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Geothermal Energy Resource Potential Investigation of the Southern Benue Trough using High-Resolution Aeromagnetic Data

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Abstract

Nigeria's commitment to decarbonizing its energy sector and achieving net-zero greenhouse gas emissions by 2060 has intensified the search for sustainable and cleaner alternative energy resources, including geothermal energy, to support long-term economic development. However, geothermal exploration within frontier basins such as the Southern Benue Trough (SBT) remains constrained by the absence of deep borehole temperature data required for detailed characterization of the subsurface thermal regime, as well as the complex geological framework controlling regional heat flow distribution. This study employed high-resolution aeromagnetic data as an indirect geophysical approach to evaluate the geothermal energy potential of the SBT through the estimation of Curie Point Depth (CPD), geothermal gradient (GG), and heat flow (HF). The estimated CPD values range from 3.73 to 15.56 km, with an average of 10.99 km, reflecting considerable spatial variability in crustal thermal structure. Correspondingly, geothermal gradient values vary between 37.28 and 155.50 °C km^{-1}, averaging 58.34 °C km^{-1}, while calculated heat flow values range from 93.19 to 388.74 mW m^{-2}, with a mean of 141.85 mW m^{-2}. The northeastern sector of the SBT is characterized by anomalously shallow CPD values that spatially coincide with elevated geothermal gradients and heat flow, indicating enhanced subsurface thermal conditions and significant geothermal resource prospectivity. These findings demonstrate the effectiveness of aeromagnetic-derived thermal parameters for geothermal assessment in data-limited frontier basins. The study provides a robust geophysical framework to guide future geothermal exploration and resource development within the Southern Benue Trough and other geological provinces sharing comparable tectono-thermal evolution.

Keywords
Geothermal energy,
Curie point depth,
Geothermal gradient,
Heat flow,
SBT

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1. INTRODUCTION

The Southern Benue Trough (SBT) is the southern sub-division of the NE-SW oriented intra-continental Benue megarift system that lies within the extensive and prolific deep-seated extensional oil-bearing fault system of West Africa (Yenne et al., 2019). It is located geographically between longitude 7°00′ - 9°00' E and latitude 5°00' N - 7°00' N, with an aerial coverage of about 48,400 km2 (Fig. 1). The Benue Trough evolved as a failed arm (or aulacogen) of a triple RRR junction during Late Jurassic opening of the Southern Atlantic Ocean, as South America and Africa Continents separated from each other (Ofoegbu, 1985; Obaje, 2009; Yenne et al., 2019; Abdullahi and Kumar, 2020). The multiphase deformations and thermo-tectonic activities related to the basin's evolution introduced subsurface complexities in the morpho-structural geometry and thermal architecture of the entire Benue megarift system (Nwachukwu, 1972; Benkhelil, 1989; Obaje, 2009). Hence, detailed understanding of the thermal distributions, tectonic patterns, and basement configuration in the context of rift basin development and geodynamic evolution of the Gulf of Guinea remains critical to unlocking the geothermal energy resource potential of the SBT (Abdullahi et al., 2019; Abdullahi and Kumar, 2020).

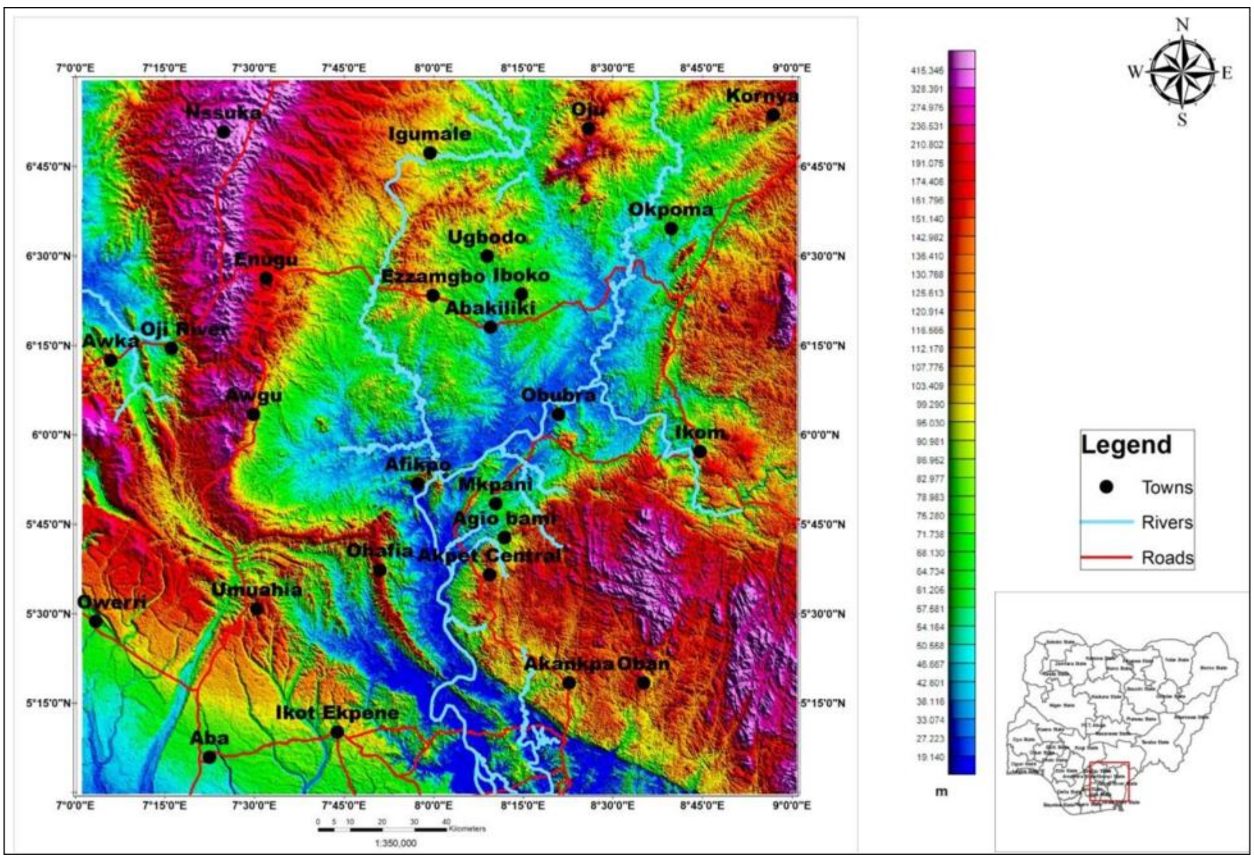

Figure. 1. Digital elevation model of the Southern Benue Trough.

The need to decarbonize Nigeria's energy sector, and the increasing demand for low-carbon energy sources that will power the country's sustainable energy future, necessitates aggressive exploration for alternative energy sources in the poorly explored Cretaceous SBT, which is believed to hold considerable potentials for the geothermal energy resources needed to drive the nation's sustainable economic development (Yassah et al., 2024; Nneji et al., 2026). However, the search for cleaner energy sources in the SBT have been challenging owing to poor availability of data for detailed studies.

This problem is further exacerbated by lack of borehole temperature data from deep petroleum exploration wells that would throw more light on the subsurface heat flow variations and thermal gradient changes. Hence, the geothermal energy reserve of the area remains largely unquantified. In view of these challenges and other constraints, the need therefore arises for detailed evaluation of the SBT to ascertain the geothermal energy resource potential using cost-effective geophysical approach.

Geothermal energy is an alternative energy resource tipped to be critical in solving the global sustainable energy supply needs (Jolie et al., 2021; Abraham and Okechukwu, 2024; Boumehdi et al., 2025; Kumar et al., 2025). It symbolizes the shallow surface manifestation of the Earth's internal heat that is transferred to the surface from the Earth's core (Jolie et al., 2021). Globally, geothermal energy resources are known to occur in regions characterized by high surface heat flow due to widespread magmatic activity and/or crustal thinning (Elders and Moore, 2016; Kwaya et al., 2016; Jolie et al., 2021).

The Benue megarift system fits into the above description, and has attracted increasing interest from researchers who are keen to understand how subsurface thermal conditions control geothermal anomaly expressions in form of warm springs scattered in the northern and central parts of the trough (e.g., Obande et al., 2014; Abraham et al., 2015, 2018; Abdullahi and Kumar, 2020; Ijeh et al., 2023; Abraham and Okechukwu, 2024; Yassah et al., 2024; Onwubuariri et al., 2025). Aeromagnetic data analysis provides an alternative means of assessing the thermal conditions beneath an area for geothermal energy resource investigation, in the absence of borehole temperature measurements from deep petroleum exploration wells (Hussein et al., 2012; Pamuk, 2019; Shirani et al., 2020).

This geophysical method enables indirect characterization of the thermal structure of a sedimentary basin by estimating the Curie point depth (CPD), which serves as a proxy for geothermal gradient and heat flow determination from borehole data (Njeudjang et al., 2020; Özsöz, 2021; Aboud et al., 2022; Harash and Chen, 2022; Yaro and Abir, 2023). Thus, CPD computation from aeromagnetic data is a quick and low-cost approach for regional scale subsurface thermal studies (Okubo et al., 1985; Bhattacharyya and Leu, 1975; Bansal et al., 2011; Geng et al., 2023). The technique has found wide application in different geologic terrains because of its spatial coverage and ability to enhance geothermal energy exploration targeting in areas with sparse data availability (Khojamli et al., 2016; Bilim et al., 2021; Harash and Chen, 2022; Adetona et al., 2024).

Successful application of aeromagnetic method for geothermal energy assessment in various regions of the world has been documented in classical literature (Ross et al., 2006; Abraham et al., 2015, 2018; Pamuk, 2019; Shirani et al., 2020; Özsöz, 2021; Harash and Chen, 2022; Geng et al., 2023; Yaro and Abir, 2023; Akar, 2024; Yassah et al., 2024; Boumehdi et al., 2025).

In addition, the robustness of deploying the CPD technique for accurate delineation of subsurface thermal conditions in regions of complex geology has been demonstrated in recent studies, both in Nigeria and other parts of the globe. Bilim et al. (2021) investigated the geothermal energy potentials of the northwestern part of Turkey using spectral analysis of aeromagnetic data. The obtained heat flow and geothermal gradient maps highlighted a zone that showed greater promise for detailed geothermal energy exploration studies. Geng et al. (2023) computed the depth to the Curie isotherm beneath the United Arab Emirates (UAE) from aeromagnetic data, and identified potential prospective regions of shallow CPD and high heat flow for future concentration of geothermal energy exploration campaign. Yassah et al. (2024) carried out regional determination of the CPD, geothermal gradient, and heat flow based on the analysis of aeromagnetic data, and utilized the obtained results to evaluate the geothermal energy resource prospectivity of the region.

Similarly, Abraham and Okechukwu (2024) investigated the potential for geothermal energy occurrence around the Ruwan-Zafi Hot Spring region in northeastern Nigeria, using spectral analysis of high-resolution aeromagnetic data. The study revealed areas of near-surface high heat flow distributions related to the presence of magmatic intrusions, symbolizing potential for geothermal energy exploration and possible steam production at depths shallower than 2 km. This study investigated the SBT's geothermal energy resource potential utilizing high resolution aeromagnetic data. A major objective of the work was to determine the CPD from aeromagnetic data by employing the spectral centroid technique, and utilize the obtained results to assess the geothermal gradients and heat flow distributions for improved understanding of the thermal conditions and temperature gradient changes underneath the SBT. This knowledge is vital to uncover potential prospective locations for further detailed geothermal energy resource exploration studies in the region.

2. Geology of the Southern Benue Trough (SBT)

Discussions on the tectonostratigraphic framework and structural development of the Benue megarift system as a component of the Central and West African Rift System (CWARS) have been extensively addressed Benkhelil (1989), Obaje (2009), Fairhead et al. (2013), among others (Fig. 2). It is widely believed that the Benue megarift structure resulted from deep crustal movements and basement re-organizations controlled by major fracture zones at the time of splitting of the Gondwana Supercontinent in the Early Cretaceous (Ofoegbu, 1985; Benkhelil, 1988, 1989; Guiraud et al., 2005; Fairhead et al., 2013; Nwajide, 2013; Fairhead, 2023). Earlier workers opined that the structural disposition of the Benue Trough was impacted by four different orogenic episodes, including the Cenomanian, Santonian, Post Maastrichtian, and Paleocene events (e.g., Nwachukwu, 1972; Olade, 1975; Agagu and Adighije, 1983; Ofoegbu, 1985).

These periods of intense deformations, characterized by either extensional or compressional block movements, left their imprints on almost all parts of the trough, and thus, played a key role in shaping and re-shaping the orientation, architecture, and geometry of the SBT (Fairhead et al., 2013; Bute et al., 2024; Anudu et al., 2025).

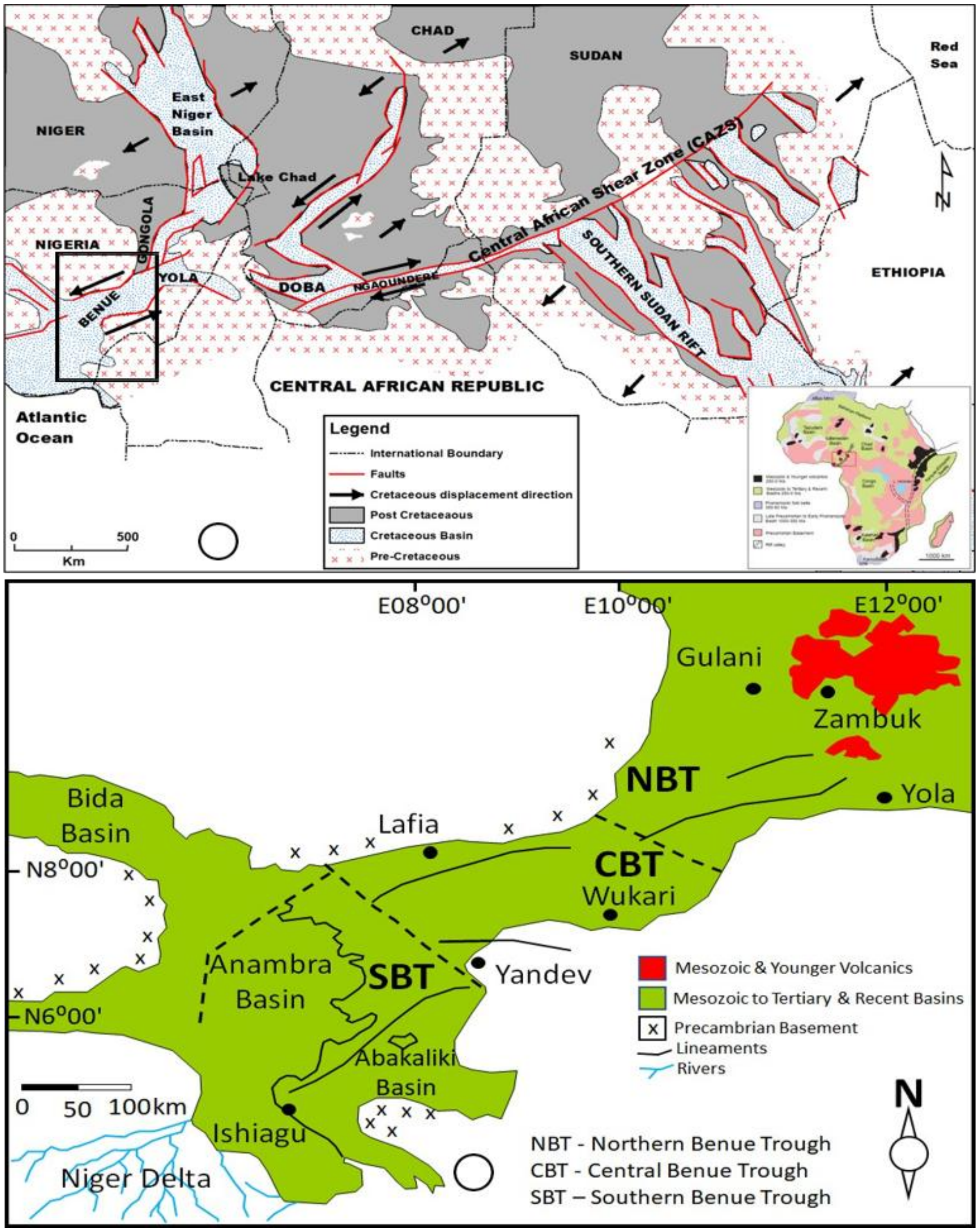

Figure 2: (a) Tectonic map of the WCARS showing the position of the Benue Trough (modified after Obaje, 2009; Yenne, 2022). (b) Geologic map of the Benue Trough showing the position of the SBT (modified after Vincent et al., 2021; Bute et al., 2024).

Prominent structural elements in the SBT include the Abakaliki Anticline, Afikpo Syncline, Oban Massif, Bamenda Hills, Anambra Basin, and magmatic intrusive bodies emplaced within the Pre Santonian sequences (Obaje, 2009; Akande et al., 2012; Abubakar, 2014; Anudu et al., 2014; Abubakar and Kumar, 2020; Yenne, 2022). These tectonic elements embody the geological framework of the area. The crystalline basement which comprises mainly of gneisses and granitic rocks are exposed at the southeastern and eastern portions of the SBT (Anudu et al., 2014; Abdullahi et al., 2019; Abdullahi and Kumar, 2020). Cretaceous sedimentary rocks cover every other part of the region, except the southwestern part that is underlain by the Cenozoic sediments of the Niger Delta Basin (Figure. 3).

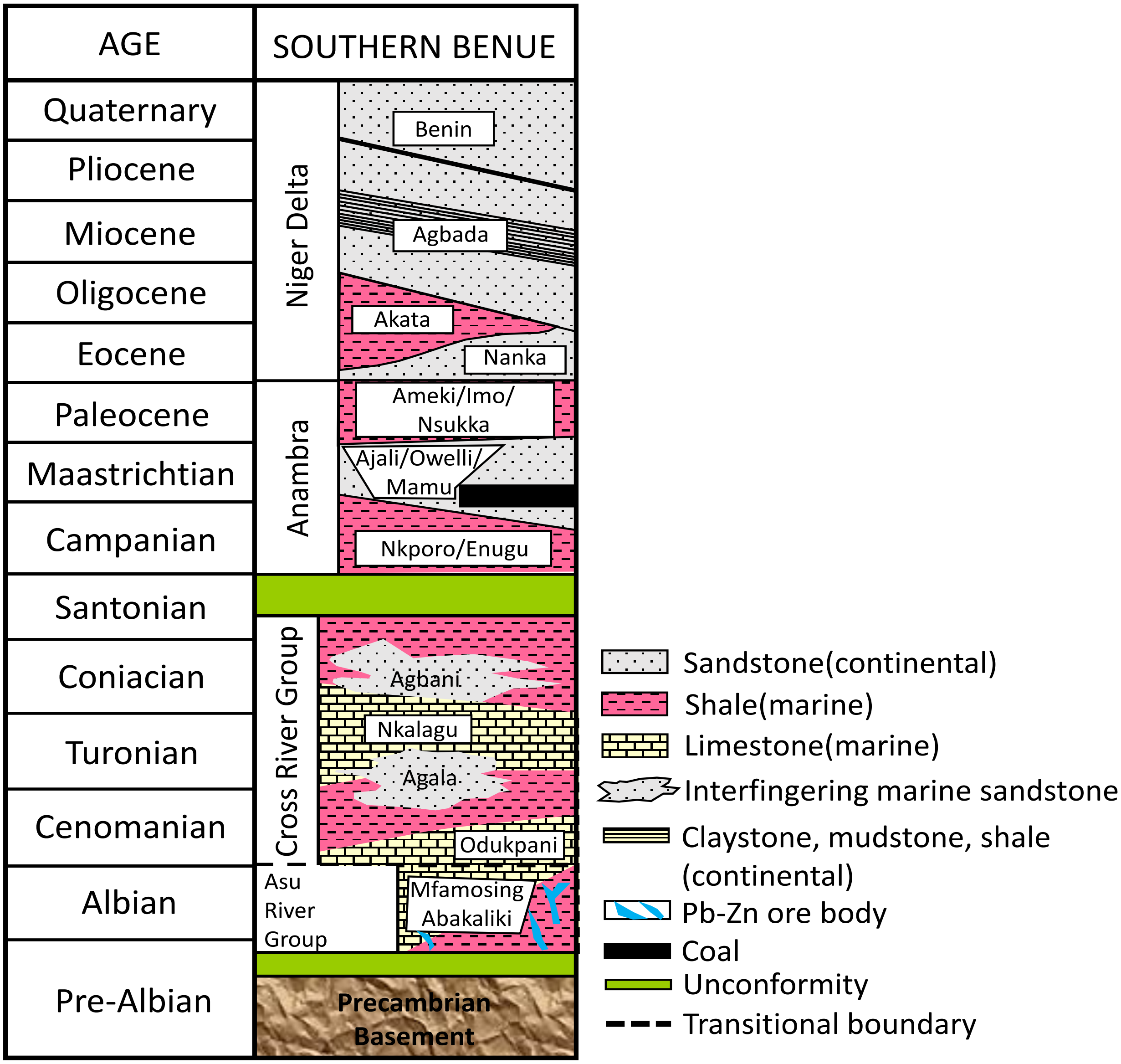

Figure 3: Stratigraphic Successions of the SBT (modified after Abubakar, 2014; Bute et al., 2024).

The sedimentary sequences attained thicknesses up to 9 km in the deepest part of the SBT (Abdullahi et al., 2019). The oldest stratigraphic succession in the SBT include the Albian Asu River Group comprising of limestones, fine-grained sandstone, siltstones, dark shales, and sandstones at the base (Nwachukwu, 1972; Ofoegbu, 1985; Obaje, 2009). The Asu River Group is overlain by the Turonian Ezeaku Group, made up of calcareous sandstones, siltstones, sandstones, and black shales (Ofoegbu, 1985; Obaje, 2009). It is overlain by the Awgu Group that comprises of calcareous sandstone, limestones, and fossiliferous marine shales (Obaje, 2009; Akande et al., 2012). The shales and mudstones of the Nkporo Formation overly the Awgu Group, followed by the carbonaceous shales, coal seams, sandy shales, and sandstone of the Mamu Formation (Ofoegbu, 1985; Obaje, 2009). This is overlain by the Nsukka Formation which consists of coal seams, false-bedded sandstones, and carbonaceous shales (Ofoegbu, 1985; Obaje, 2009; Abdullahi and Kumar, 2020) (Figure. 3).

The pre-Santonian sediments were intensely folded during the Santonian compressional event, resulting in the development of several anticlines and synclines (Nwachukwu, 1972; Akande et al., 1989; Benkhelil, 1989). This tectonic episode was also responsible for the injection of magmatic plutons into the Cretaceous strata, and subsequent mineralization of the Ezeaku Group and Asu River Group (Maluski et al., 1995; Onuoha and Ekine, 1999; MMSD, 2010; Obaje, 2009; Anudu et al., 2014; Abdullahi et al., 2019).

3. Materials and methods

High-resolution aeromagnetic data

The Nigerian Geological Survey Agency (NGSA) provided the high-resolution aeromagnetic data used in this study. Acquisition of the data was done by Fugro Airborne Surveys on behalf of NGSA in 2009. The data was acquired using 3x Scintrex CS3 Caesium Vapor Magnetometer, attached to an aircraft flown at a height of 80 m above sea level, along 500 m spaced flight lines oriented in the northwest – southeast direction, and nominal tie lines spaced 2000 m apart. The geomagnetic gradient was removed from the dataset using the 2005 International Geomagnetic Reference Field (IGRF) model (Reeves, 2005). Pre-processing techniques including removal of cultural effects, micro-levelling, and deculturing were employed to simplify the magnetic data, so that it can have geologic meaning and make interpretation of the anomalies easier. The resulting total magnetic intensity (TMI) data were gridded into half-degree sheets of 55 × 55 km, and 1:100,000 scale.

A total of sixteen (16) aeromagnetic sheets were utilized in this study. These include 287 (Nsukka), 288 (Igunmale), 289 (Ejekwe), 290 (Ogoja), 301 (Udi), 302 (Nkalagu), 303 (Abakaliki), 304 (Bansha), 312 (Okigwe), 313 (Afikpo), 314 (Ugep), 315 (Ikom), 321 (Aba), 322 (Ikot-Ekpene), 323 (Uwet) and 324 (Oban). The sheets were combined together to generate the total magnetic intensity data of the region. Analysis of the data to assess the geothermal energy resource potential of the region was achieved using appropriate software packages.

Calculation of Curie point depth (CPD), geothermal gradients (GG), and heat flow (HF)

To investigate the thermal structure of the crust beneath the Southern Benue Trough and evaluate the geothermal energy resource prospectivity of the region, the CPD was computed from the airborne magnetic data using the spectral centroid approach (Spector and Grant, 1970; Bhattacharyya, 1975; Bhattacharyya and Leu, 1975; Okubo et al., 1985; Bansal et al., 2011, 2013; Nwankwo and Sunday, 2017; Abraham et al., 2018). The derived CPDs were applied to determine subsurface heat flow and geothermal gradients employing an empirical approach. The centroid method was adopted in this study because it provides more reliable estimates with reduced depth uncertainties compared to other CPD estimation techniques (Ravat et al., 2007); Yassah et al., 2024).

The CPD refers to the depth of the Curie isotherm (~580 °C), where the dominant magnetic mineral (magnetite) in the crust undergoes a transition from a ferromagnetic to a paramagnetic state with increasing temperature (Hinze et al., 2013; Boumehdi et al., 2025). CPD determination from aeromagnetic data using the centroid approach has been widely applied in Nigeria and in other regions of the world (e.g., Okubo et al., 1985; Tanaka et al., 1999; Bansal et al., 2013; Obande et al., 2014; Abraham et al., 2014, 2015; Chukwu et al., 2018; Abdel Zaher et al., 2018; Boumehdi et al., 2025).

The mathematical formulation of the centroid method is founded on the analysis of the geometry of isolated magnetic anomalies, as developed by Bhattacharyya and Leu (1975, 1977), and on the statistical characterization of magnetic source ensembles by Spector and Grant (1970). Blakely (1995) later incorporated the use of the power spectral density of the total magnetic field, $\phi\Delta T(kx, ky)$, defined as:

$$\phi\Delta T(kx, ky) = \phi M(kx, ky) \cdot 4\pi^2 C M^2 |\theta M|^2 |\theta f|^2 e^{-2|k|z_t} (1 - e^{-2|k|(z_b - z_t)})^2 \quad (1)$$

where

$\phi M(kx, ky)$ represents the power spectrum of the magnetization,

CM is a constant,

kx is the wavenumber in *x*, *ky* is the wavenumber in *y* direction,

θM represents the magnetization direction factor, *θf* represents the geomagnetic field direction factor,

Zb represents the depth to magnetic source bottom, and

Zt represents the depth to magnetic source top.

If the magnetization of the layer, *M* (*x*, *y*), is treated as a random function of *x* and *y*, then $\phi M(kx, ky)$ becomes a constant, and consequently, the azimuthally averaged power spectrum, $\phi(|k|)$, is expressed as:

$$\phi(|k|) = Ae^{-2|k|Zt}(1 - e^{-2|k|(Zb-Zt)})^2 \quad (2)$$

The depth to the top of the magnetic source is thus determined from the slope of the high-wavenumber segment of the power spectrum, given as:

$$\mathrm{Ln}(P(k)^{1/2}) = A - |k|Z_t \quad (3)$$

where *P* (*k*) denotes the azimuthally averaged power spectrum,

k represents the wavenumber (2π km-1),

A is a constant, and

Zt denotes the depth to the top of magnetic sources. Similarly, the depth to centroid of magnetic sources can be calculated from the low-wavenumber segment of the wavenumber scaled power spectrum as follows:

$$\ln(P(k)1/2/k) = B - |k|\ Z0 \quad (4)$$

where *Z0* represents the depth to centroid of magnetic source, and *B* is a constant (Tanaka et al., 1999).

The depth to magnetic bottom (*Z*b) can then be computed using the relation by Okubo et al. (1985):

$$Zb = 2Z0 - Zt \quad (5)$$

Utilizing the calculated depth to magnetic source bottom (*Z*b), geothermal gradients (d*T*/d*z*) were assessed by applying the following equation:

$$(dTdz) = (\theta cZb) \quad (6)$$

where θc represents the Curie temperature (Ross et al., 2006; Nwankwo and Sunday, 2017; Yassah et al., 2024). Next, the obtained *Z*b and d*T*/d*z* values were utilized to compute the heat flow (*qz*) following the equation by Okubo et al. (1985):

$$qz = -\sigma\ (\ \theta c\ Zb) = -\sigma\ (dTdz) \quad (7)$$

where σ represents the thermal conductivity. An average thermal conductivity of 2.5 W m-1 °C-1 assumed for igneous rocks, together with a Curie temperature of 580 °C was adopted in this work (Okubo et al., 1985; Trifonova et al., 2009; Nwankwo and Sunday, 2017; Yassah et al., 2024).

The analyzed aeromagnetic dataset was partitioned into twenty-five (25) cells (blocks), each measuring 110 × 110 km, ensuring a minimum of 50 % overlap on all sides (Fig. 5). The radially average power spectrum for each cell was computed using the Fast Fourier Transform (FFT) filtering method within Oasis Montaj software (Connard et al., 1983; Blakely, 1988; Tanaka et al., 1999; Khojamli et al., 2016).

The 2D power spectrum of the blocks was then loaded into a Matlab program for plotting the log of frequency against wavenumber, in order to compute the depths to top and centroid of magnetic sources for each block. Using equation (5), the CPD for each block was determined, while equation (6) and equation (7) were employed to calculate the heat flow and geothermal gradients for each block.

4. Results and discussion

Aeromagnetic characteristics of the SBT region

The variability in intermediate, high, and low anomalies observed on the TMI map of the SBT region (Figure 4) are indicative of contrasts in magnetic susceptibilities of the different subsurface rock types. The signatures range in values from -69.4 nT to 158.9 nT, reflecting varying depths, compositions, and magnetic source ensembles which make up the overall subsurface geological framework of the region. The peak amplitude signatures seen on the central part of the TMI map indicated major trend in the E-W and NE-SW directions. Anomalies of intermediate grade (greenish color) are widespread across the northeastern, northern, eastern, and southeastern zones, whereas the southern region is marked by low anomalies. The signatures generally reflect clean and sharp gradients from near-surface and deep-seated sources distributed within the subsurface throughout the area. In addition, high magnetic intensities observed in areas where the subsurface is underlain by sedimentary rocks suggests presence of igneous intrusions within the Cretaceous sediments sitting above the basement.

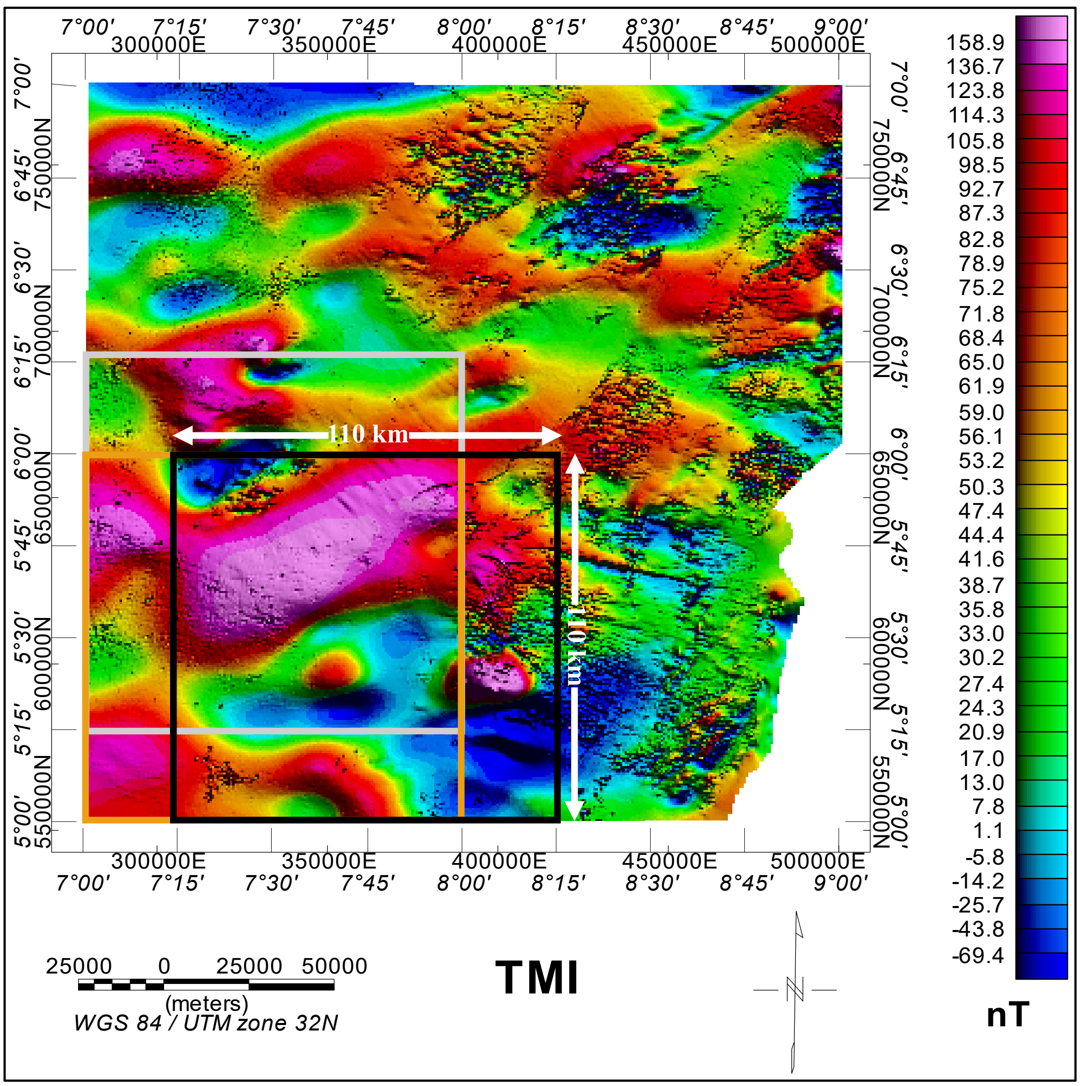

Figure 5: Total magnetic intensity (TMI) map of the study area illustrating sections of 110 km × 110 km overlapping blocks analyzed for CPD determination.

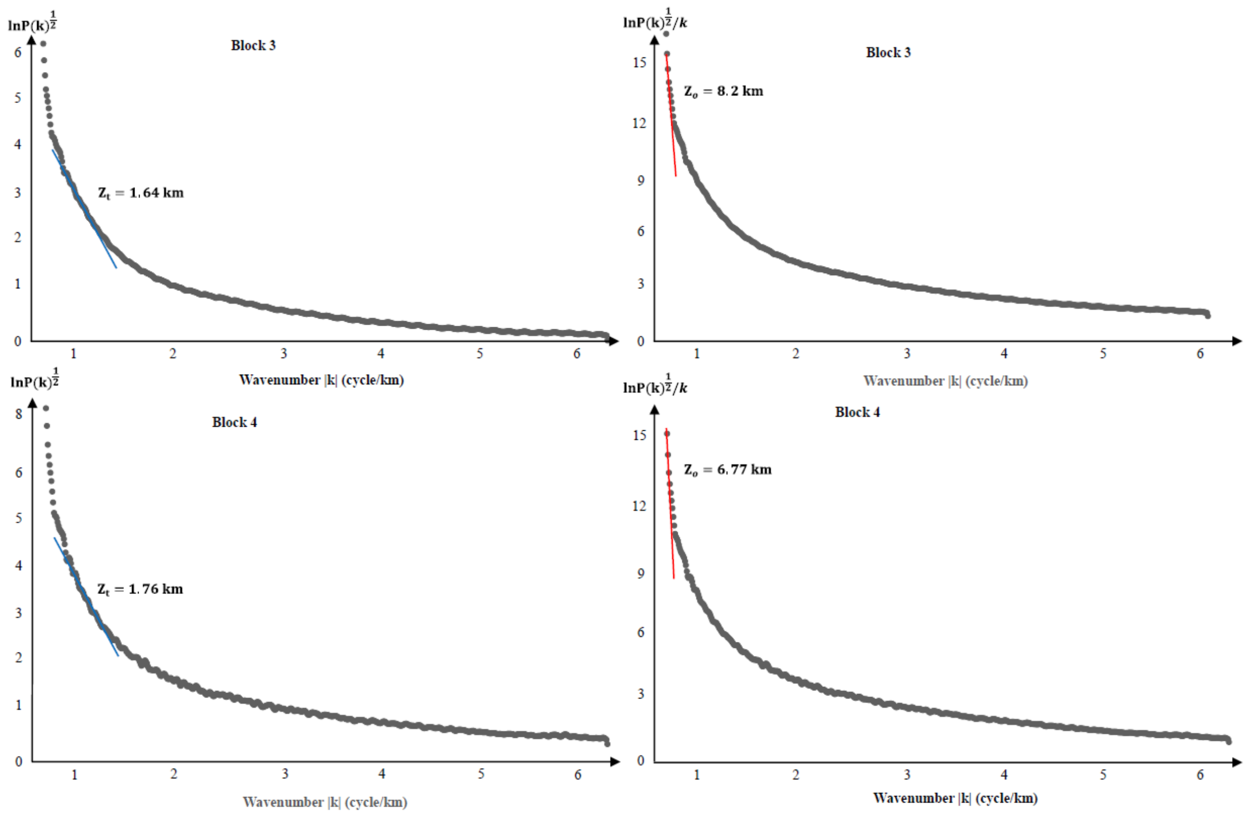

Figure 6: 2D power spectrum curves of Block 3 and Block 4 showing the estimated depths to top (Zt) and centroid (Zo) of magnetic sources.

Table 1: Estimated Curie Point depths, heat flow and geothermal gradients values.

Block	X	Y	Zo (km)	2Zo (km)	Zt (km)	Zb (CPD) (km)	GG (ºC)	HF (W/m²)
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**

Thermal characteristics of the SBT region

The derived 2D power spectrum for some of the blocks (i.e., Block 3 and Block 4) and their estimated depths are presented in figure 6, while Table 1 is the summary of the results of the obtained CPD, geothermal gradient, and heat flow values from the analysis of the twenty-five (25) blocks. The computed CPD values vary from 3.73 to 15.56 km, with an average of 10.99 km; the geothermal gradients values range from 37.28 to 155.50 °Ckm^{-1}, with an average of 58.34 °Ckm^{-1}, while the heat flow values range from 93.19 to 388.74 mWm^{-2}, with an average of 141.85 mWm^{-2}. These values were gridded and contoured by applying the minimum curvature algorithm in Surfer 18.1 software to produce the CPD, heat flow and geothermal gradients maps of the study area as seen in Figure (7, 8, 9).

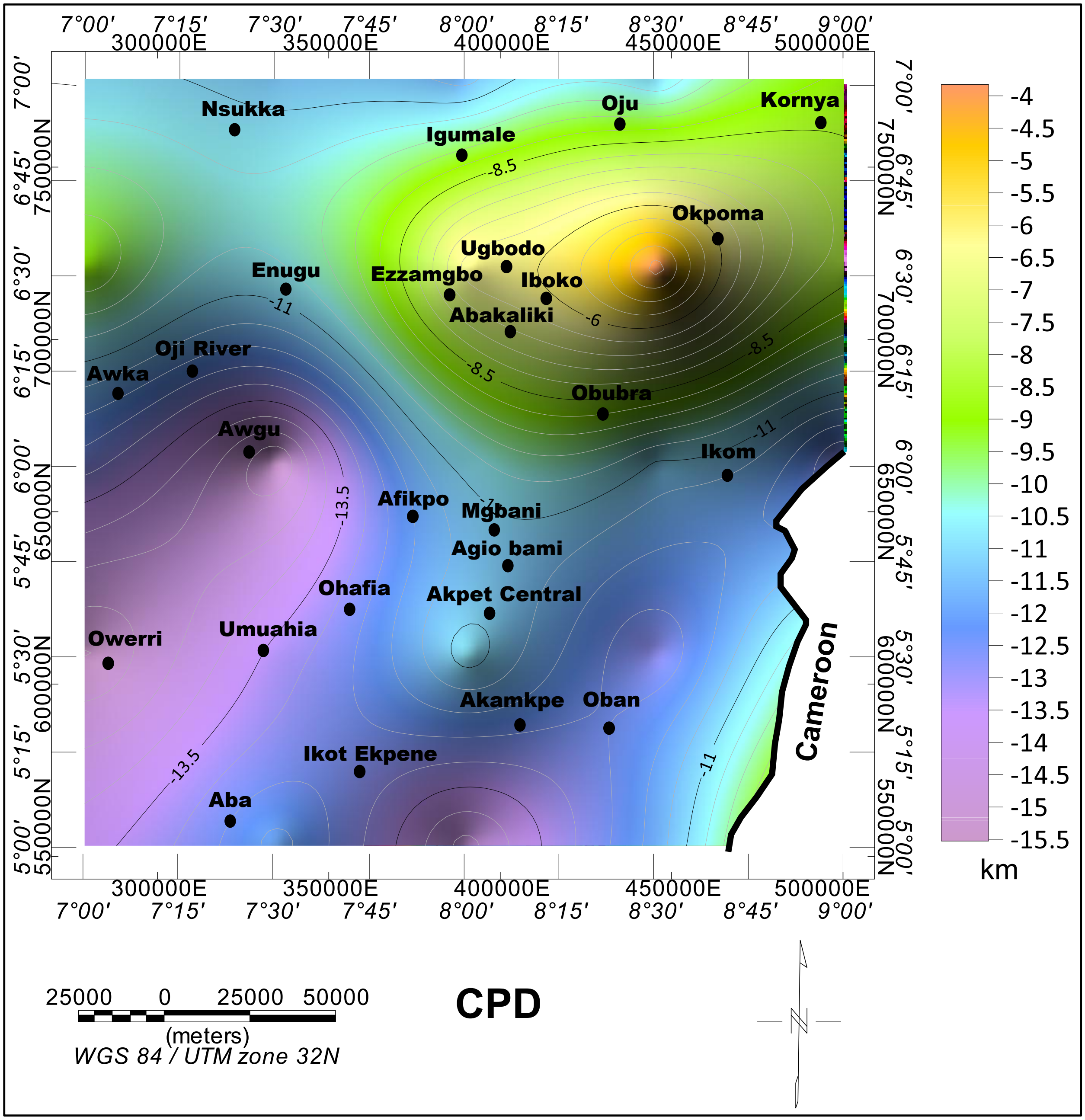

Figure 7: Curie point depth map of the study area.

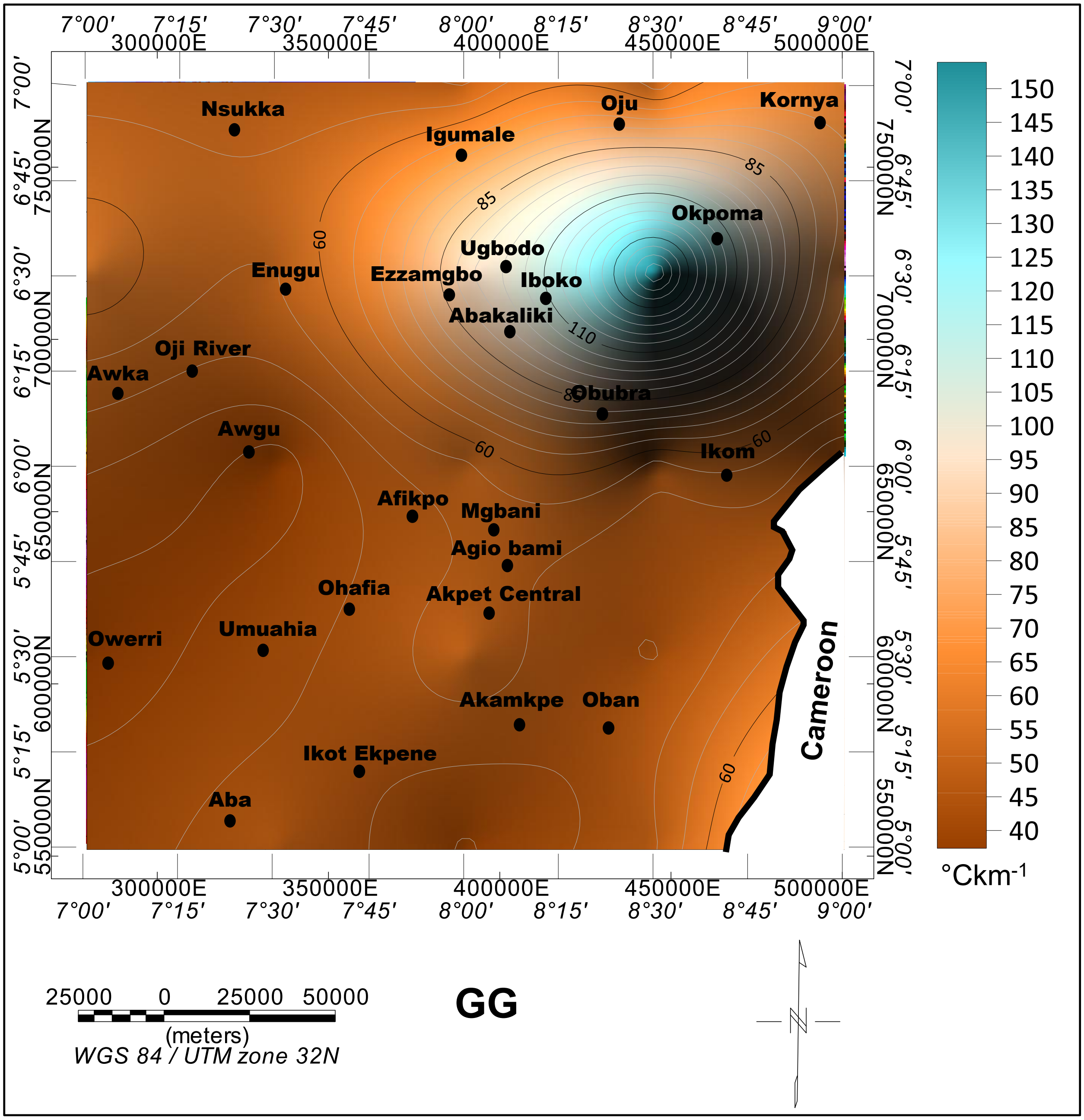

Figure 8: Geothermal gradients (GG) map of the study area.

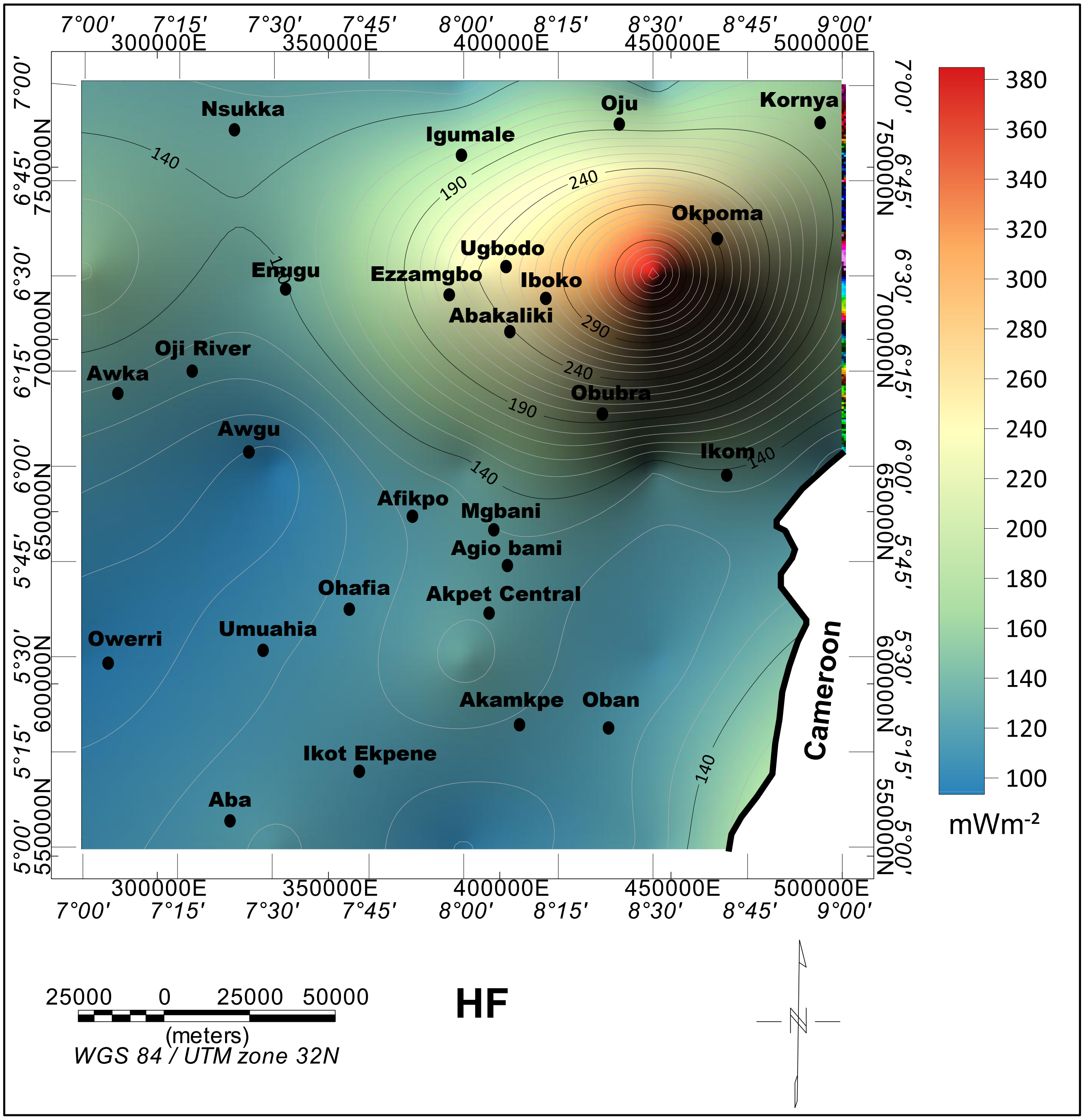

Figure 9: Heat flow (HF) map of the study area.

The CPD map of the SBT (Fig. 7) showed shallow zones (< 4 km) around the northeastern, northwestern, and southeastern sectors. Shallowest CPD zones were observed beneath Ezzamgbo, Ugbodo, Iboko, Obubra, and Abakaliki areas located within the northeastern part of the region. These areas are known to be underlain by shallow-seated magmatic intrusions that were emplaced within the Cretaceous sequences of the SBT (Fig. 3). Deeper CPD zones characterized the western, southwestern, and southern portions of the area around Afikpo, Awgu, Owerri, Umuahia, and Ikot Ekpene areas. As observed by Gao et al. (2019), CPD differs from one region to another owing largely to differences in the regional geology, geothermal heat flow, and mineral composition of the rocks. Tanaka et al. (1999) associated volcanic and tectono-thermal regions with CPDs below 10 km.

CPDs in the range of 15 to 25 km depict areas underlain by ridges and island arcs, while CPDs in excess of 25 km suggests stable continents and plateaus. The SBT region showed a general NE - SW trend of shallow and deeper CPD zones. The least value of CPD (3.73 km) was calculated in Block 19 which included parts of the northeastern portion of the region, while the deepest value of CPD (15.56 km) was estimated in Block 6, enclosing the southwestern and western zones of the region (see Table 1). The mean CPD of 10.99 km determined in this work suggests reduction in thickness of the crust beneath the SBT. This could be attributed to asthenospheric bulging or magma upwelling beneath the brittle lithosphere (Dolmaz et al., 2005; Artemieva, 2011; Kwaya and Kurowska, 2018).

Employing aeromagnetic data analysis, Yassah et al. (2024) estimated average CPD value of 11.72 km within the Shelleng area of Northern Benue Trough, while average CPD value of 10.2 km was determined in the Central Benue Trough, around the Akiri Hot Spring region by Usman et al. (2025). CPD values in the range of 6.8 - 20 km was recorded at the northern portion of the Anambra Basin (Salawu and Ojo, 2024), with the shallow CPD zones attributed to the effects of magmatic intrusions related to the Santonian orogeny that impacted the entire Southern Benue Trough (Nneji et al., 2026).

The CPD values determined in this study compares fairly with results obtained in different parts of the globe. For instance, CPD values in the range of 18 to 20 km were obtained at the coast of Vøring Basin and Trøndelag Platform of the mid-Norwegian continental margin; the value reached about 12 km at the continental - oceanic transitional boundary, and over 9 km beneath the oceanic plate (Ebbing et al., 2009; Salawu and Ojo, 2024). Extremely shallow CPD values of below 10 km, with minimum values reaching 4.8 km, have been reported in the Rift System of West Antarctic (Dziadek et al., 2021). Similar remarkably shallow CPD values have also been noted in the northern section of the Anambra Basin (Salawu and Ojo, 2024).

The geothermal gradient map (Fig. 8) of the area revealed abnormal thermal conditions within the northeastern portion of the SBT, attributable to the presence of volcanic intrusions at shallower depth intervals beneath that part of the region. A decrease in geothermal gradients was noted towards the west, southwest, and southern parts of the investigated area. Similar anomaly distribution pattern was observed on the heat flow map which also indicated anomalous values at the northeastern part, and lower values at other parts of the SBT (Fig. 9). Thus, a consistent relationship was therefore observed among CPD, heat flow, and geothermal gradient, where zones with shallow CPDs were associated with anomalous geothermal gradients and elevated heat flow, whereas deeper CPDs regions corresponded to areas exhibiting low geothermal gradients and reduced heat flow.

The shallow CPD values recorded in the northeastern part of figure 7 is interpreted to represent parts of the SBT underlain by igneous intrusions emplaced within the Cretaceous sedimentary sequences, following the Santonian Orogenic event that affected the region. The areas exhibiting near-surface CPDs align with the thermal anomaly trends identified within the region, indicating that intrusive bodies may be contributing heat support to sedimentary successions within the SBT. Therefore, the minimal CPDs recorded at the northeastern sector of the Southern Benue Trough suggest zones of elevated thermal gradients, higher heat flow distribution, and potential location of significant geothermal resources (Okubo et al., 1985; Abraham et al., 2018; Abdel-Fattah et al., 2021; Abraham and Okechukwu, 2024; Salawu and Ojo, 2024).

Implications for geothermal energy resource prospectivity in the Southern Benue Trough

Integrated interpretation of aeromagnetic data is essential for assessing subsurface geothermal conditions in areas where borehole temperature measurements are unavailable, like the Southern Benue Trough (Elmasry et al., 2022; Yassah et al., 2024; Salawu and Ojo, 2024; Nneji et al., 2026). Investigation of the subsurface thermal structure can reveal the deep structural characteristics of magnetic materials, and enhance the understanding of regional geological tectonics and their evolutionary processes (Rajaram et al., 2009). Furthermore, assessing regional CPD variations offers valuable insights into the geothermal energy potential, hydrocarbon resource prospectivity, as well as mineral resource potential of a region (Utada et al., 2000; Nyabeze and Gwavava 2016; Zhang et al., 2017; Wen et al. 2019). The SBT is located within the passive continental margin of the Equatorial Atlantic, believed to be devoid of any known seismicity or earthquake activities (Eze et al., 2011; Nwankwoala and Orji, 2018; Olowafemi et al., 2018). However, the high geothermal conditions observed in the region through study may be attributed to prolonged effects of various tectono-thermal episodes and associated magmatic events that dominated the evolution of the Benue Trough from the Late Jurassic times when Africa and South American Continents separated from one another (Coker and Ejedawe, 1987; Nemčok et al., 2015; Salawu and Ojo, 2024; Nneji et al., 2026).

The distribution of Curie depths showed a decrease in values from the western, southwestern, and southern parts towards the northeastern portion of the region (Fig. 10). Block 19 showed the shallowest CPD at ~3.73 km, while Block 5 showed the deepest CPD at ~15.56 km (Table 1). Hence, the CPD extends from the shallowest part of the basin in the northeast and deepens both to the west, southwest, and southern portions of the SBT. The mean CPD of 10.99 km obtained in the investigated area could be attributable to reduction in crustal thickness beneath the Benue Trough, as opposed to the continental interior with significant crustal thickness. In addition, the overall shallow CPD characteristic of the SBT (< 16 km) can be associated with the abundance of magmatic intrusions injected into the Cretaceous successions during the Santonian thermo-tectonic episode that impacted the entire region (Salawu and Ojo, 2024; Nneji et al., 2026).

The finding from this study agrees fairly with previous study in the area by Eldosouky et al. (2023) who estimated an average CPD value of 8.96 km in parts of southeastern Nigeria using magnetic data. Abraham et al. (2018) estimated CPD values ranging from approximately 9.77 to 19.33 km, with a mean value of 15.69 km in southeastern Nigeria. They associated deeper CPD zones around the Afikpo, Okposi, and Enugu areas with depocenters in the SBT that were created as a result of the Santonian tectonic inversion, leading to the subsidence of the Afikpo synclinorium and the Anambra Basin (Obaje, 2009). According to Kogbe and Obialo (1976), structural instability of the crust and the Santonian thermo-tectonic cycle were associated with extensive faulting, folding, and magmatism, which resulted in the upliftment of the Abakaliki Anticlinorium. The pronounced igneous activities associated with the late Santonian events accounted for the presence of numerous intermediate and basic magmatic bodies that intruded the Asu River Group (Abraham et al., 2018; Nneji et al., 2026). It is possible that these subsurface intrusions might be responsible for the reduced CPD values calculated in this study. Hence, the shallowest CPD value of 3.73 km identified in the northeastern part of the region (Fig. 7) represents the effects of basic intrusions located at shallow depths. The shallow CPD could also result from crustal thinning due to uplifted mantle plume beneath the basement rocks (Dolmaz et al., 2005; Artemieva, 2011; Kwaya and Kurowska, 2018).

Movement of hot waters at shallow depths can also account for the apparent thermal anomalies noted around the northeastern zone of the investigated area. Generally, the shallow average CPD estimated for the study area can be correlated with the stretched and thinned crust beneath the Benue megarift structure or the presence of magmatic intrusive bodies at shallower depths (Abraham et al., 2018; Yassah et al., 2024). The abnormal heat flow and geothermal gradient anomalies observed at the SBT's northeastern sector, coupled with the elevated thermal conditions in southeastern zone beyond Nigeria's territorial boundary (Fig. 11, Fig. 12) coincided with parts of the region with shallow CPD values, which emphasizes the influence the thermal structure exerts on temperature and heat flow changes in the subsurface.

The average geothermal gradient value of 58.34 °Ckm-1 determined in this research compares fairly with borehole-derived temperature measurements from deep petroleum exploratory wells drilled in the adjacent Anambra Basin, where temperature gradients as high as 50 °Ckm-1 have been documented (Onuoha and Ekine, 1999). Borehole thermal investigations across sedimentary basins in Nigeria indicated a progressive increase in heat flow distribution from the Niger Delta Basin (approximately 25 mWm-2) to the northern part of the Benue Trough where values as high as 150 mWm-2 were reported near the Lamurde and Wikki Hot Springs in the northeastern region of the country (Akinyemi and Zui, 2019), suggesting that areas with geothermal gradients exceeding 50 °Ckm-1 may hold significant potential for geothermal energy.

prospectivity (Akinyemi and Zui, 2019; Yassah et al., 2024; Usman et al., 2025). Interpretation of the maps reveals a consistent relationship between CPD, geothermal gradients, and heat flow, whereby areas with shallow CPD are associated with elevated geothermal gradients and heat flow values, whereas regions with deeper CPD correspond to zones of reduced geothermal gradients and heat flow (Li et al., 2017). The anomalously elevated heat flow recorded in the northeastern sector of the investigated area correlated to region of shallowest estimated CPD and very high geothermal gradient values.

Accordingly, the northeastern sector of the area, marked by elevated geothermal gradient and heat flow anomalies, is delineated for further geothermal energy resource assessment. This section of the investigated area is covered by Blocks 18, 19, 20, 24, and 25. Major towns in this part of the region include Ezzamgbo, Ugbodo, Abakaliki, Iboko, Okpoma, Obubra, Igumale, Oju, and Kornya areas. The derived heat flow and geothermal gradient in each of these blocks were in excess of 50 °Ckm-1 and 150 mWm-2, and thus, suggests anomalous temperature conditions possibly due to the prevalence of igneous bodies at shallower depth intervals, or the effects of mantle activities below the thinned/stretched crust, in addition to the effects geothermally heated groundwaters circulating at shallow depth intervals (Kurowska and Schoeneich, 2010; Eletta and Udensi, 2012; Obande et al., 2014; Yassah et al., 2024). The mean CPD of the blocks mentioned above is below 10 km (i.e., 7.61 km), connoting abnormal geothermal conditions (Tanaka et al., 1999). Hence, a low enthalpy geothermal energy resources is inferred in this study, owing to the shallow CPD characteristics of the northeastern sector of the investigated region.

Furthermore, the presence of volcanic intrusive bodies that were injected into the Cretaceous sedimentary rocks could contribute to heating-up of aquifers deep underground to become geothermal waters that are brought to the surface (Abraham et al., 2015). Such situation can explain the intersection of a warm artesian aquifer with temperature of about 55 °C during the drilling of a water borehole at Umulokpa area of the SBT (Onuoha and Ekine,1999 that impacted the entire region (Salawu and Ojo, 2024; Nneji et al., 2026). The finding from this study agrees fairly with previous study in the area by Eldosouky et al. (2023) who estimated an average CPD value of 8.96 km in parts of southeastern Nigeria using magnetic data. Abraham et al. (2018) estimated CPD values ranging from approximately 9.77 to 19.33 km, with a mean value of 15.69 km in southeastern Nigeria.

They associated deeper CPD zones around the Afikpo, Okposi, and Enugu areas with depocenters in the SBT that were created as a result of the Santonian tectonic inversion, leading to the subsidence of the Afikpo synclinorium and the Anambra Basin (Obaje, 2009). According to Kogbe and Obialo (1976), structural instability of the crust and the Santonian thermo-tectonic cycle were associated with extensive faulting, folding, and magmatism, which resulted in the upliftment of the Abakaliki Anticlinorium. The pronounced igneous activities associated with the late Santonian events accounted for the presence of numerous intermediate and basic magmatic bodies that intruded the Asu River Group (Abraham et al., 2018; Nneji et al., 2026). It is possible that these subsurface intrusions might be responsible for the reduced CPD values calculated in this study. Hence, the shallowest CPD value of 3.73 km identified in the northeastern part of the region (Fig. 7) represents the effects of basic intrusions located at shallow depths. The shallow CPD could also result from crustal thinning due to uplifted mantle plume beneath the basement rocks (Dolmaz et al., 2005; Artemieva, 2011; Kwaya and Kurowska, 2018). Movement of hot waters at shallow depths can also account for the apparent thermal anomalies noted around the northeastern zone of the investigated area. Generally, the shallow average CPD estimated for the study area can be correlated with the stretched and thinned crust beneath the Benue megarift structure or the presence of magmatic intrusive bodies at shallower depths (Abraham et al., 2018; Yassah et al., 2024).

The abnormal heat flow and geothermal gradient anomalies observed at the SBT's northeastern sector, coupled with the elevated thermal conditions in southeastern zone beyond Nigeria's territorial boundary (Fig. 11, Fig. 12) coincided with parts of the region with shallow CPD values, which emphasizes the influence the thermal structure exerts on temperature and heat flow changes in the subsurface. The average geothermal gradient value of 58.34 $°Ckm^{-1}$ determined in this research compares fairly with borehole-derived temperature measurements from deep petroleum exploratory wells drilled in the adjacent Anambra Basin, where temperature gradients as high as 50 $°Ckm^{-1}$ have been documented (Onuoha and Ekine, 1999).

Borehole thermal investigations across sedimentary basins in Nigeria indicated a progressive increase in heat flow distribution from the Niger Delta Basin (approximately 25 mWm^{-2}) to the northern part of the Benue Trough where values as high as 150 mWm^{-2} were reported near the Lamurde and Wikki Hot Springs in the northeastern region of the country (Akinyemi and Zui, 2019), suggesting that areas with geothermal gradients exceeding 50 $°Ckm^{-1}$ may hold significant potential for geothermal energy prospectivity (Akinyemi and Zui, 2019; Yassah et al., 2024; Usman et al., 2025).

Interpretation of the maps reveals a consistent relationship between CPD, geothermal gradients, and heat flow, whereby areas with shallow CPD are associated with elevated geothermal gradients and heat flow values, whereas regions with deeper CPD correspond to zones of reduced geothermal gradients and heat flow (Li et al., 2017).

The anomalously elevated heat flow recorded in the northeastern sector of the investigated area correlated to region of shallowest estimated CPD and very high geothermal gradient values. Accordingly, the northeastern sector of the area, marked by elevated geothermal gradient and heat flow anomalies, is delineated for further geothermal energy resource assessment. This section of the investigated area is covered by Blocks 18, 19, 20, 24, and 25. Major towns in this part of the region include Ezzamgbo, Ugbodo, Abakaliki, Iboko, Okpoma, Obubra, Igumale, Oju, and Kornya areas. The derived heat flow and geothermal gradient in each of these blocks were in excess of 50 $°Ckm^{-1}$ and 150 mWm^{-2}, and thus, suggests anomalous temperature conditions possibly due to the prevalence of igneous bodies at shallower depth intervals, or the effects of mantle activities below the thinned/stretched crust, in addition to the effects geothermally heated groundwaters circulating at shallow depth intervals (Kurowska and Schoeneich, 2010; Eletta and Udensi, 2012; Obande et al., 2014; Yassah et al., 2024).

The mean CPD of the blocks mentioned above is below 10 km (i.e., 7.61 km), connoting abnormal geothermal conditions (Tanaka et al., 1999). Hence, a low enthalpy geothermal energy resources is inferred in this study, owing to the shallow CPD characteristics of the northeastern sector of the investigated region. Furthermore, the presence of volcanic intrusive bodies that were injected into the Cretaceous sedimentary rocks could contribute to heating-up of aquifers deep underground to become geothermal waters that are brought to the surface (Abraham et al., 2015). Such situation can explain the intersection of a warm artesian aquifer with temperature of about 55 °C during the drilling of a water borehole at Umulokpa area of the SBT (Onuoha and Ekine, 1999).

It is worthy to note that there was no constraint to the geothermal gradient and heat flow estimations in this study due to unavailability of temperature data from deep oil and gas exploration wells to compare to the results from aeromagnetic data analysis over the region. However, the mean geothermal gradient (58.34 $°Ckm^{-1}$) and heat flow (145.85 mWm^{-2}) values were found to align closely with results reported from borehole temperature measurements in the adjacent Anambra Basin (Onuoha and Ekine, 1999). Pollack et al. (1993) have shown that thermally normal continental regions are characterized by an average heat flow of about 65 mWm^{-2}, while heat flow values in excess of about 80 - 100 mWm^{-2} may imply elevated subsurface thermal condition (Sharma, 2004; Abraham et al., 2014, 2018; Obande et al., 2014; Yassah et al., 2024; Usman et al., 2025). Hence, the computed average heat flow value (145.85 mWm^{-2}) emphasizes the likelihood of viable geothermal energy resources in the region. The northeastern section of the region exhibits elevated crustal heat flow, with the peak value of 388.74 mWm^{-2}. This suggests an anomalous crustal thermal state beneath this portion of the investigated area.

Therefore, the northeastern section of the SBT is recommended for further studies to establish its potential for geothermal energy resource occurrence and exploitation.

5. Conclusion

Regional assessment of the geothermal resource prospectivity of the Southern Benue Trough has been attempted through this research using integrated analysis of high-resolution aeromagnetic data. A major focus of the study was to evaluate the thermal structure to ascertain how subsurface temperature gradient variations controlled the distribution of crustal heat flow beneath the region. The analyzed 2D power spectrum curves gave insights into the distribution of CPD beneath the region. The area is generally characterized by CPDs shallower than 16 km. Near-surface CPD zones (< 10 km) dominated the northern, northwestern, northeastern, and extreme southeastern sections of the investigated region, whereas the southwestern, western, southern, and segments of the southeastern portion of the region is dominated by CPDs ranging from 12.5 to 15.5 km.

Anomalously elevated geothermal gradient and heat flow values were identified at the northeastern axis, with average values of 58.34 $°Ckm^{-1}$ and 145.85 mWm^{-2}, indicating higher subsurface thermal conditions. This anomalous zone coincided with areas characterized by low CPDs in the northeastern part of the region, interpreted to represent thermal effects from the Santonian igneous intrusions emplaced into the Cretaceous sequences of the SBT, with possible contributions from mantle activities below the thinned crust and near-surface circulation of hot geothermal waters. Hence, the northeastern section of the study region exhibiting anomalous subsurface thermal conditions is isolated in this study for further in-depth studies to establish its geothermal energy resource prospection. This present work can serve as guide for future studies on the geothermal resource prospects in the SBT and other geological regions with similar tectono-thermal history.

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Declaration of competing interests

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.