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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 analyse high-resolution airborne potential field (PF) data.

^[0]► The Moho depths (Curie point depth (CPD)) within the study area is in the range of 6.0 and 15.5 km. It was observed that the Gboko Anticlines (GA) that are interrelated with the Santonian intrusions of Abakaliki Anticlinorium (AA) are characterized by thin crustal thicknesses (6.0-8.5 km). The mapped geothermal anomalies within the GA with shallow CPD (8.5 km) are dominated by the high geothermal gradient (GG) (78 °C/km) and heat flow (HF) (190 mW/m⁻²) values. The adjoining areas within the study area are defined by medium-deep Moho depths (8.5-15.5 km), medium-low GG (78 °C/km), and HF (190 mW/m⁻²) values. Further integrated geophysical investigation and subsequent exploitation programs should be sited in the delineated GA and adjoining AA.

Keywords: Magnetic method; Spectral depth analysis; Curie point depth; Heat flow; Centroid depth, Geothermal gradient.

1.0 Introduction

Nigeria is believed to be rich in geothermal energy resources, particularly, in 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 neighbourhood 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 complementary energy sources to Nigeria which is challenged with 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 focused 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 PF 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, 1995; Nwachukwu, 1976).

PF data are potent tools that can be applied to probe natural resources in the subsurface (Ejiga et al., 2022; Abdullahi and Kumar, 2020; Ben et al., 2022a; 2022b), including geothermal reservoirs. Furthermore, PF methods have been effectively used in delineating the subsurface bedrock topography, and mapping sediment-basement contacts, and geologic structures (Agagu and Adighije 1983; Adighije, 1981; Adighije, 1979), during the early phases of geothermal development. The magnetic and gravity data often applied in tandem make analyses easier, and address uncertainties during the interpretations (Mariita, 2010). Additionally, it can considerably lessen the number of drilled wells desired to appraise probable geothermal fields. PF has been reported to be the most cost-effective geophysical method for generating satisfactory models for geothermal structures (Mohammadzadeh-Moghaddam et al., 2016).

In this research, PF data which investigate various physical properties (like magnetic susceptibility and density) 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 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, while gravity data is appropriate for hydrothermal system evaluation, mapping of buried anomalies initiated by magmatic and granitic bodies as well as connected geologic structures (Ekwok et al., 2022c; 2022d; 2022e).

2.0 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, and 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 (consist 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 of 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).

3.0 Materials and method

3.1. ^[12] 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. ^[6] The data used in this study were processed into total magnetic intensity and Bouguer gravity gridded data, which were then displayed as images in colour raster format (Fig. 2). Since the data were collected at low latitude, the magnetic data were reduced to the equator (RTE). Jain (1988) reported that RTE generates more reliable results, especially at middle and lower latitudes.

3.2 Spectral analysis of PF anomalies involving centroid depth method

Spectral analysis using centroid method, is a potent tool used in the determination of Curie point depth (Tanaka et al., 2017; Tanaka et al., 1999). It is often applied using the azimuthally averaged power spectrum of PF anomalies (Tanaka et al., 2017). The power spectra of the magnetic/gravity 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/gravity anomaly and the magnetization/density, respectively, k_x and k_y , are the wavenumbers in the direction of x and y, respectively, and

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

where C_m is the constant. Θ_f and Θ_m are the factors related to the geomagnetic/gravitational field direction and the magnetization/density direction, correspondingly. Z_t and Z_b are the top depth and bottom depth of the magnetic/gravity 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.^[3]

Assuming that the magnetization/density and geomagnetic/gravitational field directions are constant, Eq. (1) can be rewritten as (Tanaka et al. 1999):^[0]

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

where A is a constant.

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

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

where B is a constant.^[3] With some simplification, equation 4 can be used to compute the top depth Z_t of the magnetic/gravity layer. Equation 4 approximates at short wavelengths:

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

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/gravity layer (Tanaka et al., 1999):

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

where B_2 is a constant. When the top depth (Z_t) and centroid depth (Z_c) of the magnetic/gravity layer are gotten from equations (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/density in the crust is random and uncorrelated, the azimuthally averaged power spectrum can be used to calculate Z_t and Z_b by equations (5)-(7).

3.2 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. Equations (8) and (9) were used to calculate HF and GG values, which were based on CPD estimates derived from magnetic/gravity computations. We utilize the Curie point (h) for magnetite (580 °C) with an average thermal conductivity of 1.80 and 2.5 Wm⁻¹ k⁻¹ for regions of the sedimentary shale formation and igneous rock/older granite (Abraham et al., 2019), respectively.

4.0 Result

PF methods are powerful procedures 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 PF data (Fig. 2) used in this study were partitioned into 216 spectral blocks with a 50% overlap of each block before the creation of a power spectrum plot for each block. Associated parameters like CPD or Z_b , GG, and HF were obtained, which were afterward gridded in 2- and 3-D formats.

The CPD values (Fig. 3) were observed to vary from 6-8 km and 6 -7.5 km (shallow), 8-12 km and 7.5 -12 km (medium), and 12-16 km and 12-14.5 km (deep) from magnetic and gravity 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 AA (Abdullahi and Kumar, 2020). The remaining area which is dominated by medium-deep CPD is characterized by some sparsely distributed shallow CPD. The GG maps (Fig. 4) for magnetic and gravity data are characterized as low ($38\text{-}58 \text{ }^\circ\text{C}/\text{km}$ and $40\text{-}60 \text{ }^\circ\text{C}/\text{km}$), medium ($58\text{-}78 \text{ }^\circ\text{C}/\text{km}$ and $60\text{-}80 \text{ }^\circ\text{C}/\text{km}$), and high ($78\text{-}94 \text{ }^\circ\text{C}/\text{km}$ and $80\text{-}96 \text{ }^\circ\text{C}/\text{km}$), respectively. Additionally, the magnetic ($195\text{-}235 \text{ mW}/\text{m}^2$) and gravity ($190\text{-}240 \text{ mW}/\text{m}^2$) results indicate 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 of $95\text{-}135 \text{ mW}/\text{m}^2$ and $100\text{-}130 \text{ mW}/\text{m}^2$ from magnetic and gravity results, respectively. The correlated high GG (Fig. 4) and HF (Fig. 5) coincide with the locations (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.

5.0 Discussion of result

PF techniques are the main operational geophysical tools that can efficiently map geothermal reservoirs, and interconnected geothermal systems (Represas et al., 2013). The range of CPD

which represents the Moho depths (6.0-15.5 km) obtained in this study varies fairly with Curie depth of 11 ± 2 – 18 ± 4 km and 9-20 km obtained by Abdullahi and Kumar (2020), and Abraham et al. (2019) findings, respectively.^[6] The GG range (38-96 °C/km) from the PF data are higher than the range of values (29.0-45.8 °C/km) obtained in the AA (Abraham et al., 2019; Onuoha and Ekine, 1999). The shallow CPD (6.0-8.5 km) (Figs. 3 and 6 (a and b)) 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 Moho depths (8.5-15.5 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 10–20 km (Abdullahi et al. 2019; Fairhead et al. 1991). Likewise, the reported HF (Fig. 6 (e and f)) values (100-230 mW/m⁻²) were significantly greater than previous results (Abraham et al., 2019; Onuoha and Ekine, 1999). Generally, previous research has shown that regions with anomalous HF values > 80 mW/m⁻² indicate geothermal anomaly (Abraham et al., 2015; Sharma, 2004). The delineated structures (Figs. 4 and 5) within GA, which coincide with shallow Moho depth (8.5 km) match with high GG (78 °C/km) and HF (190 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 characterized by high geothermal potentials. The shallow CPD zones (8 km) defined by spikes (Fig. 6 (a and b)) correlate with the positions of high GG (Fig. 6 (c and d)) and HF and (Fig. 6 (e and f)). Bansal et al. (2011) observed that probable geothermal regions are defined by shallow CPD, and high GG and HF.^[0] These main geothermal anomalies (in Gboko and Otukpo) plus the scantily distributed geothermal anomalies (Ofoegbu, 1985) in the remaining parts of the study area, are thought to be the main source of brines (Ekwok et al., 2022b; 2021c; 2020a; 2019) and lead-zinc mineralisation (Ekwok et al., 2022a; Akpan et al., 2014).

6.0 Conclusion

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 6.0-15.5 km. The locations of thin crustal thicknesses (6.0-8.5 km) coincide with GA related to expansive Santonian intrusions of AA. The delineated geothermal zones within the GA indicate shallow CPD (8.5 km), and high GG (78 °C/km) and HF (190 mW/m⁻²) values. Other areas within the study area characterised by medium-deep Moho depths (8.5-15.5 km), are dominated by medium-low GG (78 °C/km) and HF (190 mW/m⁻²) values.^[14] It can be concluded that this research involving PF 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.