



Original article

Exploratory assessment of geothermal resources in some parts of the Middle Benue Trough of Nigeria using airborne potential field data

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ABSTRACT

Some parts of the Middle Benue Trough (MBT) of Nigeria were evaluated with the aim of detecting prospective geothermal potential regions. Spectral depth analysis using a modified centroid procedure was applied to analyze high-resolution airborne magnetic data. The Curie point depth (CPD) within the study area is in the range of 6.0 and 16 km. It was observed that the Gboko Anticlines (GA) that are interrelated with the Santonian intrusions of Abakaliki Anticlinorium (AA) are characterized by thin CPD (6.0–8.0 km). The mapped geothermal anomalies within the GA with shallow CPD (<8.0 km) are dominated by the high geothermal gradient (GG) (>74 °C/km) and heat flow (HF) (>155 mW/m²) values. The adjoining areas within the study area are defined by medium-deep CPD (8.0–16.0 km), medium-low GG (<74 °C/km), and HF (<155 mW/m²) values. The further integrated geophysical investigation and subsequent exploitation programs should be sited in the delineated GA and adjoining AA

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1. Introduction

Nigeria is believed to be rich in geothermal energy resources, particularly, the eastern, western, and central parts of Nigeria, where hot springs, brine fields, lead–zinc and barite veins (Ekwok et al., 2020a; Amoo, 2019; Abraham et al., 2015; Nwachukwu, 1976) exist in the neighborhood of extensive magmatic intrusions. However, only a few geothermal investigations involving high-resolution airborne potential data have been carried out in Nigeria (Ejiga et al., 2022; Abdullahi and Kumar, 2020; Abraham et al., 2019). The recent geothermal exploration activities are aimed at offering a complementary energy source to Nigeria which is challenged with an inadequate hydro-power supply.

In recent times, extensive geoscience investigations have been carried out in the Nigerian Benue Trough (Ekwok et al., 2019;

Ofoegbu and Onuoha, 1991). Earlier studies in this geological region and adjoining areas were focused on the search for groundwater (Akpan et al., 2016), coal (Simpson, 1955), lead–zinc (Mackay, 1946), barites (Akpan et al., 2014), brine (Ekwok et al., 2022a; Tijani, 2004), limestone (Akpan et al., 2004), hydrocarbon (Ofoegbu and Onuoha, 1991), etc. Contemporary geoscience investigations in the Nigerian Benue Trough are focussed on reconnaissance exploration activities for geothermal energy (Ejiga et al., 2022; Abdullahi and Kumar, 2020; Abraham et al., 2019; Abraham and Nkitnam, 2017; Abraham et al., 2015) applying magnetic data. Nevertheless, supplementary geophysical methods like the bottom hole temperature, seismic, transient electromagnetic, electrical resistivity, and magnetotelluric can be used for geothermal energy investigation and monitoring (Mariita, 2010; Nwachukwu, 1976).

Magnetic data is a potent tool that can be applied to probe natural resources in the subsurface (Ejiga et al., 2022; Abdullahi and Kumar, 2020; Pham et al., 2021a; Melouah et al., 2021; Saada et al., 2021a, 2021b; Ben et al., 2022a, 2022b; Ibrahim et al., 2022), including geothermal reservoirs. Furthermore, the magnetic method has been effectively used in delineating the subsurface bedrock topography (Eldosouky et al., 2022a, 2022b; Pham et al., 2018), and mapping sediment–basement contacts (Agagu and

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Adighije 1983; Adighije, 1981; Adighije, 1979), during the early phases of geothermal development. Geologic structures and related rift minerals associated with igneous intrusions can be effectively studied using the magnetic method (Eldosouky et al., 2021, 2022a; Saada et al., 2022; El-Sehamy et al., 2022; Pham et al., 2022). Additionally, it can considerably lessen the number of drilled wells desired to appraise probable geothermal fields. Magnetic methods have been reported to be the most cost-effective geophysical methods for generating satisfactory models for geothermal structures (Mohammadzadeh-Moghaddam et al., 2016). Procedures of magnetic data acquisition, reduction, presentation, and analysis have advanced considerably over the years. However, the inverse problem associated with magnetic data is often ill-posed which makes the solution non-unique and unstable (Ekwok et al., 2019). A stable solution to an ill-posed issue can be achieved by using some advanced approaches coupled with a priori geologic information (Ekwok et al., 2019).

In this research, magnetic data which investigate various physical properties (like magnetic susceptibility) of rocks (Ekwok et al. 2022b), were employed to provide a better understanding of the buried geothermal structures (Abraham et al., 2019). These procedures have been useful in mapping geologic structures linked to geothermal reservoirs, mapping of basement structures, and igneous intrusions (Ekwok et al., 2021a), and magma chambers related to the heat source of a geothermal system (Represas et al., 2013). Furthermore, the magnetic data can be applied in the location of zones with lessened magnetization triggered by thermal activities, hydrothermal system evaluation, and mapping of buried anomalies initiated by magmatic and granitic bodies (Elkhateeb and Eldosouky, 2016; Elkhateeb et al., 2021; Bencharef et al., 2022; Mahdi et al., 2022; Saada et al., 2022; Eldosouky et al., 2022b; Pham et al., 2019) as well as connected geologic structures (Pham et al., 2021b; Eldosouky et al., 2022c; Ekwok et al., 2022c, 2022d, 2022e).

2. Location and geologic setting of the area

The study location is part of the MBT, and it straddles some parts of Benue and Nasarawa States of Nigeria. Geographically,

the study location lies between latitudes 7.0°N to 8.5°N and longitudes 8.0°E to 9.5°E (Fig. 1).

The MBT is part of the Nigerian Benue Trough that connects the Gulf of Guinea in the South to the Chad Basin in the North. It is believed to be associated with the opening of the Atlantic Ocean that ended in the early Tertiary with the creation of the Tertiary Niger Delta (Obaje, 2009). The Benue Trough is characterized by extensive magmatic and tectonic activities as evidenced by the widespread occurrence of intrusive and extrusive rocks (Ofoegbu, 1985).

The Asu River Group (ARG) of Mid-Albian to Late-Albian, composed of shale, limestone with sandstone intercalation (Offodile, 1976) sits unconformably on the crystalline basement rocks (Offodile, 1976; Offodile and Reyment, 1978). At various locations, the Keana Formation (made up of poorly sorted feldspathic coarse-grained sandstone that sometimes contains pebbly conglomerate) and the Awe Formation (consisting of flaggy whitish coarse-medium grained sandstone interbedded with carbonaceous shale, clay, and sandy limestone), both overlies the ARG. The Ezeaku and Awgu Formations (Offodile and Reyment, 1978) comprise black shale, sandstone, coal, and limestone. The reportedly youngest Lafia Formation is dominated by coarse-grained sandstone, loose sands, mudstone, and clay (Offodile, 1976; Offodile and Reyment, 1978).

3. Materials and method

3.1. Data acquisition

The dataset was acquired using a Flux-Adjusting Surface Data Assimilation System with 0.1 km of flight-line space, 0.5 km of tie-line space, and terrain clearance ranging from 0.08 to 0.1 km, by Fugro Airborne Surveys, Canada. The data used in this study were processed into total magnetic intensity gridded data, which were then displayed as images in colour raster format (Fig. 2). Since the data were collected at low latitudes, the magnetic data were reduced to the equator (RTE). Jain (1988) reported that RTE

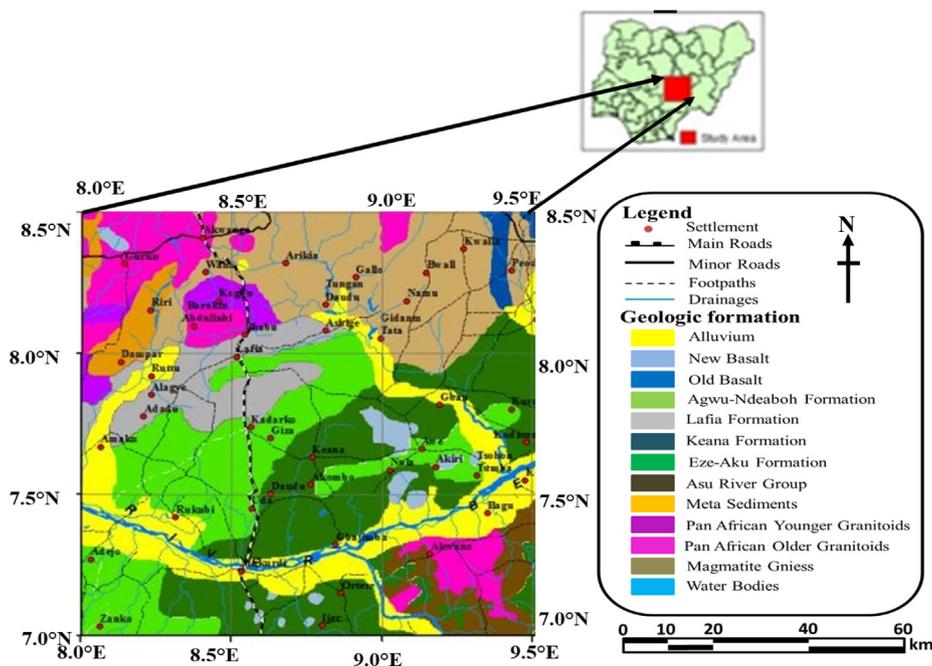


Fig. 1. Geologic map of the study area.

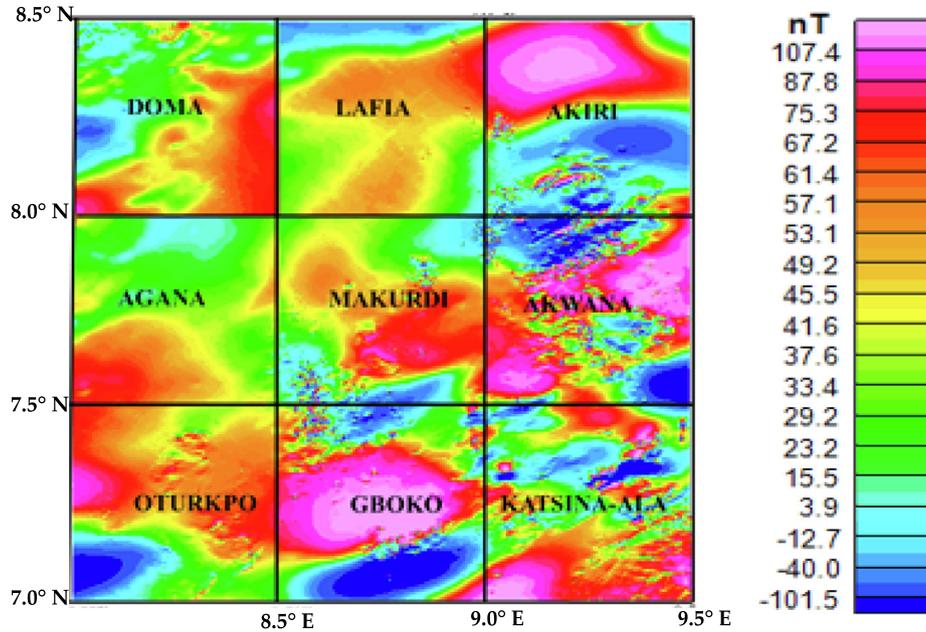


Fig. 2. (a) Total magnetic intensity map of the study area.

generates more reliable results, especially at middle and lower latitudes.

3.2. Spectral analysis of magnetic anomalies involving centroid depth method

Spectral analysis using the centroid method is a potent tool used in the determination of Curie point depth (Tanaka, 2017; Tanaka et al., 1999). It is often applied using the azimuthally averaged power spectrum of magnetic anomalies (Tanaka, 2017). The power spectra of the magnetic anomaly are expressed as:

$$\Phi_{\Delta T}(k_x, k_y) = \Phi_M(k_x, k_y) \cdot F(k_x, k_y) \quad (1)$$

where $\Phi_{\Delta T}$ and Φ_M are the power spectra of the magnetic anomaly and the magnetisation, respectively, k_x and k_y , are the wavenumbers in the direction of x and y , respectively, and

$$F(k_x, k_y) = 4\pi^2 C_m^2 |\Theta_m|^2 |\Theta_f|^2 e^{-2kz_t} (1 - e^{-k(Z_b - Z_t)})^2 \quad (2)$$

where C_m is the constant. Θ_f and Θ_m are the factors related to the geomagnetic field direction and the magnetisation direction, correspondingly. Z_t and Z_b are the top depth and bottom depth of the magnetic layer, respectively. $k = \sqrt{k_x^2 + k_y^2}$, k_x and k_y are the wavenumbers in the directions of x and y , correspondingly.

Assuming that the magnetization and geomagnetic field directions are constant, Eq. (1) can be rewritten as (Tanaka et al. 1999):

$$\Phi_{\Delta T}(k_x, k_y) = A \Phi_M(k_x, k_y) \cdot e^{-2kz_t} (1 - e^{-k(Z_b - Z_t)})^2 \quad (3)$$

where A is a constant.

Using random magnetisation models, and if magnetisation $M(x, y)$ is completely random, $\Phi_M(k_x, k_y)$ will be constant (Tanaka et al., 1999). As a result, Eq. (3) becomes:

$$\Phi_{\Delta T}(k_x, k_y) = B e^{-2kz_t} (1 - e^{-k(Z_b - Z_t)})^2 \quad (4)$$

where B is a constant. With some simplification, Eq. (4) can be used to compute the top depth Z_t of the magnetic layer. Eq. (4) approximates at short wavelengths:

$$\ln(\Phi_{\Delta T}(k_x, k_y)) = B_1 - 2kz_t \quad (5)$$

where B_1 is a constant.

The low-wavenumber portion of the power spectrum can be approximated to estimate the centroid depth (Z_c) of the magnetic layer (Tanaka et al., 1999):

$$\ln(\Phi_{\Delta T}(k_x, k_y)^{1/2} k) = B_2 - kz_c \quad (6)$$

where B_2 is a constant. When the top depth (Z_t) and centroid depth (Z_c) of the magnetic layer are gotten from Eqs. (5) and (6), respectively, the bottom depth (Z_b) can be computed as:

$$Z_b = 2Z_c - Z_t \quad (7)$$

Assuming the distribution of the magnetization in the crust is random and uncorrelated, the azimuthally averaged power spectrum can be used to calculate Z_t and Z_b by Eqs. (5)–(7).

3.3. Conductive heat flow

Fourier's law is a fundamental relationship when considering conductive heat conveyance (Tanaka et al. 1999). Fourier's law takes the following form in the one-dimensional case, assuming a vertical direction for temperature variation and a constant temperature gradient dT/dz :

$$q = k \frac{dT}{dz} \quad (8)$$

where q is described as the heat flux and k is the coefficient of thermal conductivity.

The Curie temperature (θ) can be defined as:

$$\theta = \left(\frac{dT}{dz} \right) Z_b \quad (9)$$

where Z_b is the CPD, so long as there is no heat sinks or heat sources between the Earth's surface and the CPD, the surface temperature is 0°C and dT/dz is constant. Tanaka et al. (1999) demonstrated that any given depth to a thermal isotherm is inversely proportional to heat flow. Eqs. (8) and (9) were used to calculate HF and GG values, which were based on CPD estimates derived from magnetic computations. We utilize the Curie point (θ) for magnetite (580°C) with an average thermal conductivity of 1.80 and $2.5 \text{ Wm}^{-1} \text{ K}^{-1}$ for regions

of the sedimentary shale formation and igneous rock/older granite (Abraham et al., 2019), respectively.

3.4. Results

The magnetic method is a powerful procedure in the assessment of the lateral extent of several high-temperature geothermal sources (Ben et al., 2022a, 2022b), paleo-permeability structures (Ejiga et al., 2022), and the magnitude of hydrothermally altered rocks. To map both small and large geothermal anomalies, the magnetic data (Fig. 2) used in this study were partitioned into 216 spectral blocks with 50% overlap of each block before the creation of power spectrum plot for each block. Associated parameters like CPD or Z_b , GG and HF were obtained, which were afterwards gridded in 2- and 3-D formats.

The CPD values (Fig. 3) were observed to vary from 6 to 8 km (shallow), 8–12 km (medium), and 12–16 km (deep) from magnetic data analysis. Fig. 3 indicates shallow CPD (red colour) within Gboko and Otukpo areas. Research showed that Gboko and Otukpo regions that fall within the GA dominated by granite (2.64 gcm^{-3}) and gabbro (2.90 gcm^{-3}) are the contributing effects of Abakaliki Anticlinorium (Abdullahi and Kumar, 2020). The remaining area which is dominated by medium-deep CPD is characterised by some sparsely distributed shallow CPD. The GG maps (Fig. 4) for magnetic data are characterised as low ($38\text{--}62 \text{ }^\circ\text{C/km}$), medium ($62\text{--}74 \text{ }^\circ\text{C/km}$) and high ($74\text{--}94 \text{ }^\circ\text{C/km}$), respectively. Additionally, the magnetic ($155\text{--}235 \text{ mW/m}^2$) result indicates that the Otukpo and Gboko regions are dominated by high HF. Other areas like Agana, Doma, Lafia, Akiri, and Akwana are characterized by low HF values ($95\text{--}125 \text{ mW/m}^2$). The correlated high GG (Fig. 4) and HF (Fig. 5) locations coincide with the positions (Gboko and Otukpo) of shallow CPD in Fig. 3. In general, it has been observed by Ejiga et al. (2022) and Abraham et al. (2019) that CPD and other related parameters are reliant on tectonic events.

4. Discussion

Magnetic technique is the main operational geophysical tool that can efficiently map geothermal reservoirs, and interconnected geothermal systems (Represas et al., 2013). The range of CPD ($6.0\text{--}16.0 \text{ km}$) obtained in this study differs fairly with Curie depth of $11 \pm 2\text{--}18 \pm 4 \text{ km}$ and $9\text{--}20 \text{ km}$ obtained by Abdullahi and Kumar (2020), and Abraham et al. (2019) findings, respectively. The GG range ($38\text{--}94 \text{ }^\circ\text{C/km}$) from the magnetic data are higher than the range of values ($29.0\text{--}45.8 \text{ }^\circ\text{C/km}$) previously obtained in the AA (Abraham et al., 2019; Onuoha and Ekine, 1999). The shallow CPD ($6.0\text{--}8.0 \text{ km}$) (Figs. 3 and 6) witnessed within Gboko and Otukpo indicates the signature of Santonian intrusions related to the AA (Abdullahi and Kumar, 2020; Abraham et al., 2019) that straddled into the MBT. The remaining parts within the study area are defined by medium-deep CPD ($8.0\text{--}16.0 \text{ km}$) characterised by some pockets of relatively medium-low GG and HF (Figs. 4 and 5). However, results of Moho depths from regional seismological and gravity investigations reported Moho depths of $10\text{--}20 \text{ km}$ (Abdullahi et al. 2019; Fairhead et al. 1991). Likewise, the reported HF (Fig. 6) values ($95\text{--}235 \text{ mW/m}^2$) were significantly greater than previous results (Abraham et al., 2019; Onuoha and Ekine, 1999). Generally, previous researches have shown that regions with anomalous HF values $>80 \text{ mW/m}^2$ indicate geothermal anomaly (Abraham et al., 2015; Sharma, 2004). The delineated structures (Figs. 4 and 5) within GA, which coincide shallow CPD ($<8.0 \text{ km}$) matches with high GG ($>74 \text{ }^\circ\text{C/km}$) and HF ($>155 \text{ mW/m}^2$) region. These geothermal anomalies are associated to AA (Ekwok et al., 2022a, 2021a, 2021b, 2020b). The 3-D presentation of CPD, GG and HF (Fig. 6) revealed succinctly that the GA is characterised by high geothermal potentials. The shallow CPD zones ($<8 \text{ km}$) defined by spikes (Fig. 6(a)) correlate with the positions of high GG (Fig. 6(b)) and HF and (Fig. 6(c)). Bansal et al. (2011) observed that probable geothermal regions are defined by shallow CPD, and

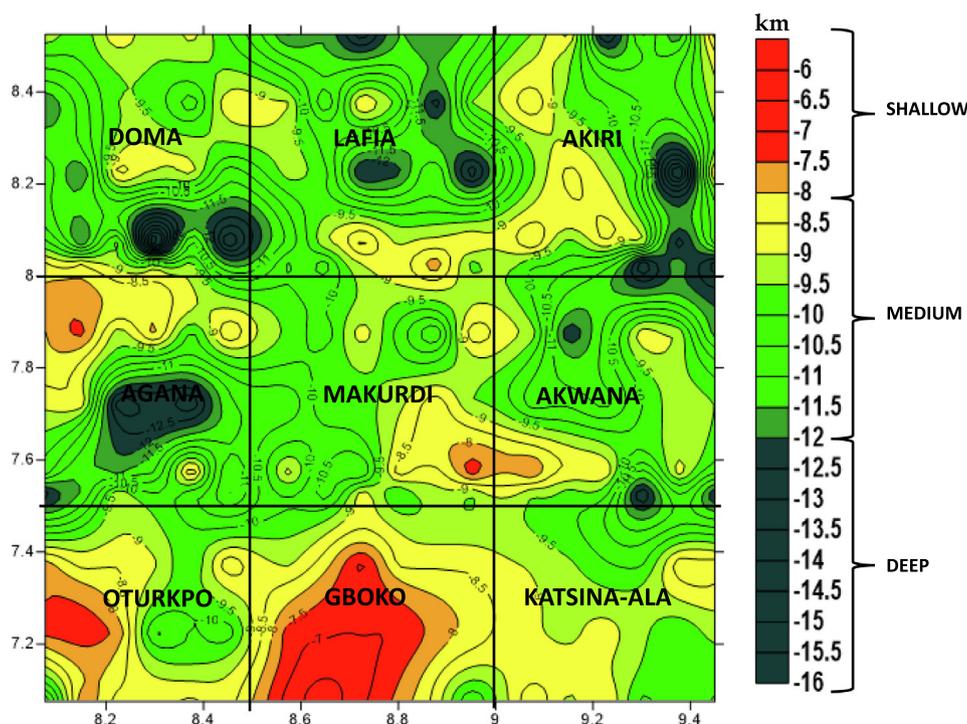


Fig. 3. Curie point depth map of the study area.

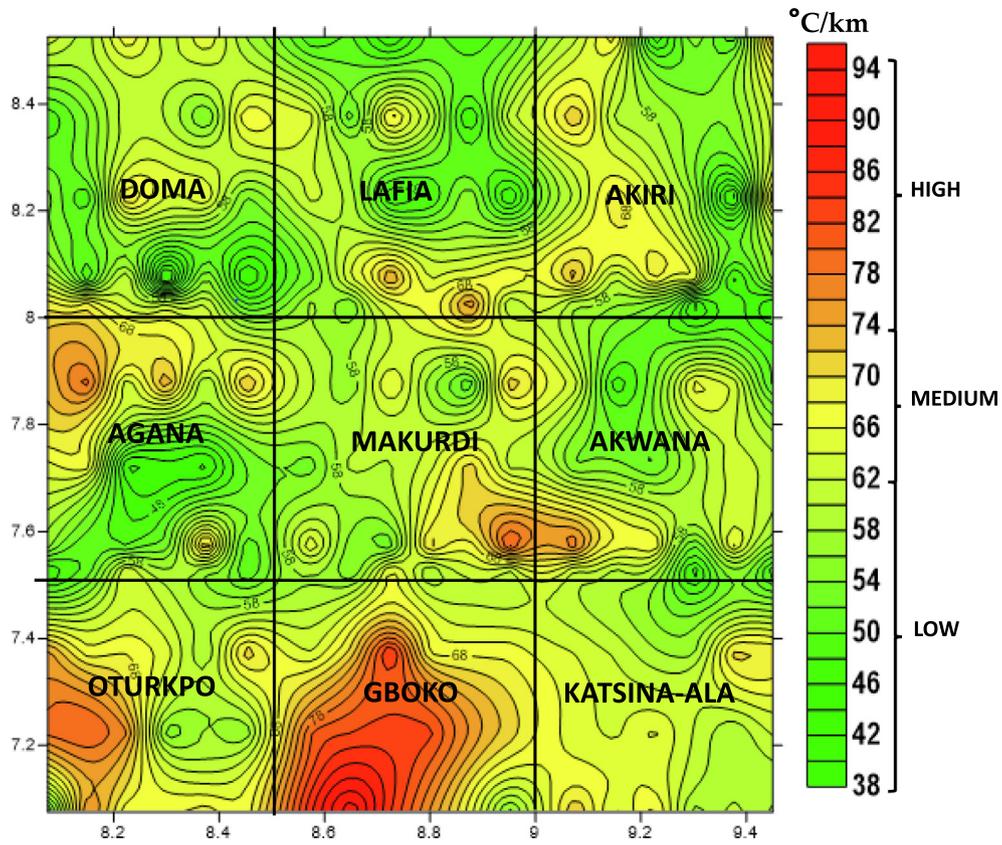


Fig. 4. Geothermal gradient map of the study area.

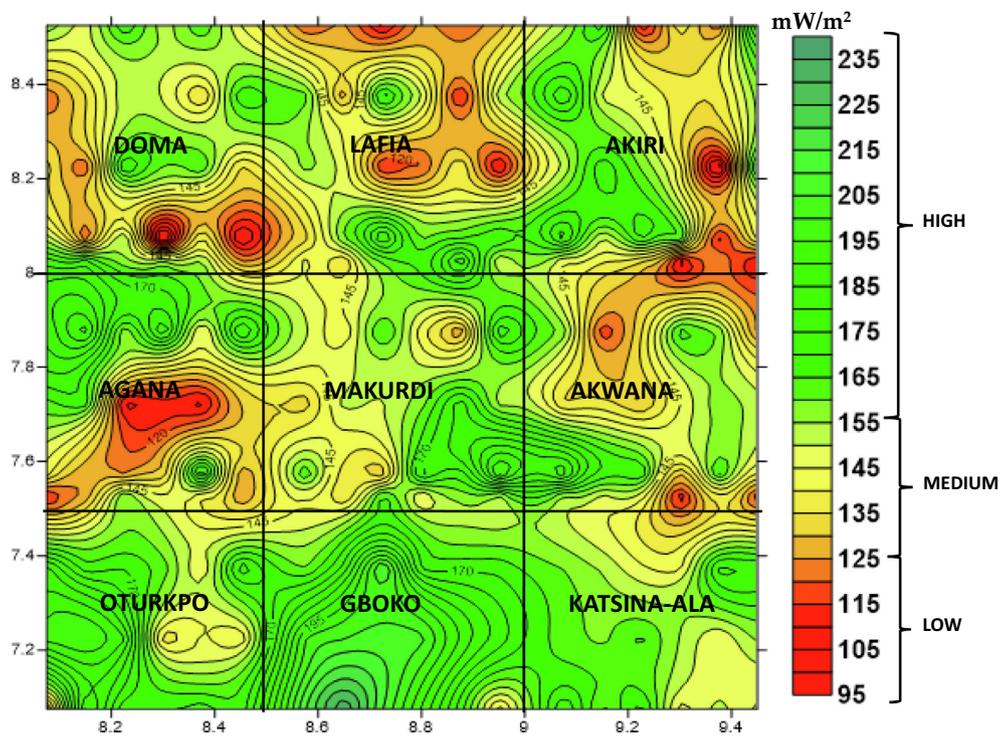


Fig. 5. Heat flow map of the study area.

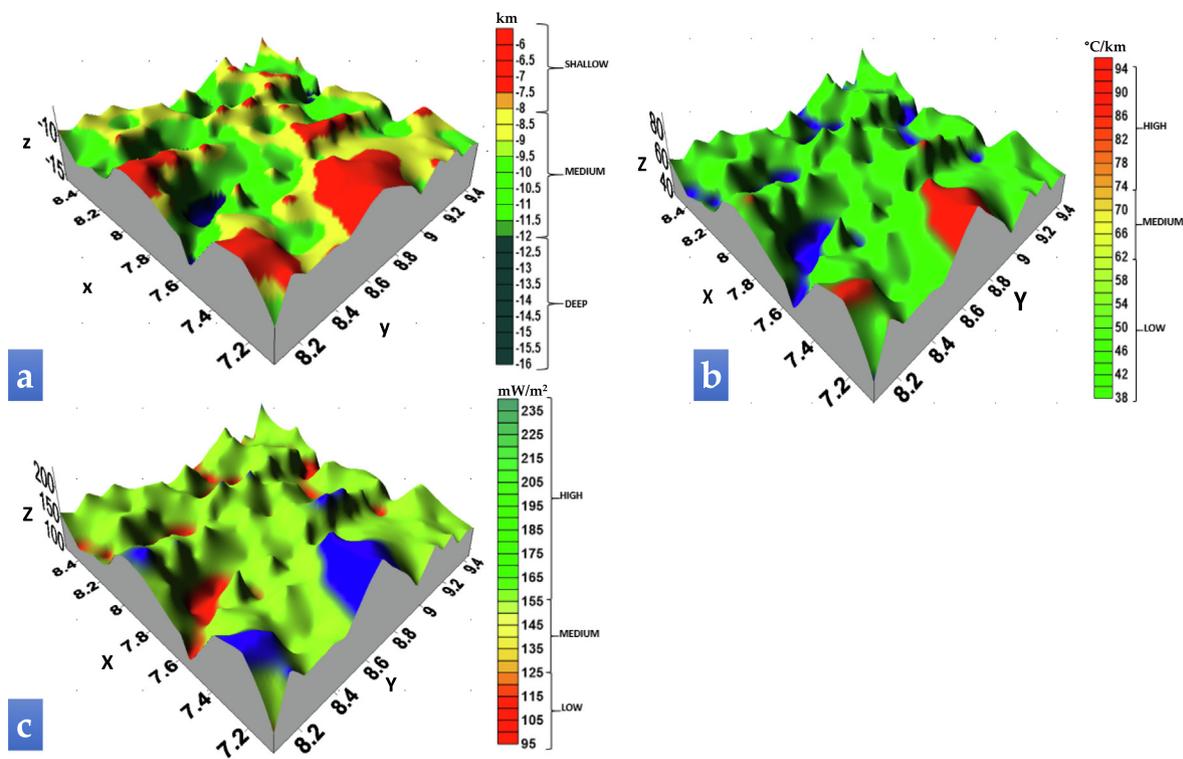


Fig. 6. (a) 3-D Curie point depth, (b) geothermal gradient, and (c) heat flow models of the study area.

high GG and HF. These main geothermal anomalies (in Gboko and Otukpo) plus the scantily distributed geothermal anomalies (Ofogebu, 1985) in the remaining parts of the study area, are thought to be the main source of brines (Ekwok et al., 2022b, 2021c, 2021a, 2019) and lead–zinc mineralisation (Ekwok et al., 2022a; Akpan et al., 2014).

5. Conclusions

In this research, CPD, GG and HF estimates of the Middle Benue Trough of Nigeria were presented. The Curie depths computed from this study vary from 6.0 to 16.0 km. The locations of shallow CPD (6.0–8.0 km) coincide with GA related to expansive Santonian intrusions of AA. The delineated geothermal zones within the GA indicate shallow CPD (<8.0 km), and high GG (>74 °C/km) and HF (>155 mW/m²) values. Other areas within the study area characterised by medium–deep CPD (8.0–16.0 km), are dominated by medium–low GG (<74 °C/km) and HF (<155 mW/m²) values. It can be concluded that this research involving magnetic data serves as reconnaissance investigation for geothermal energy resources in the MBT. Notwithstanding the successful delineation of geothermal anomalies within GA, further study involving the integration of deep boreholes, seismic, magneto–telluric, electromagnetic and geochemical data, should be carried out to further evaluate and sufficiently model the geothermal reservoir of GA and adjoining AA.

Declaration of Competing Interest

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jksus.2022.102521>.

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