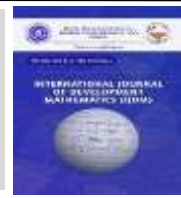




INTERNATIONAL JOURNAL OF DEVELOPMENT MATHEMATICS

ISSN: 3026-8656 (Print) | 3026-8699 (Online)

journal homepage: <https://ijdm.org.ng/index.php/Journals>



Magnetic Basement and Geothermal Potential of the Southern Part of Nigerian Benue Trough

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ARTICLE INFO

Article history:

Received 02 May 2026

Received in revised form 10 August 2026

Accepted 30 August 2026

Keywords:

Magnetic basement, Geothermal energy, Geodynamic process, Lower and Middle Benue trough, Anambra basin

MSC 2020 Subject classification:

86A08, 42A38, 35Q60

ABSTRACT

Understanding the geodynamic processes of a region requires a detailed study of geothermal parameters within the Earth's crust. In this study, Curie depth and surface heat flow were estimated using modified centroid method and 1-D Fourier law respectively beneath southern Benue trough in Nigeria. The calculated values for the Curie depth beneath the study area is 11 km at Abakaliki and 27 km over the area of Anambra basin. Surface heat flow is also found between 54 mWm⁻² around Anambra basin and 132 mWm⁻² around Abakaliki anticlinorium. The large variations in the values of the Curie depth as compared to the smaller dimension of the study area explained the complex geodynamic process of the region. Magnetic basement of around 2.8 km and 9.4 km for the region have also been calculated using Euler deconvolution method. We also presented a separate map, showing the spatial distribution of volcanic plugs in the region, which are belief to control the thermo-tectonics of the region.

1 Introduction

Curie depth refers to the depth within the Earth's crust at which magnetic minerals lose their permanent magnetism due to high temperature, known as the Curie temperature. Beyond this point, rocks exhibit only induced magnetism. The Curie depth is commonly approximated from aeromagnetic data using the spectral analysis approach (Bhattacharyya, 1966; Naidu, 1968; Spector and Grant, 1970; Bhattacharyya and Leu, 1975, 1977; Shuey et al., 1977; Okubo et al., 1985; Blakely, 1996; Maus et al., 1997; Tanaka et al., 1999; Ravat et al., 2007; Bouligand et al., 2009; Ravat et al., 2016).

Curie depth is commonly estimated from aeromagnetic data using spectral analysis techniques. Surface heat flow, on the other hand, represents the transfer of heat from the Earth's interior to the surface. This heat originates from processes such as cooling of the Earth's core and radioactive decay within the crust, typically occurring between depths of 20 km and 40 km. Regions with high tectonic activity or thinner crust generally exhibit higher surface heat flow (Abdullahi et al., 2023).

The estimation of Curie depth and surface heat flow is important because it provides insight into the geothermal energy potential of a region, which is valuable for sustainable development. The Benue Trough in Nigeria is a major geological structure trending in a northeast–southwest direction. Its formation is associated with the separation of Africa and South America during the opening of the South Atlantic Ocean (King, 1950; Carter et al., 1963; Stonley,

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<https://doi.org/10.62054/ijdm/0303.19>

1966; Burke and Whiteman, 1973; Benkhelil, 1982, 1989; Fairhead and Binks, 1991; Fearhead et al., 1991; Maluski et al., 1995; Anudu et al., 2014; Abdullahi et al., 2019b). Despite other studies for the estimation of Curie depth as well as the heat flow over some regions of Nigerian sediments (Onwuemesi, 1997; Nwankwo et al., 2009; Obande et al., 2014; Abraham et al., 2015; Nwankwo, 2015; Chukwu et al., 2017; Lawal et al., 2018), however, there is still the need to present a more comprehensive estimation of Curie depth as well as the surface heat flow using some robust modern techniques for this present study area that is rich in structures of geological interest. Published articles in the region have suggested Curie depths between 11 km and 33 km and surface heat flow between 51 mW/m² and 126 mW/m² (Onwuemesi, 1997; Nwankwo et al., 2009; Obande et al., 2014; Abraham et al., 2015; Nwankwo, 2015; Chukwu et al., 2017; Lawal et al., 2018; Abdullahi et al., 2023).

In the present study, modified centroid method was used in the calculation of Curie depth beneath the lower and middle Benue Trough including Anambra basin as well as calculated the surface heat flow for the region using 1-D Fourier law and the magnetic basement was estimated using Euler deconvolution model..

2 The Geology and Tectonics of the Study Area

The Benue Trough is an elongated rift system extending across Nigeria (Fig. 1). It is geologically significant and rich in mineral resources (Abdullahi et al., 2019a). The basement rocks in the study area consist mainly of granites and gneisses, which are intruded by older Pan-African granitoids and migmatite-gneiss complexes. In some areas, younger granitoids also intrude these older formations (Maluski et al., 1995; Obaje, 2009; Anudu et al., 2014; Abdullahi et al., 2019a).

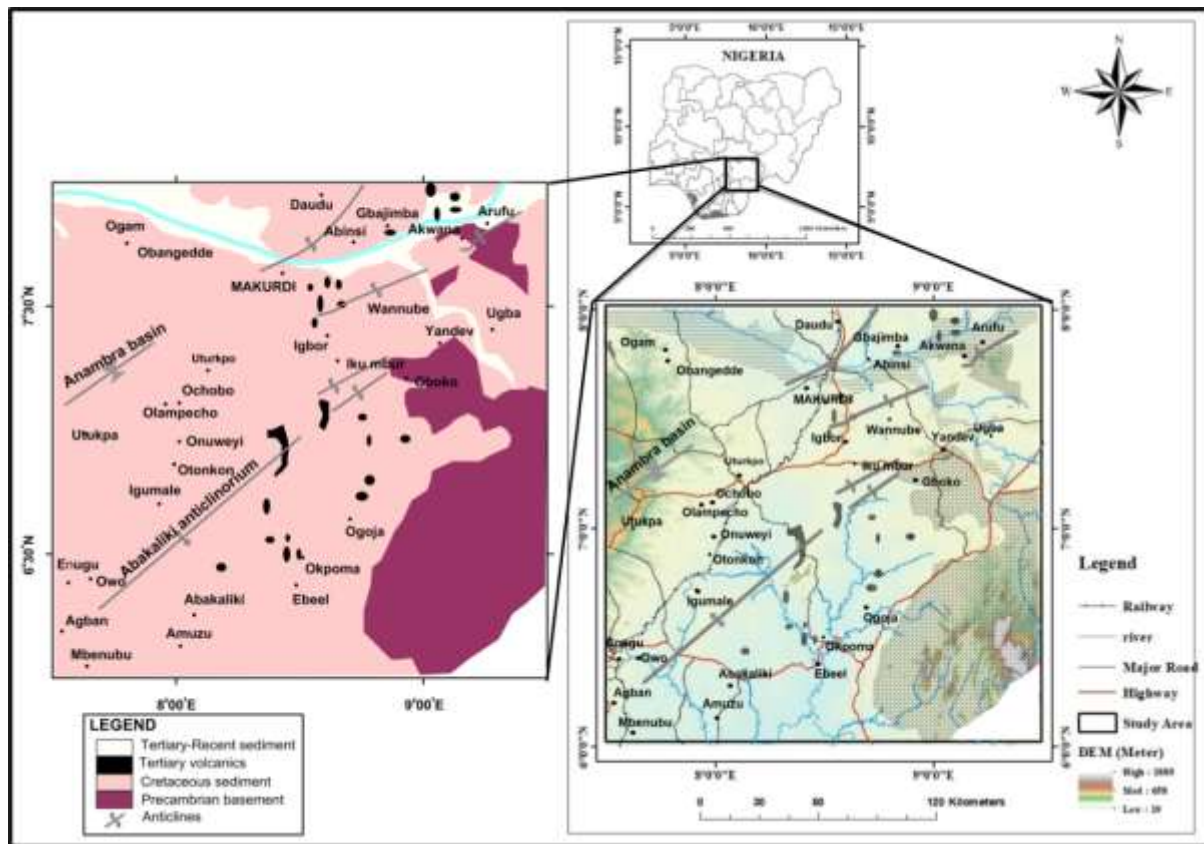


Figure 1. Geological map of the study location modified after Abdullahi et al., 2019 (a) and the Digital Elevation Map (DEM) of the study area (b). The anticlines found in the study region are also superimposed.

A prominent feature of the region is folding, which affects both the sedimentary rocks and the underlying basement rocks. Additionally, volcanic activity; especially in the Abakaliki area has introduced igneous intrusions (Abdullahi and Singh, 2018). The folds are present both within the Cretaceous and the Neoproterozoic basement rocks (Abdullahi and Singh, 2018). Tertiary volcanics have intruded many places where Abakaliki area received the highest thermo-tectonic activity in the region. These structural features have contributed to crustal thinning, uplifted basement rocks, and a relatively shallow (crust-mantle boundary) Moho (Abdullahi and Singh, 2018; Figure 1).

The southern part of the Benue Trough forms an intracratonic rift basin in Nigeria characterized by deep fault-bounded sub-basins, thick Cretaceous sedimentary fills with localized magmatic intrusions/extrusions reflecting prolonged thermal and extensional modification and crustal thinning driven by extensional and strike-slip tectonics (Obaje, 2009). Structurally, the region shows intense fracturing and localized depocentres linked to major Santonian compressional folding and wrench tectonics with lineaments/faults interpretation in the region suggested the dominant NE-SW, ENE-WSW, NNE-SSW within the Cretaceous sedimentary fills and the minor NW-SE with the basement rock complex (Abdullahi et al., 2019a).

3 Methodology

Curie depth was estimated using the modified centroid method, which is based on the spectral analysis of aeromagnetic data (Spector and Grant, 1970; Bhattacharya and Leu, 1975; Shuey et al., 1977; Blakely, 1988, 1995; Okubo et al., 1985; Tanaka et al., 1999; Okubo and Matsunga, 1994; Ross et al., 2006; Bansal et al., 2011, Bansal and Dunri, 2013) and correlated or scaling/fractal source distribution (Maus et al., 1997; Ravat et al., 2007; Bansal et al., 2013, 2016; Salem et al., 2014; Li et al., 2017).

This method improves upon the conventional approach by considering correlated distributions of magnetic sources rather than purely random ones (Maus and Dimri, 1996; Pilkington and Todoeschuck, 1993; Pilkington et al., 1994; Bouligand et al., 2009; Bansal et al., 2010). It is in common practice to use power law: $\varphi_m(k_x, k_y) \propto k^\beta$ (Pilkington and Todoeschuck, 1995; Maus and Dimri, 1994; 1995; Fedi et al., 1997) for describing the scaling nature of magnetization. Where φ_m stand as magnetization power spectra, k_x and k_y are the wavenumbers in the x and y directions and their Euclidean norm $k = \sqrt{k_x^2 + k_y^2}$ in rad/km, and β represent the scaling exponent which is related to rock type, extent of heterogeneity and geological structures of the region (Bansal et al., 2010).

By adopting scaling nature of magnetization distribution, the 1-D radially averaged power spectrum of aeromagnetic field ($\Phi_f(k)$) can be expressed in terms of top depth (Z_t) and bottom depth (Z_b) of the anomalous magnetic body (Bansal et al., 2011; Li et al., 2017)

$$\ln [\Phi_f(k)] = \ln [A_1 k^\beta e^{2|k|Z_t} (1 - e^{-|k|(Z_b - Z_t)})^2] \quad (1)$$

where A_1 is a constant.

The equation (1) can be simplified for the estimation of top depth of anomalous magnetic body (e.g., Bansal et al., 2011, 2013, 2016)

$$\ln(\Phi_f(k)) = A_2 - 2kZ_t - \beta \ln(k) \quad (2)$$

where A_2 is a constant.

The centroid depth of the anomalous magnetic body can be estimated from the low wavenumber part of the equation (1) as in (Bansal et al., 2011).

$$\ln\left(\frac{\Phi_f(k)}{k^2}\right) = A_3 - 2kZ_0 - \beta \ln(k) \quad (3)$$

where A_3 is a constant.

The Curie depth (Z_b) can be estimated from top and centroid depth (Tanaka et al., 1999).

$$Z_b = 2Z_0 - Z_t \quad (4)$$

The estimation of top and centroid depths using equations (2) and (3) requires a simultaneous evaluation of depth and β values. The inversion methods do not provide stable and consistent results for the simultaneous estimation of depths and β (Ravat et al., 2007; Bouligand et al., 2009; Li et al., 2017). Many studies prefer to fix the β values (Fedi et al., 1997; Bansal et al., 2013, 2016; Li et al., 2017). We fixed $\beta=1$ corresponding to 1/f scaling noise for calculation of the Curie depth values as described by Bansal et al., 2011 and used by Nwankwo, 2015 in nearby

region to present study. The statistical error in Curie depths due to fitting is calculated using Okubo and Matsunga, 1994 approach.

Surface heat flow was then calculated using the one-dimensional Fourier law, which assumes heat transfer occurs mainly through conduction. The method also assumes constant temperature gradient and no significant convection or radiogenic heat effects (Tanaka et al., 1999) by 1-D Fourier law that based on a conductive mode of heat transportation (Turcotte and Schubert, 1982). The Fourier law works where there is no heat transportation by mode of convection, no radiogenic heat, temperature variation in vertical direction, constant temperature gradient (dT/dz). Empirically the Fourier law can be written as (Turcotte and Schubert, 1982)

$$q_s = k \frac{dT}{dz} \quad (5)$$

Where, q_s stands for surface heat flow, k is thermal conductivity ($W/m^{\circ}C$) depends on lithology, temperature, and pressure (Beardsmore and Cull, 2001). The average thermal conductivity for the continent is found to be $2.5 W/m^{\circ}C$ (Li et al., 2017). The Curie temperature is a function of temperature gradient and Curie point depth as (Turcotte and Schubert, 1982)

$$\theta_c = \left(\frac{dT}{dz} \right) Z_b \quad (6)$$

From the above equations (5) and (6), the surface heat flow can be derived as:

$$q_s = \frac{k\theta_c}{Z_b} \quad (7)$$

Here, we assumed the Curie temperature, $\theta_c = 580^{\circ}C$ corresponds to magnetite.

In addition, Euler deconvolution was applied to estimate the depth to magnetic basement structures, using different structural index of 0 for geological features such as faults/contacts (Keating 1998).

4 Aeromagnetic Data of the Study Area

The aeromagnetic data used for the present study is obtained from the recent national high-resolution aeromagnetic data flown between 2006 and 2007 by Fugro Airborne Survey under the authority of the Nigerian Geological Survey Agency (NGSA). The survey was done along the dominant NW-SE regional strike (i.e. parallel to the orientation of the Trough). The traverse line spacing for the acquisition was 500 m with 2 km control line spacing. The survey was carried out at just 80 m above the ground surface and sampled at 0.1 s. Figure 2, shows the total magnetic intensity (TMI) high-resolution aeromagnetic data of the area with the geological formations superimposed over it. The total magnetic intensity (TMI) map was divided into 25 (i.e., B01, B02, ..., B25) 50 % overlapping blocks to improve the accuracy of depth estimations. The white dots are the centre of block.

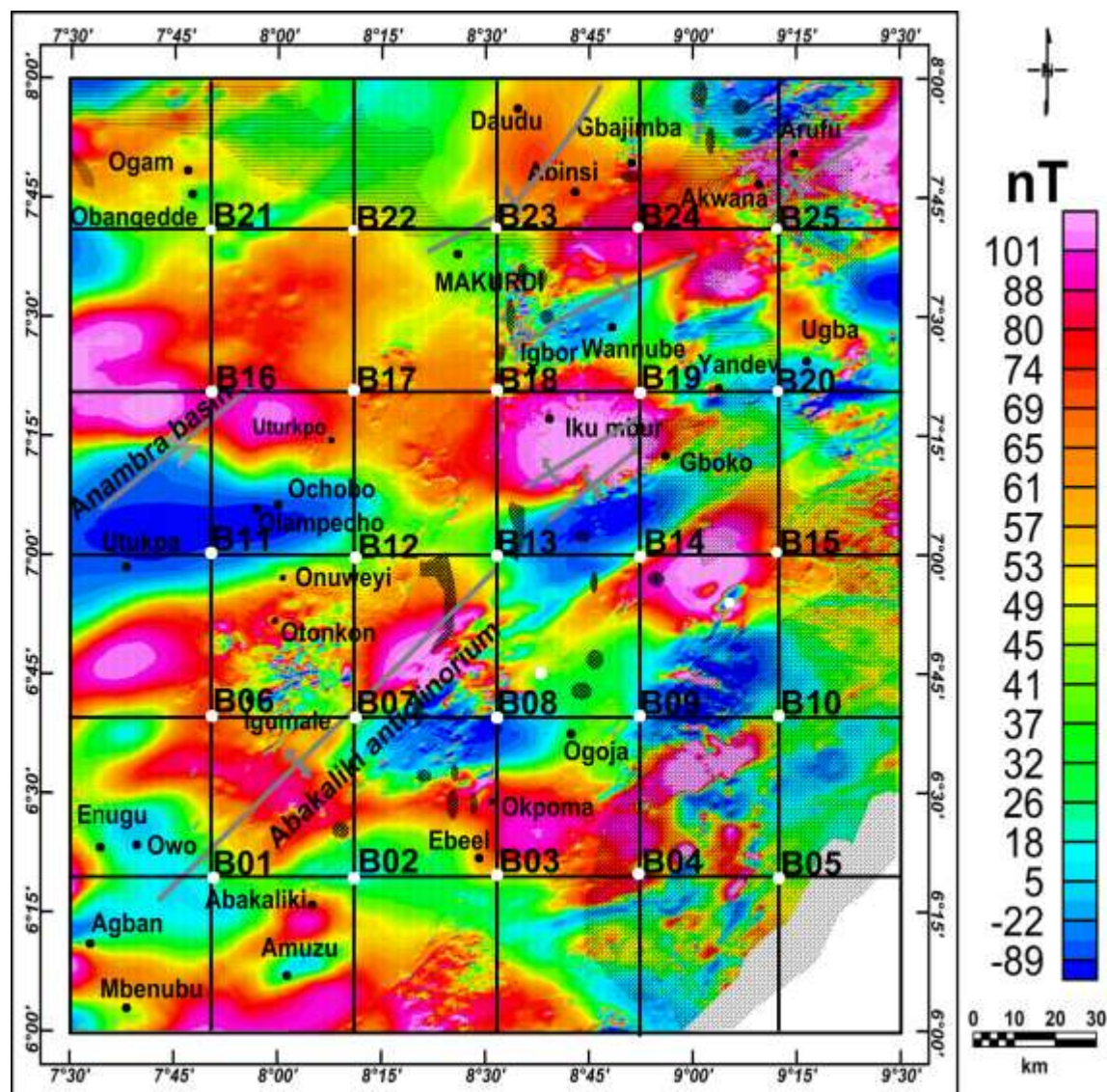


Figure 2. The high-resolution aeromagnetic anomaly map of the study area and the centres of blocks labeled (B01, B02, B03, ..., B25) for Curie depth estimates as well as the surface heat flow beneath the study area. The each blocks are made with 50 % overlap.

5 Results and discussion

The study area was divided into 25 overlapping blocks, and a power spectrum was generated for each block. From these, the top depth, centroid depth, and Curie depth were calculated using equation (2), the centroid depth from equation (3) and the Curie depth using equation (4) respective whereas surface heat flow is carried out using equation (7). Overlapping of blocks are made such as to obtain good number of observational points for better resolution of

depths (Kumar et al., 2017; Abdullahi et al., 2019).

A detail analysis and interpretation of the Curie depth and surface heat flow beneath the Cretaceous sedimentary rocks of the southern part Benue Trough of Nigeria has been done (Table 1). Power spectrum of blocks (B01 and B09) for the estimation of Curie depth is presented in Fig. 3. The Curie depth across the region ranges from 11 km to 27 km (Figure 4). This wide variation suggests a highly complex geological and tectonic environment influenced by past volcanic and tectonic activities (Abdullahi and Singh, 2018; Abdullahi et al., 2019a, 2019b). The result of surface heat flow as calculated in the present work which varies between 54 mWm^{-2} and 132 mWm^{-2} . The 3D surface anomaly map of the surface heat flow as calculated in the study area is presented in Figure 5. The recorded higher values of surface heat flow are associated with regions of intense tectonic and volcanic activity (Abdullahi et al., 2019b).

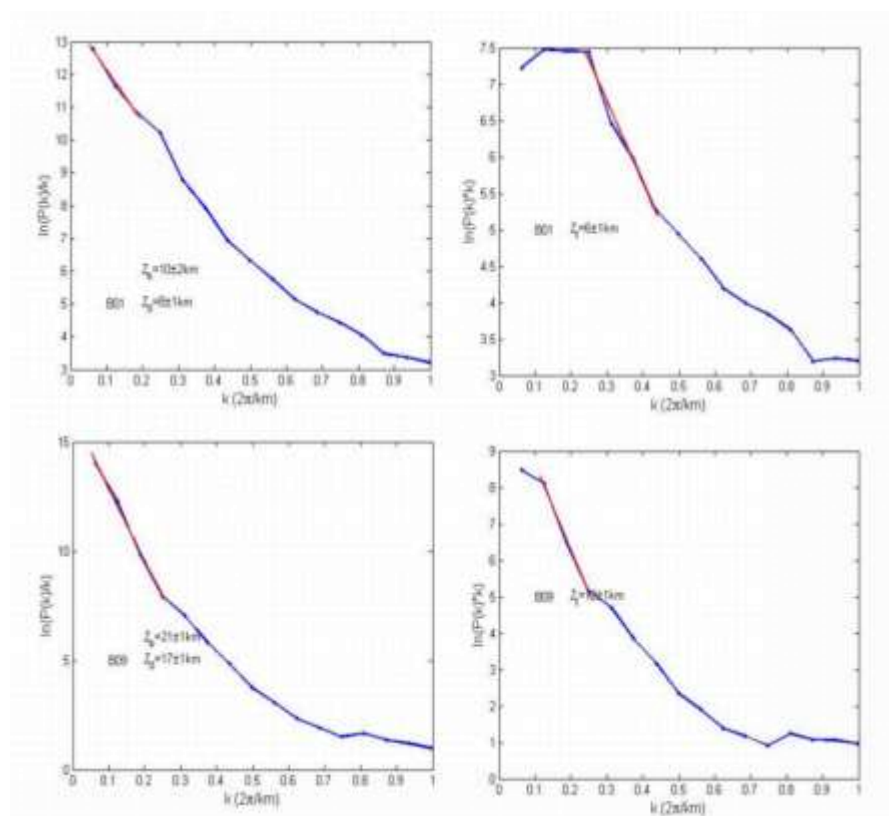


Figure 3. Plots of power spectrums for blocks (B01 and B09) for the curie depth estimation with the red lines showing the selected best fit for the estimations. Results of depth estimations are as shown.

Table 1: Results of Curie depth (Km) and that of Surface Heat Flow for the 25 (B1 - B25) sampled blocks in the southern Benue Trough of Nigeria

Windows	Curie depths (km)	Surface Heat Flow (mWm^{-2})
B1	11 $\pm$ 2	132
B2	16 $\pm$ 1	91
B3	14 $\pm$ 0.2	104
B4	15 $\pm$ 2	97
B5	12 $\pm$ 1	121
B6	18 $\pm$ 1	81
B7	18 $\pm$ 1	81
B8	17 $\pm$ 2	85
B9	17 $\pm$ 1	85
B10	15 $\pm$ 2	97
B11	27 $\pm$ 2	54
B12	22 $\pm$ 2	66
B13	18 $\pm$ 4	81
B14	19 $\pm$ 4	76
B15	20 $\pm$ 1	72
B16	23 $\pm$ 2	63
B17	23 $\pm$ 2	63
B18	22 $\pm$ 5	66
B19	16 $\pm$ 4	91
B20	17 $\pm$ 1	85
B21	19 $\pm$ 1	76
B22	19 $\pm$ 3	76
B23	23 $\pm$ 1	63
B24	22 $\pm$ 1	66
B25	18 $\pm$ 2	81

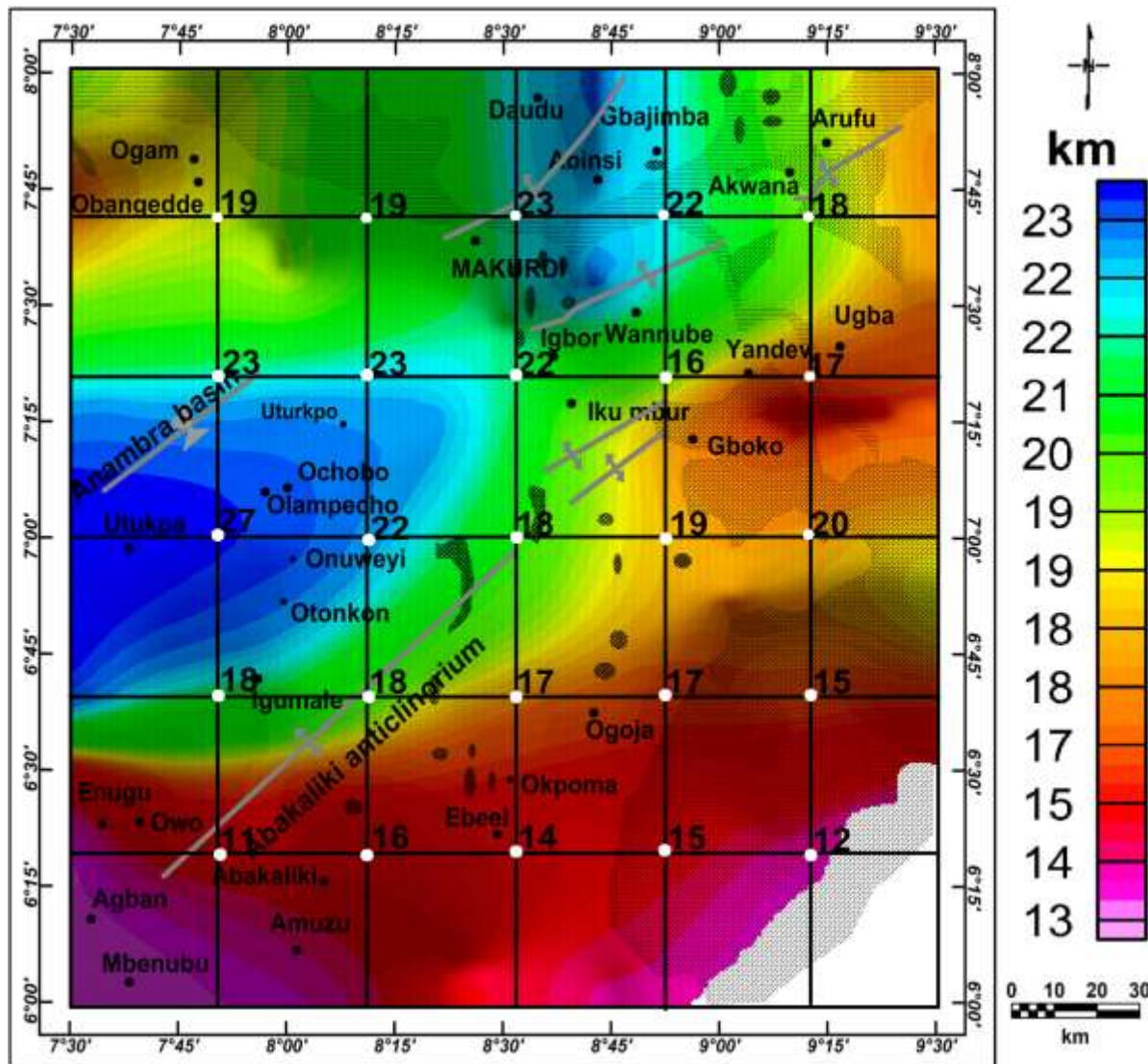


Figure 4. 3D anomaly map of the Curie depth estimated beneath the study area.

Shallow Curie depths (11–18 km), especially around the Abakaliki anticlinorium, indicate higher subsurface temperatures and correspond to higher heat flow values (up to 132 mW/m²). In contrast, deeper Curie depths (19–27 km), such as in the Anambra Basin, indicate relatively cooler conditions and lower heat flow values. The results also suggest that tectonic processes such as crustal underplating and volcanic intrusions have significantly influenced the thermal structure of the region. Interestingly, the estimated heat flow values are higher than previously measured surface values, likely due to variations in crustal composition and non-uniform geological structures (Nwachukwu, 1976; Avbovbo, 1978; Onuoha and Ekine, 1999). High heat flow may have contributed to the degradation of petroleum resources in some parts of the region (Cratchley and Jones, 1965; Adighije, 1981; Ajayi and Ajakaiye,

1981; Maluski et al., 1995; Anudu et al., 2014; Abdullahi and Singh, 2018). Seismological stations in the Benue Trough suggested the mean Moho depth at 23 km in the region (Akpan et al., 2016). This is in good agreement with our Curie depth estimates between 11 km and 23 km. The higher value of 27 km calculated in the study area from block (B09) could indicate a rifted zone. This is in association with the Anambra basin in the region. Previous findings have confirmed the Anambra basin as a rifted subsidiary of the lower part of the Benue Trough (Adighije, 1981; Fearhead and Okereke, 1987, 1988; Okereke, 1988; Onwuemesi, 1997; Obaje, 2009; Kwaya and Kurowska, 2018; Abdullahi et al., 2019b).

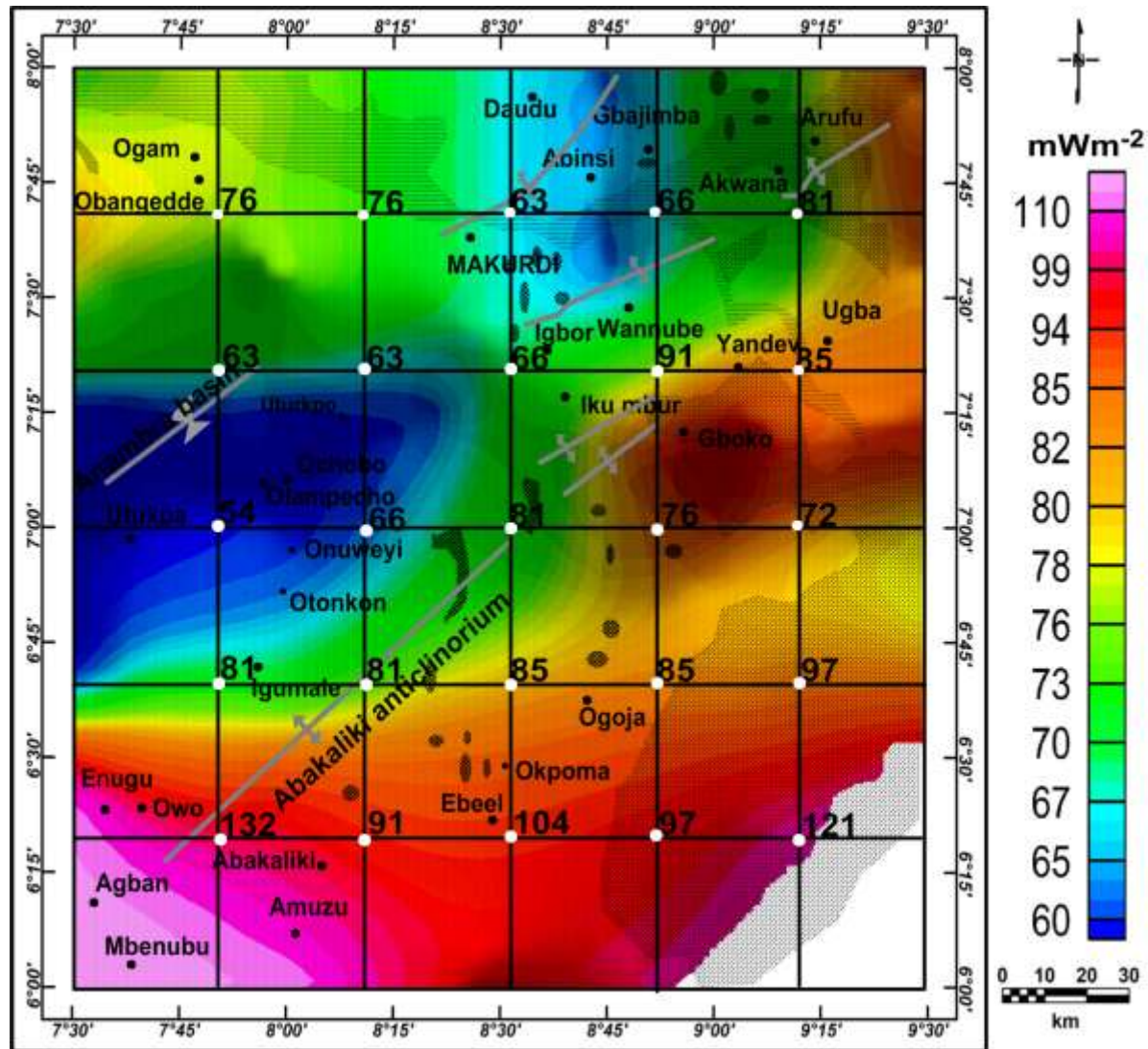


Figure 5. 3D anomaly map showing the results of the estimated surface heat flow beneath the study area.

The depth to magnetic basement of around 2.8 km to the maximum of 9.4 km (Fig. 6) was calculated for the region

of study using Euler convolution method (Keating 1998). The calculated depth values are in good agreement with the previously published basement depth values in the area from magnetic data (Abdullahi and Singh, 2018; Abdullahi et al., 2019a, b; Abdullahi et al., 2023).

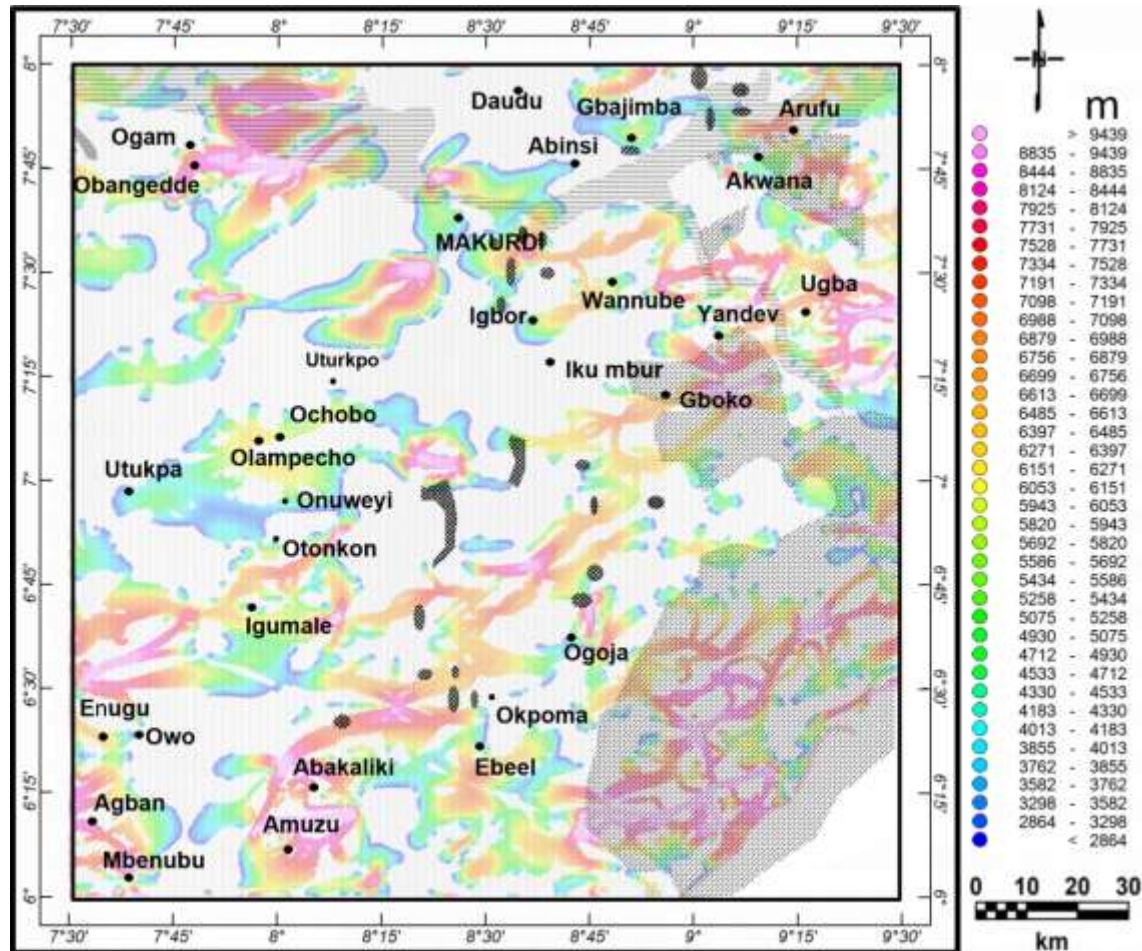


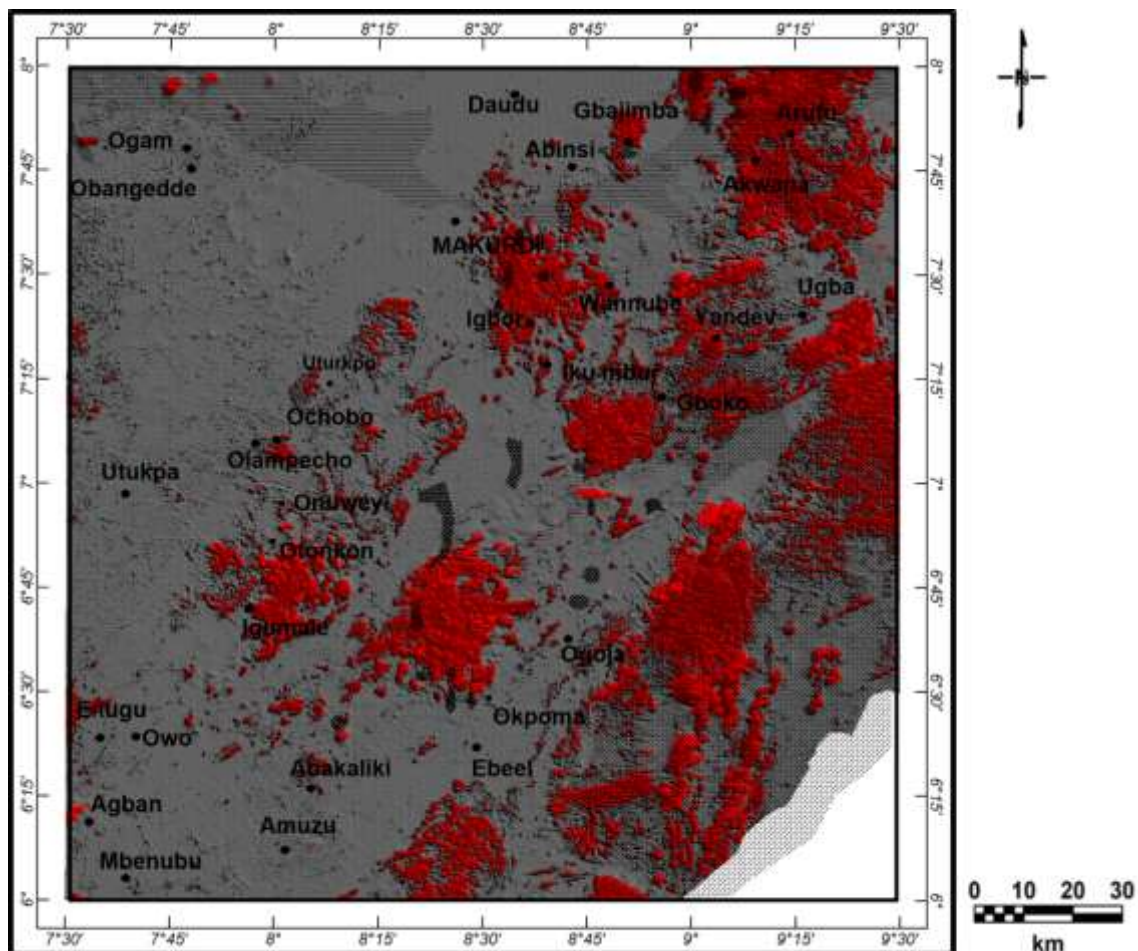
Figure 6. 3D Euler deconvolution map, showing magnetic basement range between 2.8 km and 9.4 km. This depth calculation was done using 0 (for contact/fault).

3D surface model, showing distribution of volcanic plugs in the region is prepared (Fig. 7). The mapped volcanic plugs show good agreement with those on the geological map and this widespread of volcanic activities shown, are contributing factors to the higher values of the surface heat flow and lower Curie depth recorded.

6 Conclusions

The following conclusions are drawn from the present work;

- i. The study successfully estimated the Curie depth and surface heat flow beneath the southern Benue Trough using high-resolution aeromagnetic data and the modified centroid method.
- ii. The Curie depth varies between 11 km and 27 km, indicating significant thermal and structural variations within the region. Surface heat flow values range from 54 mW/m² to 132 mW/m², with higher values linked to volcanic intrusions and tectonic activity.
- iii. Magnetic basement depth was also estimated between the values of 2.8 km and 9.4 km using Euler deconvolution technique.
- iv. These findings suggest that the study area has strong geothermal potential and could be suitable for geothermal energy exploration.



v.

Figure 7. 3D model of the ground surface of the study area. This demonstrate the spatial distribution of volcanic

plugs (intrusions) in the study region.

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