonic episodes, including the Pre-Pan-African and Pan-African orogenic events that significantly deformed the Nigerian Basement Complex (Obaje, 2009; Anudu et al., 2014). However, the present study provides further insight by demonstrating that these structures are not merely relics of past tectonic events but remain active controls on present-day subsurface processes. The NE–SW and NW–SE lineaments are interpreted as products of tectono-thermal cycles involving deformation, reactivation, and remobilization of crustal weaknesses during the Pan-African (~600 Ma) orogeny (Odeyemi, 1981; Rahaman, 1989). The E–W oriented structures are associated with extensional tectonics linked to the opening of the South Atlantic, while the oblique trends reflect subsequent wrench deformation and stress reorganization. These multi-phase tectonic cycles resulted in a

structurally heterogeneous crust characterized by zones of weakness that facilitated both magmatic intrusion and fluid migration. The alignment of magnetic anomalies with mapped structural features further confirms that brittle deformation played a major role in shaping the present-day structural framework (Burke & Dewey, 1972; Dada, 2006; Oladunjoye et al., 2016). Thus, the structural architecture of the Southern Benue Trough reflects a combination of inherited basement fabrics and later tectonic reactivation, both of which are critical in controlling hydrothermal and geothermal processes.

Tectonic Controls on Hydrothermal Mineralization and Geothermal Prospects

To further evaluate the role of structures in controlling mineralization, the extracted lineaments were used to generate a lineament density map (Fig. 28), which highlights zones of structural complexity that are favorable for hydrothermal mineral exploration (Holden et al., 2012; Bonham-Carter, 1994). Mineralized regions are commonly associated with intersections of geological structures such as faults, fractures, dykes, and joints, which act as conduits for hydrothermal fluid flow. The results of this study indicate that areas characterized by high lineament density correspond to zones of enhanced structural permeability. These zones facilitate the circulation of mineral-rich hydrothermal fluids and therefore represent favorable targets for mineral exploration.

In this study, the eastern and southeastern parts of the Southern Benue Trough are characterized by long lineament lengths and high lineament density, and are therefore identified as potential zones for hydrothermal mineralization. These zones also act as conduits for thermal fluids, indicating a direct link between structural complexity and geothermal processes. Other regions, including the northern, northwestern, western, and central parts of the study area, also exhibit high lineament density and are interpreted to be influenced by magmatic intrusions emplaced within the sedimentary sequences. The association between these zones and known mineral occurrences further supports their exploration significance (NGSA, 2008). The spatial distribution of structurally complex zones indicates that tectonic deformation not only controlled mineralization but also influenced the migration of heat and fluids within the crust. Consequently, areas with high lineament density represent zones where structural permeability enhances both hydrothermal mineralization and geothermal fluid circulation. This relationship is particularly important because it demonstrates that mineralization and geothermal systems are not independent phenomena but are genetically linked through tectono-thermal processes. In essence, the same structures that control fluid flow also facilitate heat transfer, thereby creating conditions favorable for both mineral deposition and geothermal energy accumulation.

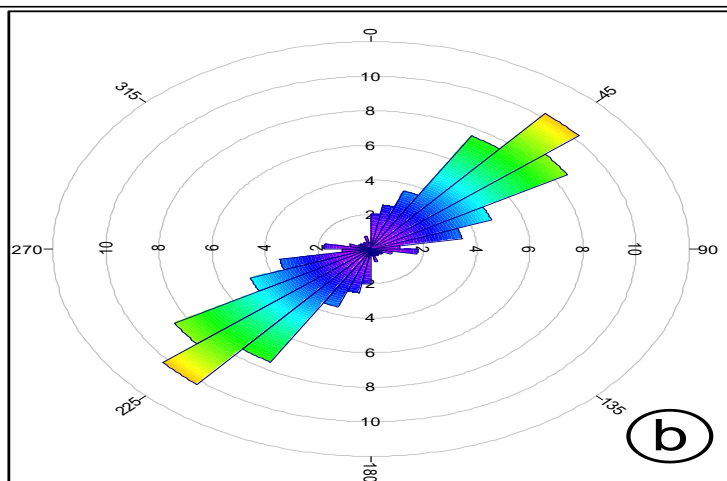
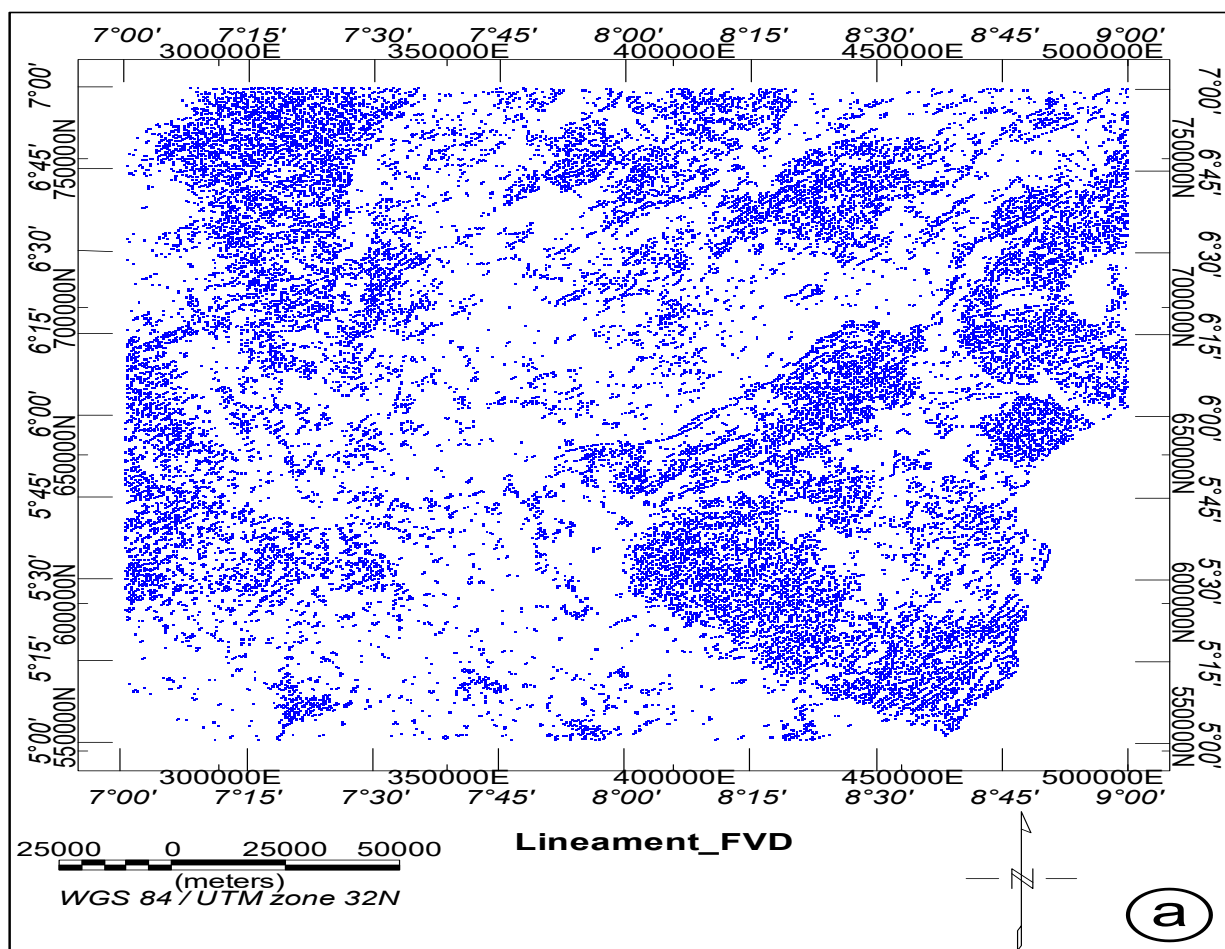


Fig 27 (a) Lineaments extracted from FVD map interpretation. (b) Rosette plot showing the major and minor orientations of lineaments

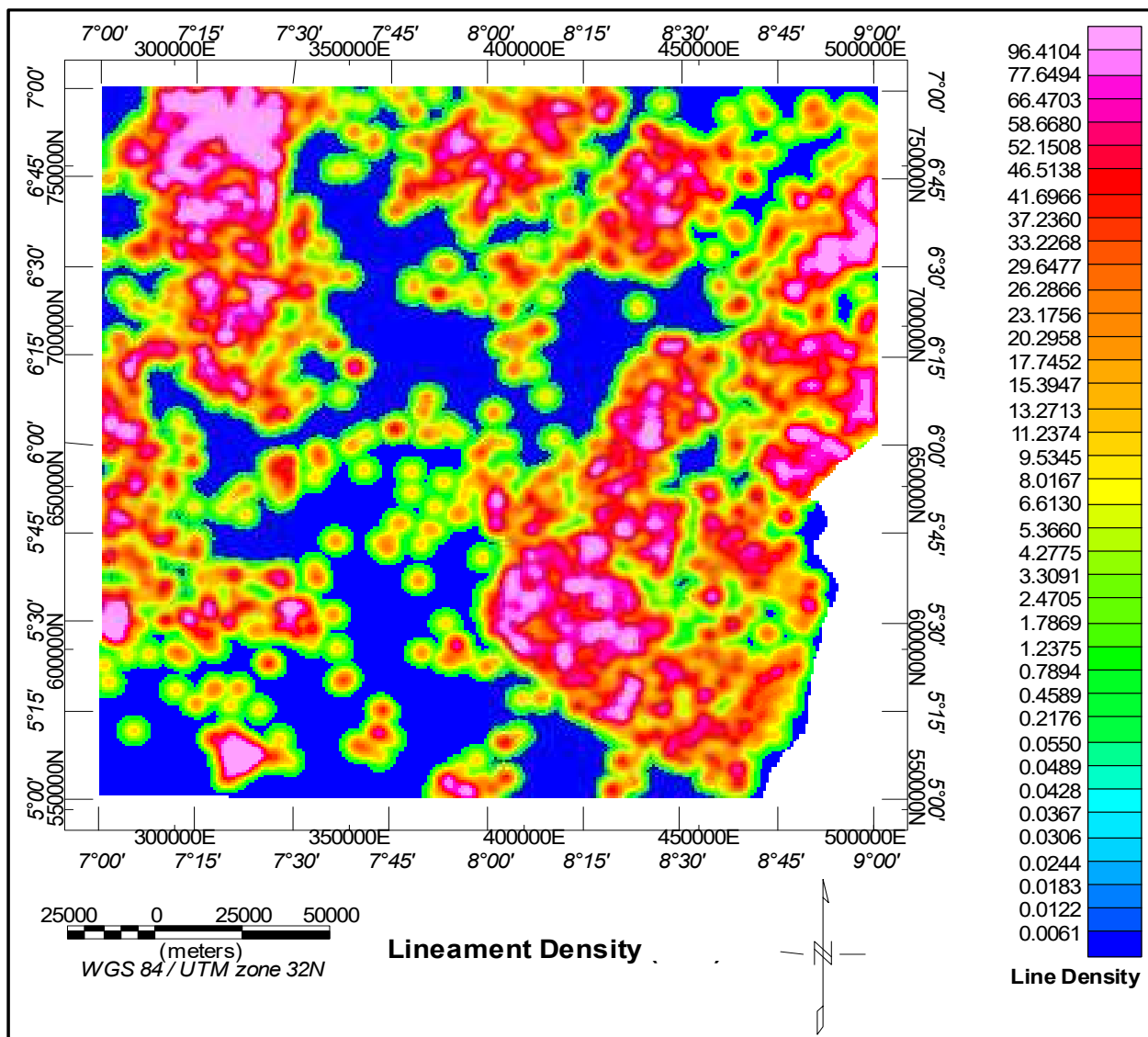


Fig. 28 Lineament Density Map

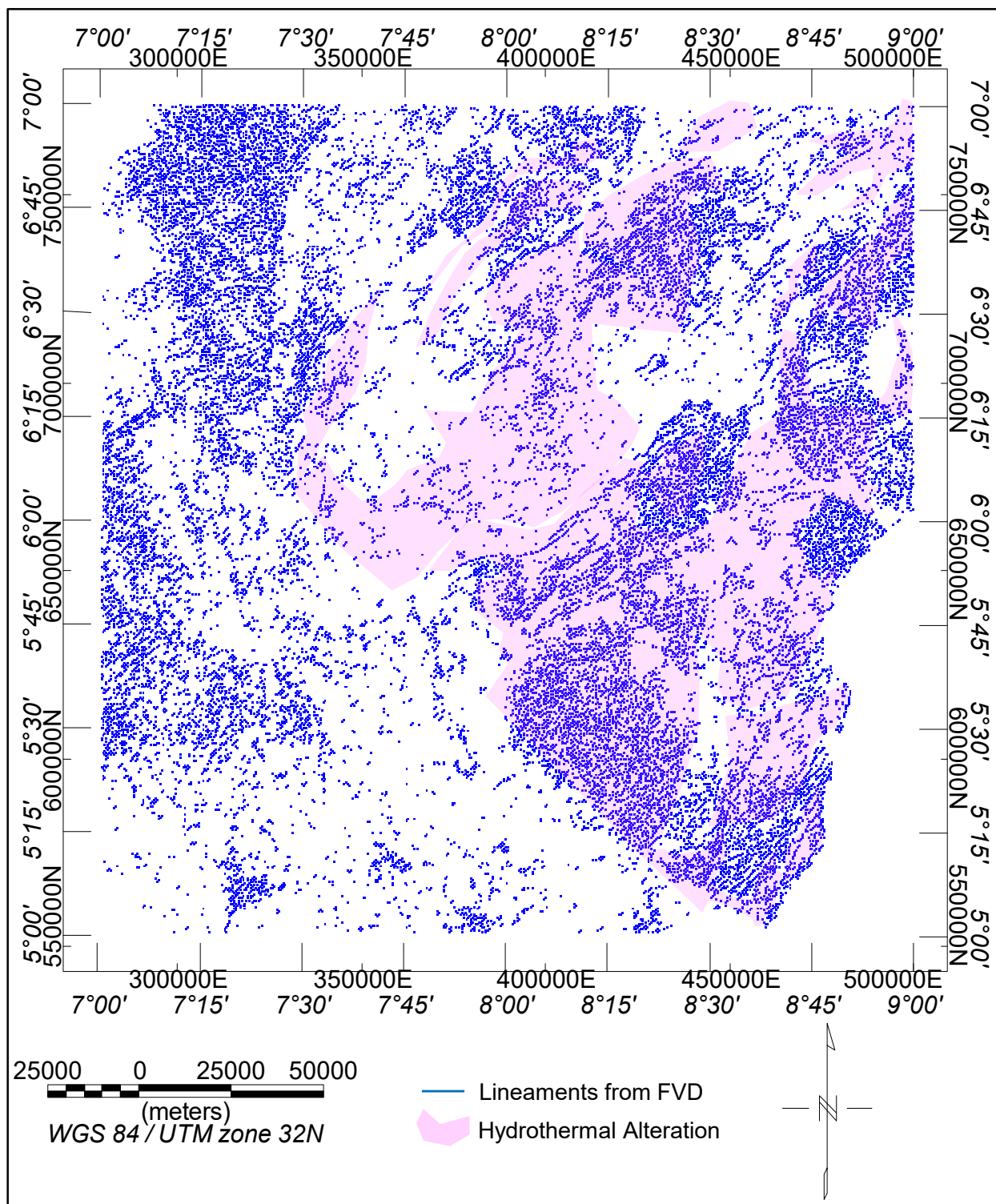


Fig. 29 Prospective mineralization targets generated from integration of the dataset

Basement Configuration, Depth Distribution and Structural Implications

Analysis of the 2D power spectra reveals the presence of both shallow and deep magnetic sources beneath the study area. The deeper magnetic sources, derived from the low-frequency (steeper) segment of the spectra, range from 2.08 km to 9.02 km with an average depth of 5.01 km, while the shallow sources range from 0.15 km to 0.846 km with an average of 0.32 km. These values indicate a highly heterogeneous crust characterized by both shallow intrusive bodies and deeper basement structures. The 3D representation of the basement depth reveals an undulating morphology defined by alternating horsts and grabens. These basement depressions act as depocenters that accommodated thick sedimentary sequences of up to 7 km. The progressive increase in basement depth toward the central, southwestern, and southern parts of the study area reflects structural subsidence associated with rifting and basin development. While these results agree with previous studies (Oha et al., 2016; Abdullahi et al., 2019), the present study provides additional insight into the role of these structures in controlling subsurface processes. The horst–graben architecture not only reflects tectonic evolution but also creates structural traps and permeability contrasts that influence fluid migration. The shallow basement depths observed across large portions of the study area indicate the widespread presence of intrusive igneous bodies. These intrusions, which underlie more than 50% of the study area, are structurally controlled and are clearly delineated by high-amplitude analytical signal responses. Their presence is significant because they represent localized heat sources capable of driving hydrothermal and geothermal processes. Thus, the basement configuration serves as both a structural and thermal framework, linking tectonic evolution with heat distribution and fluid circulation within the Southern Benue Trough.

Thermal Structure and Curie Point Depth Interpretation

The Curie Point Depth (CPD) distribution provides important insight into the thermal state of the crust. The observed CPD values (<16 km) indicate that the study area is characterized by relatively shallow thermal boundaries compared to stable continental regions. According to Tanaka et al. (1999), shallow CPD values are typically associated with geothermal and volcanically active regions, whereas deeper values correspond to stable cratonic environments. In this study, CPD values decrease from the southwestern and southern parts toward the northeastern region, where the shallowest value (~3.73 km) is observed. This spatial pattern indicates that the northeastern part of the study area is thermally more active, while the southwestern region represents relatively cooler crust. The average CPD of 10.99 km suggests that the Southern Benue Trough is characterized by moderate to high heat flow conditions, which can be attributed to crustal thinning associated with rifting processes. However, crustal thinning alone does not fully explain the observed thermal anomalies. The presence of numerous magmatic intrusions emplaced during the Santonian tectono-magmatic episode provides an additional explanation for the observed thermal anomalies. These intrusions act as localized heat sources, thereby elevating subsurface temperatures and reducing the depth to the Curie isotherm. This interpretation is consistent with previous studies (Abraham et al., 2018; Tanaka et al. 1999; Turcotte & Schubert, 2014). However, the present study further demonstrates that these intrusions exhibit a clear spatial correspondence with zones of shallow Curie Point Depth (CPD), thereby reinforcing their role in controlling the thermal structure of the region. In addition to magmatic heat input, mantle upwelling beneath a thinned crust may further contribute to elevated lithospheric temperatures, providing an additional mechanism for the observed thermal anomalies (Dolmaz et al., 2005). The combined effect of crustal thinning, magmatic intrusion, and possible mantle processes explains the anomalously shallow CPD values observed in the northeastern part of the study area. Thus, CPD variations in the Southern Benue Trough reflect a combination of tectonic, magmatic, and thermal processes, rather than a single controlling factor.

Geothermal Gradient and Heat Flow Characteristics

The geothermal gradient values (37.28–155.50 °C/km) and heat flow values (93.19–388.74 mW/m²) indicate that the study area is characterized by elevated geothermal conditions. The spatial distribution of these parameters shows a clear concentration of high values in the northeastern and southeastern parts of the study area. The strong inverse relationship between Curie Point Depth (CPD) and heat flow observed in this study indicates that zones of shallow CPD correspond to regions of elevated geothermal gradients and heat flow, consistent with established thermal theory (Li et al., 2017). This relationship provides confidence in the reliability of the thermal estimates derived from magnetic data. Although direct borehole temperature data were not available for validation, the consistency of the present results with independent studies from the nearby Anambra Basin (Onuoha & Ekine, 1999) provides confidence in their reliability. The estimated average heat flow value of 145.85 mW/m² is significantly higher than the global continental average (~65 mW/m²), indicating anomalously elevated geothermal conditions within the study area. Furthermore, the exceptionally

high heat flow values observed in the northeastern region (up to 388.74 mW/m²) suggest the presence of strong, shallow heat sources. These thermal anomalies are most likely associated with magmatic intrusions, crustal thinning, and/or enhanced convective circulation of geothermal fluids at shallow depths. These may include magmatic intrusions, mantle-derived heat, and convective circulation of geothermal fluids. The identification of Blocks 18, 19, 20, 24, and 25 as zones of elevated geothermal potential is therefore justified based on the convergence of high heat flow, high geothermal gradient, and shallow CPD. The occurrence of warm artesian groundwater (~55 °C) in the region further supports the interpretation of active geothermal systems. These findings indicate that the study area hosts low-enthalpy geothermal resources that may be suitable for direct-use applications.

Radiometric Evidence of Hydrothermal Alteration

The airborne radiometric data provide independent confirmation of hydrothermal processes within the study area. The distribution of potassium (K), thorium (eTh), and uranium (eU) reflects both lithological variation and geochemical processes associated with fluid-rock interaction. Potassium enrichment observed in the eastern, southeastern, and northeastern parts of the study area is indicative of hydrothermal alteration. Potassium is highly mobile during hydrothermal fluid circulation and is commonly associated with alteration minerals such as sericite and potassium feldspar in hydrothermal alteration zones (Elkhateeb & Abdellatif, 2018). Thorium, being relatively immobile, serves as a lithological reference, allowing distinction between primary rock composition and alteration effects. Uranium, on the other hand, is highly mobile and its distribution reflects fluid migration pathways. The K/eTh ratio provides a more sensitive indicator of hydrothermal alteration. Values exceeding the stability range (0.17–0.20 %/ppm) indicate potassium enrichment relative to thorium, which is a diagnostic signature of hydrothermal alteration processes (Hoover et al., 1992). The high K/eTh anomalies observed in this study coincide with structurally controlled zones within the Oban Massif and surrounding regions. The ternary radiometric map further highlights zones of geochemical enrichment and clearly delineates the boundary between basement and sedimentary terrains. These patterns confirm that hydrothermal alteration is spatially associated with both structural complexity and lithological contrasts.

Integrated Interpretation: Linking Structure, Heat, and Mineralization

The integration of magnetic, thermal, and radiometric datasets reveals a strong and consistent relationship between tectonic structures, geothermal conditions, and hydrothermal mineralization within the Southern Benue Trough. Structurally complex zones characterized by high lineament density act as conduits for fluid migration. These zones coincide with areas of shallow CPD, elevated geothermal gradients, and high heat flow, indicating the presence of significant subsurface heat sources. Radiometric anomalies, particularly potassium enrichment and elevated K/eTh ratios, provide geochemical evidence of hydrothermal alteration within these zones. This convergence of structural, thermal, and geochemical indicators demonstrates that hydrothermal mineralization and geothermal systems are controlled by the same underlying processes. Tectonic deformation creates permeability pathways, magmatic intrusions and crustal thinning provide heat, and fluid circulation facilitates mineral deposition. The mineral prospectivity map derived from the AHP-weighted integration further supports this interpretation. High-potential zones (4.54% of the study area) are concentrated along NE–SW and NW–SE structural intersections where elevated heat flow (>150 mW/m²), radiometric anomalies, and favorable geological conditions coincide. Moderate potential zones (39.84%) occur along major structural corridors and near intrusive bodies, indicating areas of significant but less intense hydrothermal activity. The spatial agreement between these zones and known mineral occurrences confirms the reliability of the integrated approach. More importantly, it demonstrates that the combined use of aeromagnetic and radiometric data provides a robust framework for identifying zones of hydrothermal mineralization and geothermal energy potential.

Conclusion

This study evaluated the hydrothermal mineralization potential and geothermal energy resource prospectivity of the Southern Benue Trough using an integrated interpretation of high-resolution aeromagnetic and airborne radiometric data. The analysis focused on characterizing the tectonic framework and thermal structure of the region in order to understand the interplay between structural deformation, subsurface heat distribution, and hydrothermal processes.

The key findings can be summarized as follows:

- The aeromagnetic data revealed a complex structural framework characterized by alternating high and low magnetic anomalies, reflecting lithological contrasts and basement heterogeneity. Dominant structural trends

in the NE–SW, NW–SE, and E–W directions were identified, corresponding to imprints of Pre-Pan-African and Pan-African tectonic events that significantly influenced the evolution of the Basement Complex and the structural architecture of the Southern Benue Trough.

- Lineament analysis showed that zones of high lineament density and long lineament lengths are concentrated within crystalline basement terrains. These structurally complex zones represent areas of enhanced crustal permeability and are interpreted as major conduits for hydrothermal fluid migration. Their spatial distribution highlights key targets for hydrothermal mineral exploration.
- Depth estimation results indicate a highly irregular basement configuration. The SPI-derived depths range from less than 0.10 km to over 2.7 km, while spectral analysis yielded deeper magnetic source depths ranging from 2.08 km to 9.02 km, with an average of 5.01 km. The modelled subsurface geometry reveals a rugose basement characterized by horst–graben architecture, which plays a significant role in controlling sediment deposition, structural deformation, and fluid flow pathways.
- Radiometric analysis identified zones of hydrothermal alteration characterized by potassium enrichment and elevated K/eTh ratios. These anomalies coincide spatially with structurally controlled regions and intrusive bodies, confirming that hydrothermal mineralization is strongly influenced by the interaction between tectonic structures, magmatic activity, and fluid circulation processes.

The geothermal evaluation revealed significant thermal anomalies within the study area. The northeastern region is characterized by shallow Curie Point Depth (CPD), elevated geothermal gradients, and high heat flow values, indicating anomalous subsurface thermal conditions. This zone represents a priority target for geothermal energy exploration and is interpreted to be influenced by crustal thinning, magmatic intrusions, and possible mantle contributions. Across the study area, a strong spatial relationship was observed between structural complexity, shallow basement depth, radiometric anomalies, and elevated heat flow. This relationship confirms that tectonic structures, magmatic intrusions, and thermal processes are intrinsically linked and collectively control both hydrothermal mineralization and geothermal energy potential within the Southern Benue Trough.

The integrated interpretation adopted in this study provides a unified tectono-thermal framework that bridges the gap between hydrothermal mineral exploration and geothermal resource assessment. By combining magnetic structural analysis, radiometric characterization, and geothermal modelling, this work establishes a multi-parameter exploration model that can be applied to similar intracontinental rift systems. From an application perspective, the identification of structurally controlled zones with elevated heat flow and hydrothermal alteration provides a reliable basis for mineral exploration targeting and geothermal resource development. Incorporating these integrated datasets into exploration workflows can significantly improve the accuracy of subsurface characterization and resource prediction.

Despite these advances, uncertainties remain due to data gaps in airborne datasets and the absence of borehole temperature measurements for validating geothermal parameters. Future studies should integrate geological, geochemical, and advanced geophysical methods, including magnetotellurics and seismic techniques, as well as bottom-hole temperature data from deep exploration wells, to further constrain subsurface thermal conditions.

Overall, this study provides a robust foundation for understanding the coupled tectonic and thermal processes governing hydrothermal mineralization and geothermal systems in the Southern Benue Trough. The approach not only advances geophysical exploration in the region but also offers a transferable framework for integrated resource assessment in similar geological settings.

Data Availability

The aeromagnetic and airborne radiometric datasets used in this study were obtained from the Nigerian Geological Survey Agency (NGSA) and are available upon reasonable request from the agency or the corresponding author, subject to NGSA data access policies available online.

The elevation data were obtained from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model, available through the United States Geological Survey (USGS).

651 **Ethics Declarations**
652 **Conflict of Interest**

653 The authors declare that they have no conflict of interest.

654 **REFERENCE**

- 655 Abraham EM, Usman AO, Chima KI, Azuoko G, Ikeazota I. (2024) Magnetic inversion modeling of subsurface geologic
656 structures for mineral deposits mapping in southeastern Nigeria. Bull Mineral Res Explor. 2024;173:85–105. <https://doi.org/10.19111/bulletinofmre.1267876>.
657
- 658 Abraham, E. M., Uwaezuoke, A. E., & Usman, A. O. (2024) *Geophysical investigation of subsurface mineral potentials*
659 *in North-Central Nigeria: Implications for sustainable mining and development*. Geomechanics and Geophysics for
660 Geo-Energy and Geo-Resources, 10, 192. <https://doi.org/10.1007/s40948-024-00913-3>
- 661 Anudu, G. K., Stephenson, R. A., & Macdonald, D. I. M. (2014) Using high-resolution aeromagnetic data to recognize
662 and map intra-sedimentary volcanic rocks and structures in the Cretaceous Benue Trough, Nigeria. *Journal of African*
663 *Earth Sciences*, 99, 625–636. <https://doi.org/10.1016/j.jafrearsci.2014.06.014>
- 664 Arogundade AB, Awoyemi M, Adenika CA. (2022) Integrated aeromagnetic and airborne radiometric data for mapping
665 potential areas of mineralisation deposits in parts of Zamfara, northwest Nigeria. Pure Appl Geophys. 2022;179:2267–
666 86. <https://doi.org/10.1007/s00024-021-02913-w>
- 667 Benkhelil, J. (1989) The origin and evolution of the Cretaceous Benue Trough, Nigeria. *Journal of African Earth*
668 *Sciences*, 8(2–4), 251–282. [https://doi.org/10.1016/S0899-5362\(89\)80028-4](https://doi.org/10.1016/S0899-5362(89)80028-4)
- 669 Blakely, R. J. (1995) *Potential theory in gravity and magnetic applications*. Cambridge University Press.
670
- 671 Bonham-Carter, G. F. (1994) *Geographic information systems for geoscientists: Modelling with GIS*. Pergamon.
- 672 Burke, K., & Dewey, J. F. (1972) Orogeny in Africa. In T. F. J. Dessauvage & A. J. Whiteman (Eds.), *African geology*
673 (pp. 583–608). University of Ibadan Press
- 674 Dada, S. S. (2006) Proterozoic evolution of Nigeria. In O. Oshi (Ed.), *The basement complex of Nigeria and its mineral*
675 *resources* (pp. 29–44). Akin Jinad & Co.
- 676 Dentith, M., & Mudge, S. T. (2014) *Geophysics for the mineral exploration geoscientist*. Cambridge University Press.
677 <https://doi.org/10.1017/CBO9781139024358>
- 678 Dentith, M., & Mudge, S. T. (2014) *Geophysics for the Mineral Exploration Geoscientist*. Cambridge University
679 Press. <https://doi.org/10.1017/CBO9781139024358>
- 680 Dickson, B. L., & Scott, K. M. (1997) Interpretation of aerial gamma-ray surveys—adding the geochemical factors.
681 *AGSO Journal of Australian Geology & Geophysics*, 17(2), 187–200. (No DOI available—classic reference but highly
682 cited on Google Scholar)
- 683 Dolmaz, M. N., Hisarlı, Z. M., Ustaömer, T., & Orbay, N. (2005) Curie point depth variations to infer thermal structure
684 of the crust at the African–Eurasian convergence zone, eastern Anatolia, Turkey. *Earth and Planetary Science Letters*,
685 238(1–2), 189–203. <https://doi.org/10.1016/j.epsl.2005.06.052>

Ekwo SE, Eldosouky AM, Ben UC, Alzahrani H, Abdelrahman K, Achadu OIM, Pham LT, Akpan AE, Gómez-Ortiz D. (2022) Application of high-precision filters on airborne magnetic data: a case study of the Ogoja region, Southeast Nigeria. *Minerals*.2022; 12:1227. <https://doi.org/10.3390/min12101227>.

Elkhateeb, S. O., & Abdellatif, M. A. (2018) Delineation of hydrothermal alteration zones using airborne gamma-ray spectrometry data: A case study from Egypt. *Journal of African Earth Sciences*, 147, 34–45. <https://doi.org/10.1016/j.jafrearsci.2018.06.006>

Grose, L., Holden, E.-J., Dentith, M., & Kovesi, P. (2012) Structural setting of mineral deposits using aeromagnetic data and the CET grid analysis. *Ore Geology Reviews*, 46, 293–310. <https://doi.org/10.1016/j.oregeorev.2011.12.003>

Groves, D. I., Santosh, M., & Zhang, L. (2023) A global perspective on mineral systems and their tectonic controls. *Gondwana Research*, 117, 1–15. <https://doi.org/10.1016/j.gr.2023.01.001>

Holden, E.-J., Dentith, M., Kovesi, P., & Grose, L. (2012) Towards the automated analysis of regional aeromagnetic data to identify regions prospective for gold deposits. *Computers & Geosciences*, 38(1), 1–14. <https://doi.org/10.1016/j.cageo.2011.05.007>

Hoover, D. B., Pierce, H. A., & Adams, S. S. (1992) Introduction to applied geophysics. In H. L. Barnes (Ed.), *Geochemistry of hydrothermal ore deposits* (2nd ed., pp. 73–96). Wiley.

Ijeh BI, Anyadiegwu FC, Onwubuariri CN, Eze MO.(2023) Evaluation of geothermal resource potential of the lower Benue trough using aeromagnetic and radiometric data. *Model Earth Syst Environ*. 2023. <https://doi.org/10.1007/s40808-023-01796-6>

International Atomic Energy Agency (IAEA). (2003). *Guidelines for radioelement mapping using gamma ray spectrometry data*. IAEA-TECDOC 1363 <https://doi.org/10.61092/iaea.tecdoc.1363>

International Atomic Energy Agency (IAEA). (2013) *Airborne gamma ray spectrometry*. <https://doi.org/10.61092/iaea.nr-t-1.18>

Li, C., Wang, J., & Wang, X. (2017) Curie point depth, geothermal gradient, and heat flow in China derived from magnetic data. *Journal of Applied Geophysics*, 139, 203–213. <https://doi.org/10.1016/j.jappgeo.2017.02.007>

McCay, A. T., Pringle, M. S., & Rice, C. M. (2014) Quantitative interpretation of airborne gamma-ray spectrometry data for mapping hydrothermal alteration. *Journal of Geochemical Exploration*, 140, 65–76. <https://doi.org/10.1016/j.gexplo.2014.02.003>

Nabighian, M. N., Grauch, V. J. S., Hansen, R. O., LaFehr, T. R., Li, Y., Peirce, J. W., Phillips, J. D., & Ruder, M. E. (2005) The historical development of the magnetic method in exploration. *Geophysics*, 70(6), 33ND–61ND. <https://doi.org/10.1190/1.2133784>.

Nigerian Geological Survey Agency (NGSA). (2008) *Geological map of Nigeria and mineral occurrences database*. Nigerian Geological Survey Agency.

Nwajide, C. S. (2013) *Geology of Nigeria's Sedimentary Basins*. CSS Bookshops Ltd.

Obaje, N. G. (2009) *Geology and mineral resources of Nigeria*. Springer. <https://doi.org/10.1007/978-3-540-92685-6>

Odeyemi, I. B. (1981) A review of the orogenic events in the Precambrian Basement Complex of Nigeria. *Geologische Rundschau*, 70(3), 897–909. <https://doi.org/10.1007/BF01822125>

- 722 Olade, M. A., & Morton, R. D. (1985) Origin of Pb–Zn mineralization in the Benue Trough, Nigeria. *Mineralium*
723 *Deposita*, 20, 150–160. <https://doi.org/10.1007/BF00204563>
- 724 Oladunjoye, M. A., Salami, M. B., & Adabaniya, M. A. (2016) Interpretation of aeromagnetic data over part of
725 southwestern Nigeria: Implications for basement structure and tectonics. *Arabian Journal of Geosciences*, 9, 1–13.
726 <https://doi.org/10.1007/s12517-015-2093-5>
- 727 Onuoha, K. M., & Ekine, A. S. (1999) Subsurface temperature distribution and heat flow in the Anambra Basin, Nigeria.
728 *Journal of African Earth Sciences*, 28(3), 641–652. [https://doi.org/10.1016/S0899-5362\(99\)00018-4](https://doi.org/10.1016/S0899-5362(99)00018-4)
- 729 Rahaman, M. A. (1988) Recent advances in the study of the Basement Complex of Nigeria. In P. O. Oluyide, W. C.
730 Mbonu, A. E. Ogezi, I. G. Egbuniwe, A. C. Ajibade, & A. C. Umeji (Eds.), *Precambrian geology of Nigeria* (pp. 11–
731 43). Geological Survey of Nigeria.
- 732 Richards, J. P. (2011) Magmatic to hydrothermal metal fluxes in convergent and collided margins. *Ore Geology*
733 *Reviews*, 40(1), 1–26. <https://doi.org/10.1016/j.oregeorev.2011.05.006>
- 734 Roest, W. R., Verhoef, J., & Pilkington, M. (1992) Magnetic interpretation using the 3-D analytic signal. *Geophysics*,
735 57(1), 116–125. <https://doi.org/10.1190/1.1443174>
- 736 Salem, A., Ravat, D., Smith, R., & Ushijima, K. (2007) Interpretation of magnetic data using tilt derivatives. *Geophysics*,
737 72(5), L33–L41. <https://doi.org/10.1190/1.2748490>
- 738 Salem, A., Williams, S., Fairhead, J. D., Ravat, D., & Smith, R. (2007) Interpretation of magnetic data using tilt-angle
739 derivatives: A simple depth estimation method using firstorder magnetic derivatives. *The Leading Edge*, 26(12),
740 15021505. <https://doi.org/10.1190/1.2821934>
- 741 Sibson, R. H. (1996). Structural permeability of fluid-driven fault-fracture meshes. *Journal of Structural Geology*, 18(8),
742 1031–1042. [https://doi.org/10.1016/0191-8141\(96\)00032-6](https://doi.org/10.1016/0191-8141(96)00032-6)
- 743 Sillitoe, R. H. (2010) Porphyry copper systems. *Economic Geology*, 105(1), 3–41.
744 <https://doi.org/10.2113/gsecongeo.105.1.3>
- 745 Spector, A., & Grant, F. S. (1970) Statistical models for interpreting aeromagnetic data. *Geophysics*, 35(2), 293–302.
746 <https://doi.org/10.1190/1.1440092>
- 747 Talwani, M. (1965) Computation with the help of a digital computer of magnetic anomalies caused by bodies of arbitrary
748 shape. *Geophysics*, 30(5), 797–817. <https://doi.org/10.1190/1.1439654>
- 749 Tanaka, A., Okubo, Y., & Matsubayashi, O. (1999) Curie point depth based on spectrum analysis of the magnetic
750 anomaly data in East and Southeast Asia. *Tectonophysics*, 306(3–4), 461–470. [https://doi.org/10.1016/S0040-1951\(99\)00072-4](https://doi.org/10.1016/S0040-1951(99)00072-4)
- 752 Thurston, J. B., & Smith, R. S. (1997) Automatic conversion of magnetic data to depth, dip, and susceptibility contrast
753 using the SPI™ method. *Geophysics*, 62(3), 807–813. <https://doi.org/10.1190/1.1444190>
- 754 Turcotte, D. L., & Schubert, G. (2014) *Geodynamics* (3rded.). Cambridge University Press.
755 <https://doi.org/10.1017/CBO9780511843877>
- 756 Wang J, Li C. (2018) Curie point depths in Northeast China and their geothermal implications for the Songliao Basin.
757 *J Asian Earth Sci.* 2018; 163 (1):177–93. <https://doi.org/10.1016/j.jseaeas.2018.05.026>

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781 **Contributions**

782 Stella Okenu conceived and designed the study, conducted data processing and analysis, and interpreted the results. Abu
783 Mallam and Olatunji S. Ayaninnuola supervised the research and provided critical revisions. Godwin A. Alo contributed
784 to manuscript writing and proofreading. All authors reviewed and approved the final manuscript.

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