https://dx.doi.org/10.4314/dujopas.v9i4a.3
ISSN (Print): 2476-8316
ISSN (Online): 2635-3490
Dutse Journal of Pure and Applied Sciences (DUJOPAS), *Vol. 9 No. 4a December 2023*

Curie Point Depth from Spectral Analysis of Magnetic Data in Potiskum and Environs, Yobe State, Nigeria

Kamureyina Ezekiel[1] Yohanna Peter[2]

[1]Department of Geology,
Adamawa State University,
P.M.B. 25,
Mubi Nigeria

[2] Department of Geography,
Adamawa State University,
P.M.B. 25,
Mubi Nigeria

Email: Kamureyina123@gmail.com

Abstract

The area under investigation, is part of Chad basin of northeastern Nigeria, located between latitudes 11°00´ to 12°00´N and Longitudes 11°30´ to 12°30´E, with the objective to discover more about the thermal structure of the crust in the area, a research was carried out over Potiskum and surrounding regions in Yobe State, Nigeria to estimate the curie point depth, geothermal gradient, and heat flow using spectrum analysis and empirical formula of aeromagnetic data. To acquire the regional and residual data, polynomial fitting was applied to the high-resolution digital aeromagnetic data. In order to calculate the depth to the centroid and the depth to the top boundary, the upward continued residual data was processed to produce the upward continued data, that was subjected to spectral analysis. The depth to the centroid is between 10.50 and 11.50 kilometers, the depth to the top boundary is between 5.90 and 7.16 kilometers, the depth to the Curie point is between 14.84 and 16.83 kilometers, the geothermal gradient is between 34.462 and 39.083 °Ckm^{-1}, and the heat flow is between 86.135 and 97.707 mWm^{-2}. The Curie point depth inferred from the study indicates that the crust is thinning due to thermal upwhirling of magma and is moderately decreasing toward areas of volcanic activity that occurred in the area during the Tertiary Period. The Geothermal gradient shows that the area is a moderate temperature zone, which could likely result in partial thermal maturation of sediments and hence probable oil generation as time goes on with an increase in temperature. In the research area, the geothermal gradient is proportional to the heat flow, whereas the connection between curie depth and heat flow is inversely linear. These findings are in line with the geotectonic regime that is now in effect in the research area. However, this analysis shows that the heat flow that was obtained from the study is sufficient to be utilized as a geothermal energy source.

Keywords: Curie point depth, Magnetic data, Potiskum and Environs

**Author for Correspondence*

INTRODUCTION

Curie point depth is the theoretical surface with a temperature of approximately 580ºC and can be considered as an index of the bottom of a magnetic source, due to ferromagnetic minerals converting to paramagnetic minerals. Geomagnetic anomalies, which are retrieved from magnetic survey data, can be utilized to study magnetic structures above the Curie point depth (Yaro *et al*., 2023; Sun *et al*. 2022; Nwankwo *et al*., 2015; Dimgba *et al*., 2020)). Meanwhile, if the temperature on the Earth's surface is also taken into account, the geothermal gradient can be constructed from the temperature difference between the Earth's surface and 580ºC, divided by the Curie point depth.

Between 2004 and 2010, a magnetic survey of all of Nigeria was conducted. Utilizing ongoing records from the closest permanent magnetic center, effects of the diurnal fluctuation at various geo-latitudes were eliminated from the magnetic data. By subtracting the magnetic field backdrop provided by the International Geomagnetic Reference Field (IGRF), the Earth's primary magnetic fields are calculated. After the diurnal variation, latitude, elevation, and IGRF corrections, all the data points are corrected for magnetic anomalies at the same time and same datum (Chu *et al*., 2022; Peinado, 2023).

Many tectonic studies have covered most parts of Nigeria, but in the study area, not much has been reported on the base tectonic knowledge in the magnetic domain. This work is to add up to the existing knowledge of the thermal structure of the crust of the area. The magnetic data were used to investigate curie point depth and thermal gradient of the area. The area under investigation is part of the Chad Basin of Northeastern Nigeria, with a total area of 12,056.04 km^2 located between latitudes 11^{o}00´ to 12^{o}00´N and Longitudes 11^{o}30´ to 12^{o}30´E (Figure 1).

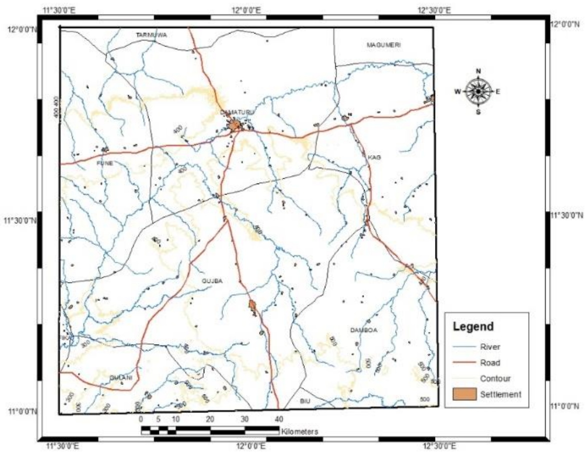

Figure 1: Topographic Map of the Area (After Digital Elevation Model, 2006).

Geology of the Area

The study region is a portion of Nigeria's Chad basin. In general, the Chad Basin is a part of a group of Cretaceous and post-Cretaceous rift basins across Central and West Africa. The early Cretaceous rift systems, when the African and South American lithospheric plates split apart and the Atlantic Ocean opened, are typically cited as the source of the phenomenon.

According to Fairhead (2023), the Cretaceous Rift system of West and Central Africa extend for over 4000 km from Nigeria northwards into Niger and Libya and eastwards through southern Chad into Sudan and Kenya. The Chad Basin with an area of about 2,335,000 km^2 (Sababa *et al*., 2023) and occupies a vast area at an altitude of between 200 m and 500 m above sea level in Central Africa. The Bornu Basin (Nigerian sector of the Chad Basin) makes up approximately 10 percent of the basin.

The geology of the study area (Figure 2) comprises sedimentary and basement areas, according to the geological map of Nigeria (2006). The sedimentary area is part of the Chad basin of northeastern Nigeria, with lithological units of Sandstones and Clay, Sandstones and Sandy Shales, Sands, Clays, Siltstones, and Limestone. While the basement area is unified into: Mylonites interlayered with Amphibolite and undifferentiated Granite-Migmatite and Granites.

MATERIALS AND METHODS

Data

The magnetic anomaly data (Figure 3) were acquired from the Nigerian Geological Survey Agency Abuja. To avoid the high-frequency noise caused by tiny structures near the ground, magnetic anomalies were filtered using polynomial fitting and upward continuation filters to obtain Regional magnetic data, Residual magnetic data, and upward continuation data.

Regional Residual Separation

The magnetic anomaly data (Figure 4) and the remaining information (Figure 5) were obtained from regional residual separation using polynomial filtering. In polynomial fitting, a low-order mathematical polynomial corresponds with the regional to reveal the residual properties as random mistakes. The method depends on statistical theory. The mathematically defined surface with the tightest fit to the magnetic field that can be achieved within a given level of detail is computed using the observed data, typically using the least squares method. This surface is considered to be the regional field and the residual is the difference between the magnetic field value thus determined (Ezekiel, 2019, Ezekiel *et al.*, 2018).

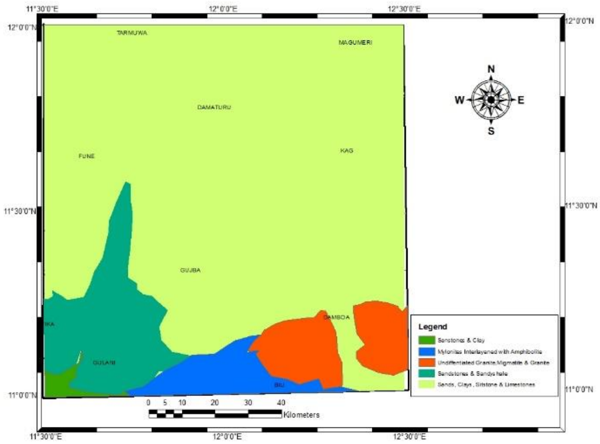

Figure 2: Geologic Map of the Area
(After Nigerian Geological Survey Agency, 2006).

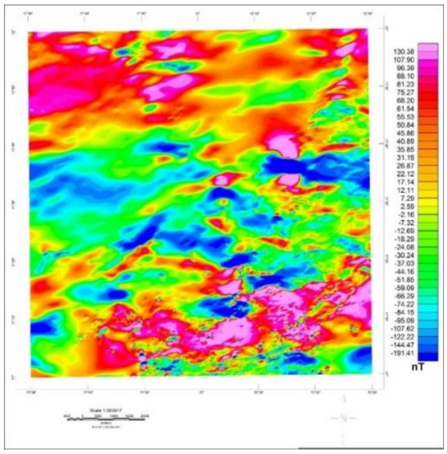

Figure 3: Map showing the Area's
Overall Magnetic Anomalies

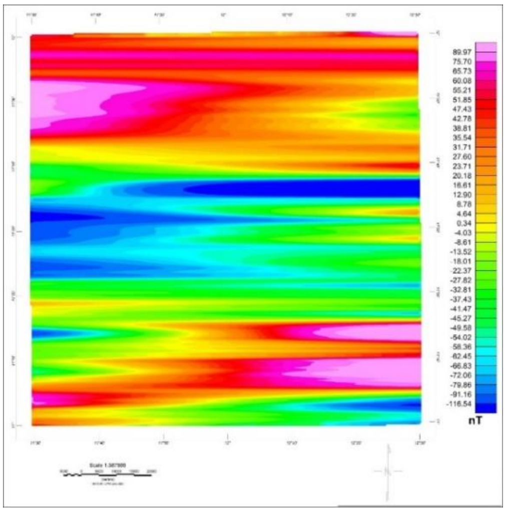

Figure 4: Regional Anomaly Map of the Area

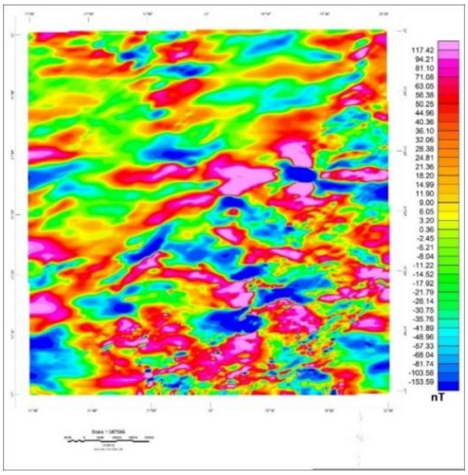

Figure 5: Residual Anomaly Map of the Area

Upward Continuation

The Residual data was upward continued to 3km to suppress near surface anomalies to enhance deep-seated regional anomalies and to obtain the upward continued data (Figure 6). By reducing the influence of local features, upward persistence is utilized to streamline the appearance of regional magnetic maps. The prevalence of local magnetic anomalies frequently masks geographic characteristics with excessive detail. Thus, upward progression smoothed out these turbulences without degrading the primary regional traits. The major goal of upward continuation is to observe the magnetic field intensity above flight level in order to highlight longer wavelength anomalies that reflect local features and eradicate short wavelength abnormalities. The equation of upward continuation is given by Xiong *et al.* (2023). The upward continued F (magnetic anomaly) at a higher level ($Z = -h$) is given by:

$$F(x, y, -h) = \frac{h}{2\pi} \iint \frac{f(x,y,0)\partial x \partial y}{(x-x')^2+(y-y')^2+h^2)^{½}} \qquad (1)$$

Where $F(x, y, -h) = total\ field\ at\ a\ point\ \ F(x', y', -h)\ above\ the\ surface\ on\ which\ F(x', y', -0)\ is\ known.\ h = continuation\ height$. This function decays steadily with increasing wave number, attenuating the higher wave number associated with such features and enhancing, relatively the anomalies of the deep-seated sources because this form continuation effectively smoothens the anomaly, by suppressing the short wavelength components.

Spectral Analysis

The upward continued data was analyzed using the spectral analysis method to estimate Curie point depth. The basic 2-D spectral analysis method was described by Tarshan *et al.* (2023). They estimated the depth to the top of magnetized rectangular prisms (Z_t) from the slope of the log power spectrum. Ukwuteyinor *et al.* (2023) further calculated the depth of the centroid of the magnetic source bodies (Z_0). Ukwuteyinor *et al.* (2023) developed a method to estimate the bottom depth of the magnetic bodies (Z_b) using the spectral analysis method of Tarshan *et al.* (2023). Following the method presented by Geng *et al.* (2023), it was assumed that the layer extends infinitely in all horizontal directions. The depth to a magnetic source's upper bound is much smaller than the magnetic source's horizontal scale, and the magnetization M(x, y) is a random function of x and y. Seritan *et al.* (2023) introduced the power-density spectra of the total-field anomaly.

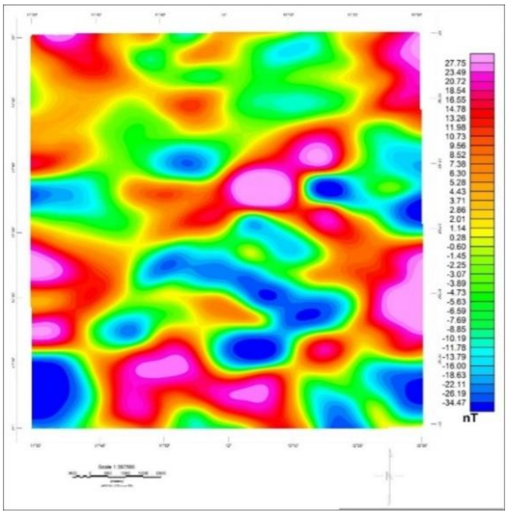

Figure 6: Upward Continued Map of the Area

To enhance the regional source for Curie point depths, geothermal gradient, and heat flow, the residual data for this study was divided into 4 square grids, each of which was 30' x 30', or 54.9 km x 54.9 km in size. This was done by extending the upward data upward to 3 km. Based on spectral analysis of the upward continuous data to establish the depths to the top (Z_t) boundary and centroid (Z_o), the Curie point depth was estimated. The spectrum data for each block was imported to MATLAB as radial SPC files after each block's spectral analysis was completed using the MAGMAP module in the Oasis Montaj environment. The depth to the upper boundary (Z_t) and the centroid (Z_o) of the magnetic bodies were estimated from the slope of the log power spectrum by fitting a straight line through the steepest and gentle wave number parts of the averaged frequency scaled power spectrum (Figure 7).

Curie Point Depth

Curie point depth is estimated in two steps (Yaro *et al.*, 2023; Mohammed *et al.*, 2023): to perform the analysis the first step is to estimate the depth to the centroid (Z_o) of the magnetic source from the slope of the longest part of the wavelength spectrum.

$$In[\frac{p(s)^{½}}{/s/}] = InA - 2\pi/s/Z_o \quad (2)$$

where $p(s)$ is the radially average power spectrum of the anomaly, $/s/$ is the wave number and A is a constant. The second step is the estimation of the depth to the top boundary (Z_t) of that distribution from the slope of the second longest wavelength special segment (Mohammed *et al.*, 2023).

$$Inp[(s)^{½}] = InB - 2\pi/s/Z_t \quad (3)$$

where B is the sum of the constant, the basal depth independent of $/s/$.

Then basal depth (Z_b) of the magnetic source is calculated from equation (4)

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

The basal depth (Z_b) of the magnetic source in the area is assumed to be the Curie point depth (Yaro *et al.*, 2023). The Curie point depth was estimated using equation 4 (Table 1).

Geothermal Gradient and Heat Flow

Heat flow is the movement of heat (energy) from the interior of the earth to the surface. The source of most heat comes from the cooling of the earth's core and the radioactive heat generation in the upper 20 to 40 km of the earth's crust. According to Abdullahi et al. (2014), the basic relationship for conductive heat flow is the Fourier's law. The estimation of heat flow and thermal gradient was calculated using Fourier's Law with the following formula:

$$q = \lambda[\frac{\partial T}{\partial Z}] \quad (5)$$

To relate the Curie point depth (Z_b) to Curie point temperature variation, the vertical direction of temperature variation and the constant thermal gradient were assumed. The geothermal gradient $\left(\frac{\partial T}{\partial Z}\right)$ between the earth and the Curie point depth (Z_b) was defined by the equation:

$$\frac{\partial T}{\partial Z} = \frac{580°\mathrm{C}}{Z_b} \tag{6}$$

where 580⁰C is the Curie temperature at which ferromagnetic minerals are converted to paramagnetic minerals. Furthermore, the geothermal gradient was related to heat flow (q) using the formula:

$$q = \lambda\left(\frac{\partial T}{\partial Z}\right) = \lambda\left(\frac{580°\mathrm{C}}{Z_b}\right) \tag{7}$$

where λ is the coefficient of thermal conductivity. A thermal conductivity of 2.5 $Wm^{-1}\,{}^{0}C^{-1}$ was used (Abdullahi et al. (2014)) as the average for igneous rocks, was used to compute the subsurface heat flow. In the above equation the Curie point is inversely proportional to the heat flow (Mohammed *et al.*, 2023; Abdullahi et al., 2014). The geothermal gradient and heat flow was calculated using Equation 7 (Table 2).

RESULTS

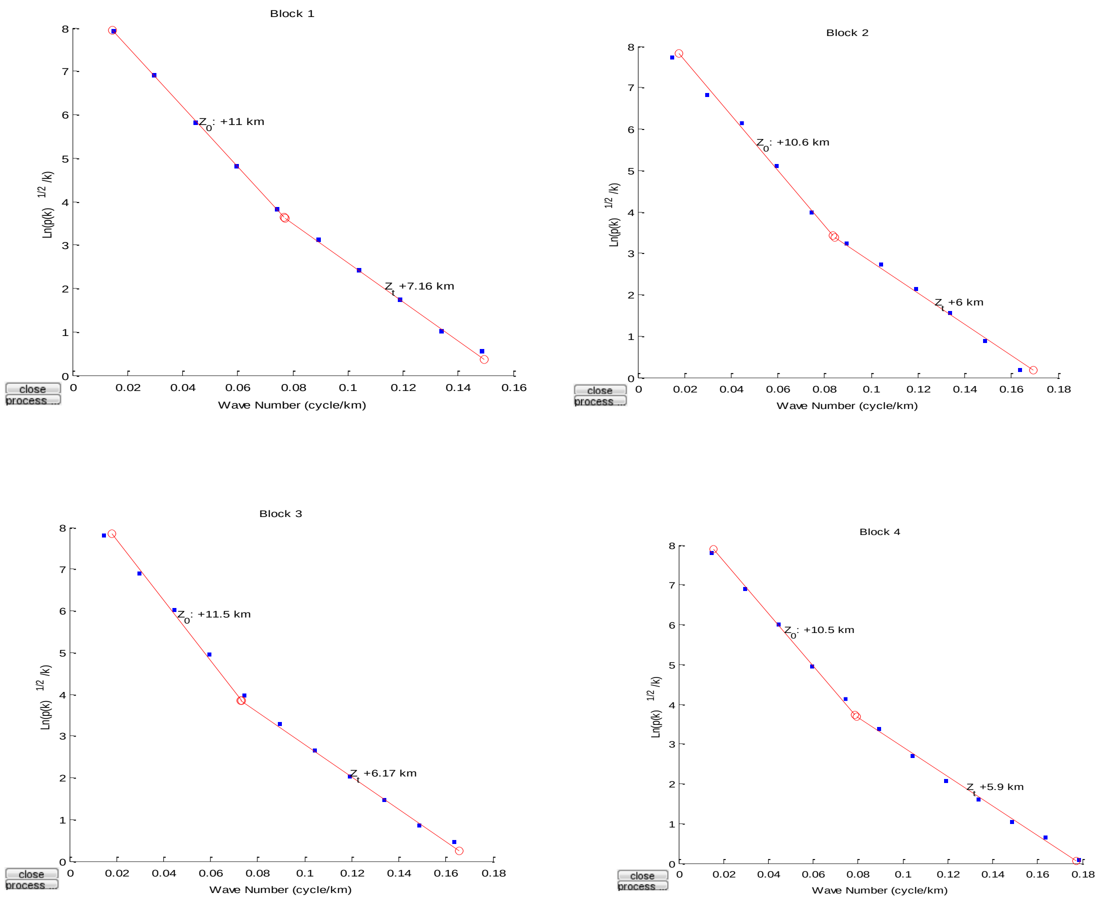

Figure 7: Spectral Blocks 1 to 4.

Table 1: Calculated average Curie point depth from graphs of the logarithms of spectral energies of blocks 1 to 4 in kilometers.

Block	Longitude	Latitude	Z_o	Z_t	Z_b
1	11°45´E	11°45´N	11.00	7.16	14.84
2	12°55´E	11°45´N	10.60	6.00	15.20
3	11°45´E	11°15´N	11.50	6.17	16.83
4	12°15´E	11°15´N	10.50	5.90	15.10
Total			43,60	25.23	61.97
Average			10.90	6.31	15.49

Table 2: Calculated heat flow and geothermal gradient from curie depths

Block	Longitude	Latitude	Z_o (km)	Z_t (km)	Z_b (km)	Geothermal gradient $\left(\frac{\partial T}{\partial z}\right)$ (°Ckm^{-1})	Heat flow ((q) (mWm^{-2})
1	11°45´E	11°45´N	11.00	7.16	14.84	39.083	97.707
2	12°15´E	11°45´N	10.60	6.00	15.20	38.157	95.392
3	11°45´E	11°15´N	11.50	6.17	16.83	34.462	86.155
4	12°15´E	11°15´N	10.50	5.90	15.10	38.410	96.025
Total			43,60	25.23	61.97	150.112	375.279
Average			10.90	6,31	15.49	37.528	93.820

DISCUSSION OF RESULTS

The graphs of spectral energies used to estimate the curie point depth, indicate that the depth to the Centroid (Z_o) ranges between 10.50 to 11.50km with an average value of 10.90km, while the depth to the Top Boundary (Z_t) varies between 5.90 to 7.16km with an average value of 6.31km and the basal depths (Curie point) (Z_b) varies between 14.84 to 16.83km Table 1 with an average value of 15.49 km. However, results from geothermal gradient and heat flow indicate 34.462 to 39.083°Ckm^{-1} and 86.135 to 97.707mWm^{-2} with average values of 37.528°Ckm^{-1} and 93.820 mWm^{-2} respectively. This results are similar to that obtained by Dimgba *et al., (*2020) in his study of the curie point depth and heat flow from spectral analysis of aeromagnetic data for geothermal potentials of Gubio Chad basin.

The obtained Curie point depth reflects the average local Curie depth point values beneath each block. It is observed that the curie depth of the study is moderate (14.84 to 16.83 km) compared to the other part of North Eastern Nigeria (Dimgba *et al.,* 2020; Kwaya *et al*., 2016), these reflect the thinning of the crust decreasing from the study area towards the Biu Basalts to Cameroon Volcanic Line, due to the upwelling of magma during the Tertiary Period. The Curie point obtained in this area is a good indicator for the exploration of alternative sources for power generation in this part of the area. Curie point depth in conjunction with heat flow values revealed a distinct inverse linear relationship. That is, heat flow increases with a decrease in Curie point depth. The average heat flow obtained in the study area is 93.820 mWm^{-2}, this may be considered typical of continental crust and falls within the range of established values of 80 to 100 mWm^{-2} for normal geothermal energy potential values. Heat flows in the majority of the studied locations were found to be less than 100 mWm^{-2}, which is consistent with the Curie point depth values obtained in this region (Dimgba *et al.,* 2020; Nwobodo *et al*., 2018; Kwaya *et al*., 2016).

The quantitative change in Curie depth shown in Table 2 suggests that the heat flow in the studied area is more or less uniform, which may be due to the constituent minerals that make up the rocks and thus their thermal conductive characteristics. The calculated geothermal gradient in the study area varies between 34.462 to 39.083°Ckm^{-1} with an average of 37.528°Ckm^{-1}. Measurements have also shown that a region with significant geothermal energy is characterized by an anomalously high-temperature gradient and heat flow. It is expected that geothermal active areas are associated with shallow Curie points. The result of heat flow obtained from this study implies that the area has the potential for geothermal energy with an average value of 93.820mWm^{-2}, which is within the recommended range of 80 to 100 mWm^{-2} according to Nwankwo *et al.* (2015); Dimgba *et al.* (2020).

CONCLUSION

The results of the spectral assessment of the aeromagnetic data over Potiskum and Environs Northeastern Nigeria showed that the Curie point depth inferred from the study indicates that the crust's thinning due to thermal upwhirling of magma is moderately decreasing toward areas of volcanic activity that occurred in the area during the Tertiary Period. The Geothermal gradient shows that the area is a moderate temperature zone, which could likely result in partial thermal maturation of sediments and hence probable oil generation as time goes on with an increase in temperature. The high heat flow observed in the area which is within the normal geothermal energy range (not anomalous) therefore is a prospective area for geothermal energy generation, if all geotechnical conditions of sitting in a geothermal plant are met.

ACKNOWLEDGEMENT

Special thanks to the Nigerian Geological Survey Agency Abuja for making available the Aeromagnetic data of Potiskum and its environs and the Geo-soft company for providing Oasis Montaj software which was used for processing the data.

REFERENCES

Abdullahi, B.U., Rai, J.K., Olaitan, O.M. and Musa, Y.A., 2014. A review of the correlation between geology and geothermal energy in North-Eastern Nigeria. *IOSR J. Appl. Geol. Geophys*, *2*(3), pp.74-83.

Chu, W., Yang, Y., Xu, S., Qin, G., Huang, J., Zeren, Z. and Shen, X., 2022. Study on Long-Term Variation Characteristics of Geomagnetic Cutoff Rigidities of Energetic Protons Caused by Long-Term Variation of Geomagnetic Field. *Frontiers in Earth Science*, *10*, p.818788.

Dimgba, B.C., Obiora, D.N., Abangwu, J.U. and Ugbor, D.O., 2020. Study of Curie point depth and heat flow from spectral analysis of aeromagnetic data for geothermal potential of Gubio, Chad Basin, Nigeria. *SN Applied Sciences*, *2*, pp.1-9.

Ezekiel, K., 2019. Geothermal Study over Sokoto Basin Northwestern, Nigeria. International Journal of Engineering Science Invention. 8(5), pp. 34-48.

Ezekiel, K., Abdullahi, A.R., Kasidi, S. and Joshua, P.T., 2018. Analysis of High-Resolution Aeromagnetic Data over Isah and Environs, Northwestern Nigeria. Adamawa State University Journal of Scientific Research. 6(1), pp.81-87.

Fairhead, J.D., 2023. The Mesozoic West and Central Africa Rift System (WCARS) and the older Kandi Shear Zone (KSZ): Rifting and tectonics of North Africa and South America and fragmentation of Gondwana based on geophysical investigations. *Journal of African Earth Sciences*, *199*, p.104817.

Geng, M., Ali, M.Y., Fairhead, J.D. and Saibi, H., 2023. The Curie depths of the United Arab Emirates: Implications for regional thermal structures and tectonic terranes. *Tectonophysics*, *848*, p.229721.

Kwaya, M.Y., Kurowska, E. and Arabi, A.S., 2016. Geothermal gradient and heat flow in the Nigeria sector of the Chad basin, Nigeria. *Computational Water, Energy, and Environmental Engineering*, *5*(02), p.70.

Mohammed, A., Adewumi, T., Kazeem, S.A., Abdulwaheed, R., Adetona, A.A. and Usman, A., 2019. Assessment of geothermal potentials in some parts of upper Benue Trough northeast Nigeria using aeromagnetic data. *Journal of Geoscience, Engineering, Environment, and Technology*, *4*(1), pp.7-15.

Nwankwo, L.I., 2015. Estimation of depths to the bottom of magnetic sources and ensuing geothermal parameters from aeromagnetic data of Upper Sokoto Basin, Nigeria. Geothermics, 54, pp.76-81.

Nwobodo, A.N., Ezema, P.O. and Ugwu, G.Z., 2018. Determination of the curie point depth, geothermal gradient and heat flow of Guzabure and its environs, Chad basin, Nigeria using Aeromagnetic data. *International Journal of Scientific and Engineering Research*, *9*(3), pp.1876-1890.

Peinado Otero, J.A., 2023. Analysis and interpretation of regional geophysical data in the region of the Paleoproterozoic Lynn Lake Greenstone Belt, Manitoba province, Canada.

Sababa, E., Ekoa Bessa, A.Z., Aye, B.A., Loubahndem, A.S.B. and Welba, M., 2023. Alluvial sediments in Bol area (Lake Chad Basin): implications for source area-weathering and tectonic settings. *Journal of Sedimentary Environments*, pp.1-24.

Seritan, M.R. and Garrick-Bethell, I., 2023. Volcanic thermal demagnetization of the Reiner Gamma magnetic anomaly. *Icarus*, p.115601.

Sun, S., Du, J., Zhi, J., Chen, C. and Xu, H., 2022. A Constrained Approach by Curie Point Depth Estimation for the 3-D Inversion of Regional Lithospheric Magnetic Anomaly Data in Spherical Coordinates and Its Application to the Northern Xinjiang, China. *Journal of Geophysical Research: Solid Earth*, *127*(8), p.e2021JB023149.

Tarshan, A., Azzazy, A.A., Mostafa, A.M. and Elhusseiny, A.A., 2023. Determination of Curie Point Depth and Heat Flow Using Airborne Magnetic Data over the Kom-Ombo and Nuqra Basins, Southern Eastern Desert, Egypt. *Geomaterials*, *13*(4), pp.91-108.

Ukwuteyinor, B.U. and Ezeh, C.C., 2023. Evaluation of depth to basement, Heat Flow, and Lead-Zinc mineralization from analysis of aeromagnetic data in some parts of Southern Benue Trough. *Evaluation*, *13*(2).

Xiong, X., Deng, K.L. and Wu, T.Q., 2023, May. Comparing the spatial domain and frequency domain algorithms for upward continuation of marine magnetic anomaly. In *Journal of Physics: Conference Series* (Vol. 2486, No. 1, p. 012065). IOP Publishing.

Yaro, U.Y., Abir, I.A. and Balarabe, B., 2023. Determination of Curie point depth, heat flow, and geothermal gradient to infer the regional thermal structure beneath the Malay Peninsula using de-fractal method. *Arabian Journal of Geosciences*, *16*(1), p.84.