https://dx.doi.org/10.4314/dujopas.v9i3b.34
ISSN (Print): 2476-8316
ISSN (Online): 2635-3490
Dutse Journal of Pure and Applied Sciences (DUJOPAS), *Vol. 9 No. 3b September 2023*

Determination of Thermal Structure of the Crust Beneath the Gongola Basin, Upper Benue Trough, Nigeria

Abdullahi Ali [1], Babangida M. Sarki Yandoka [2], Usman Yahaya Yaro [3], Bagare A.A.[4], Sani Ado Kasim [2], M.K. Ayuba [5]

[1] Department of Physics,
Faculty of Physical Science,
Bayero University Kano,
Nigeria

[2] Department of Geology,
Faculty of Earth & Environmental Sciences,
Bayero University Kano

[3] Department of Geology, Faculty of Sciences,
Abubakar Tafawa Balewa University,
Bauchi

[4] Department of Physics, Faculty of Science,
Yobe State University,
Nigeria

[5] Department of Geology,
Federal University of Dutsin-Ma,
Katsina State

Email: alicxo66@gmail.com, bmsyd.geo@buk.edu.ng

Abstract

Geothermal energy resources have been established globally to be among the sustainable and environmentally harmless means of energy generation. The data for this study came from the Earth Magnetic Anomaly Grid 2 version 3 (EMAG2V3). It was acquired at a flying elevation of 4 km above the ellipsoid and has a resolution of 2-arc minutes (3.66 km). This research aim to study the thermal structure of the crust beneath the Gongola Basin so as to determine the heat flow, geothermal gradient and the Curie point depth. In this study, the creation of an air satellite magnetic map of the Gongola Basin is accomplished through the use of a fractal magnetization approach. However, Curie point depth (commonly known as bottom most of magnetic sources depth) measure the distance between two points in space, depth to bottom magnetic source (DBMS). Geothermal characteristics of the area was evaluated using Oasis Montaj. So the earth magnetic field is utilized to determine the depth of anomalous sources that ranges from few meters to tens of kilometers. The top depth ranges from 3.4465km to 10.942km, the centroid depth ranges from 14.045km to 31.338km, the geothermal gradient ranges from 10.2566^{O}c/km to 23.4445 ^{O}c/km and the heat flow ranges from 25.6415mW/m^2 to 58.84 mW/m^2. The study identify a point (11°63E, 10°12N) with optimal values (26.44^{O}C/km, 66.11mW/m^2) at a distance 21.9km which is above the typical optimal values obtained in stable continental craton as obtainable in African plate.

Keywords: Curie Point; Geothermal Gradient; Gongola Basin; Thermal Structure

---

**Author for Correspondence*

INTRODUCTION

Geothermal energy has continued to gain attention in the global community as an alternative to environmentally harmful fossil fuels (Yusuf, Sani, and Abiri, 2022). In many countries, geothermal energy currently contributes to a substantial percentage of their energy generation (Baioumy et al. 2014). Despite several attempts by geoscientists to study geothermal potentials in many parts of the world, some information regarding the crustal temperature contents of certain regions are not thoroughly understood (Abraham et al. 2019; Obande et al. 2014). Geoscientists frequently utilized field geological mapping techniques with the aim of examining the sedimentary basin structural geological settings (e.g. Isyaku, 2018). Some of the most widely utilized geophysical tools are Seismic, Gravity and Magnetic techniques. Due to the fact that the density difference between Basement Rocks and sediments closely resembles a hyperbolic function, gravity methods for calculating basement depth are ruled out. Spectral methods have been used to figure out how far away magnetic sources are at the top and bottom.

These studies assumed that the crust has completely uncorrelated random magnetization. Scholars look at the shape of the power spectrum of geo-magnetic anomalies and figure out how far away the top and bottom of a magnetic layer are. The magnetization of the crust is more akin to fractal behavior. Therefore, magnetic properties are fractal in nature, and most borehole data fit this fractal behavior well. The magnetic properties of the underlying rocks generate anomalies in the Earth's magnetic field, which are employed in a magnetic survey to examine subsurface geology (Mono et al., 2018; Isyaku, 2018). The purpose of a magnetic survey is to investigate subsurface geology by analyzing anomalies in the Earth's magnetic field induced by the magnetic properties of the underlying rocks (Likkason, 2014). Complete crustal section may be mapped at a variety of sizes, from the strongly magnetic basement at a very large scale to the weakly magnetic sedimentary contacts at a tiny scale. Despite the obvious benefits, because of the field's dipolar structure and additional polarization effects, interpretations of magnetic data lack uniqueness.

Geologic limitations, on the other hand, can significantly minimize the level of uncertainty. Magnetic surveys collect data from rock unit's deep underground as well as those at or near the surface (Likkason, 2014). Abraham et al., (2015) used the fractal causes distribution method on aeromagnetic data to figure out the geothermal system of the Wikki Warm Spring region. He estimated the depth to bottom of magnetic sources (DBMS). The chosen computational method is based on statistical methods for determining depth from the radial power spectrum, with a fractal distribution of magnetic sources assumed. The acquired data indicate an average thermal gradient and heat flow value, indicating shallow DBMS in the northeastern region of the WWS (Wikki Warm Spring) area and increase toward the southwestern region when regional variation patterns of estimate depths are studied.

The usually shallow DBMS is attributed to magmatic intrusion in the subsurface, and it highlights the presence of large-scale tectonic events, notably the basin-initiating event, in shaping thermal history. The data will aid in determining where additional geothermal energy exploration in the area should be dug (boreholes). Also, (Nwankwo & Shehu, 2015) used spectral analysis of recently acquired high resolution aeromagnetic (HRAM) data of the entire Sokoto Basin in northwestern Nigeria, to evaluate Curie-point depths, geothermal gradients, and near-surface heat flow. Magnetic source depth at the top, centroid, and bottom are determined by analyzing each of the twenty-two (22) overlapping blocks of the HRAM data using the spectral centroid approach. The depth readings were used to calculate the geothermal gradient, Curie-point depth (CPD), and near-surface heat flow in the research area. Such heat flow values suggest that there are unusual geothermal conditions in the basin, and they should be high chances for geothermal exploration in the area. Spring et al., (2014) evaluate the geothermal potential of the WWS area using aeromagnetic data. The magnetic sources' distance from the top and centroid of the study region was determined using the spectral approach.

The power spectrum of magnetic anomalies had to be used to estimate the basal depth of the anomalies. Heat flow measurements averaged 170 milliwatts per meter, with an estimated CPD of 8 kilometers and a geothermal gradient of 68 °C/km. Section, (2002) employed the use of new high-resolution aeromagnetic data by applying the spectral analysis method for estimating the CPD, temperature gradient, and the heat flow data. Yusuf, Sani, and Abiri, (2022) determined the Curie-point depths (CPD), temperature gradients, and heat flw data over the Gongola Basin area but computed using a spectral analysis method in order to have a preliminary view of the geothermal implications (prospect) of the area. The study however, was unable to employ the use fractal analysis method.

In the study, we used the fractal spectral approach to determine how the magnetic basement's depth varies in specific regions of the Gongola Basin, such as in the north. In what follows, we start by introducing the known sedimentary basins in the study area. Then, we explain the spectral method and show how it can be used to figure out the depth of the magnetic basement using a set of synthetic result. There are a lot of factors that can change how the CPD is estimated. Using the fractal spectral method to figure out the CPD isn't a good way to do this. Later, we show the magnetic basement map of the Gongola Basin and look at other geological data to figure out what it means. However, this study's objective is to ascertain the crust's thermal condition from the Curie Point Depths (CPDs). The CPD is the depth at which, as a result of rising temperature, the dominant magnetic mineral in crust transitions from a ferromagnetic to a paramagnetic condition. It depicts the rough heat flow of the crust across the study area (e.g Spring et al., 2014). High Resolution Aeromagnetic Data acquired by the Nigerian Geological Survey Agency (NGSA) in the year 2009 was used for the research.

THEORICAL BACKGROUND

The power spectrum of a scaling distribution is frequency dependent in contrast to the white noise which is frequency independent, and it is conceptually defined as:

$$P(K) = AK^{-\beta} \qquad 1$$

P stands for power spectrum, k for wave number, and A stands for constant. The scaling exponents' values show the degree of correlation; the higher the value, the stronger the long-range correlation. Curie point depth calculations are done using Fourier domain methods on aeromagnetic data, assuming a random and uncorrelated distribution of sources. Few recent research has suggested that fractal distribution of sources can be better estimated in detail. There are two methods used in estimating Curie point depth CPD, which are:

- The centroid method
- Fractal magnetization method

Two steps are involved in estimating the Curie point depth using the centroid method: (a) computing centroid depths from the power spectrum of magnetic field data, and (b) converting those centroid depths to Curie depths (Bansal et al., 2016). This method expresses the power spectrum of the entire magnetic field in terms of the top depth and thickness of the magnetic body (Blakely, 1996). The magnetic anomaly can be defined as

$$P(K_x, K_y) = 4\pi^2 C_m^2 \varphi_m(K_x, K_y) |\theta_m|^2 |\theta_f|^2 e^{-2|k|z_t} \times \left(1 - e^{-|k|(z_b - z_t)}\right)^2 \qquad 2$$

K_x and K_y are the respective wavenumbers, C_m is the constant of proportionality, φ is the power spectrum of magnetization and geomagnetic field, Z_t and Z_b are the top to bottom depth respectively. Θ_m and Θ_f becomes constant by taking the radial average, as equation 2 becomes

$$P(K) = A_1 e^{-2|k|z_t} \times \left(1 - e^{-|k|(z_b - z_t)}\right)^2 \qquad 3$$

The right-hand side of equation 3 remains constant for very thick magnetic bodies, and A_1 does too. As a result, the previous equation becomes:

$$P(K) = A_1 e^{-2|k|z_t} \qquad 4$$

The top depth of an anomalous magnetic body can be determined using Equation 4 above, and the centroid depth of the magnetic body can be expressed as

$$\ln\left(\frac{P(K)^{\frac{1}{2}}}{K}\right) = A_2 - |k|Z_0 \qquad 5$$

The depth that is derived using the top and centroid depths is the Curie point depth. And is expressed as follows.

$$Z_b = 2Z_0 - Z_t \qquad 6$$

Centroid has become highly popular for estimating Curie point depth from aeromagnetic data, and it is being used to estimate Curie point depth from aeromagnetic data.

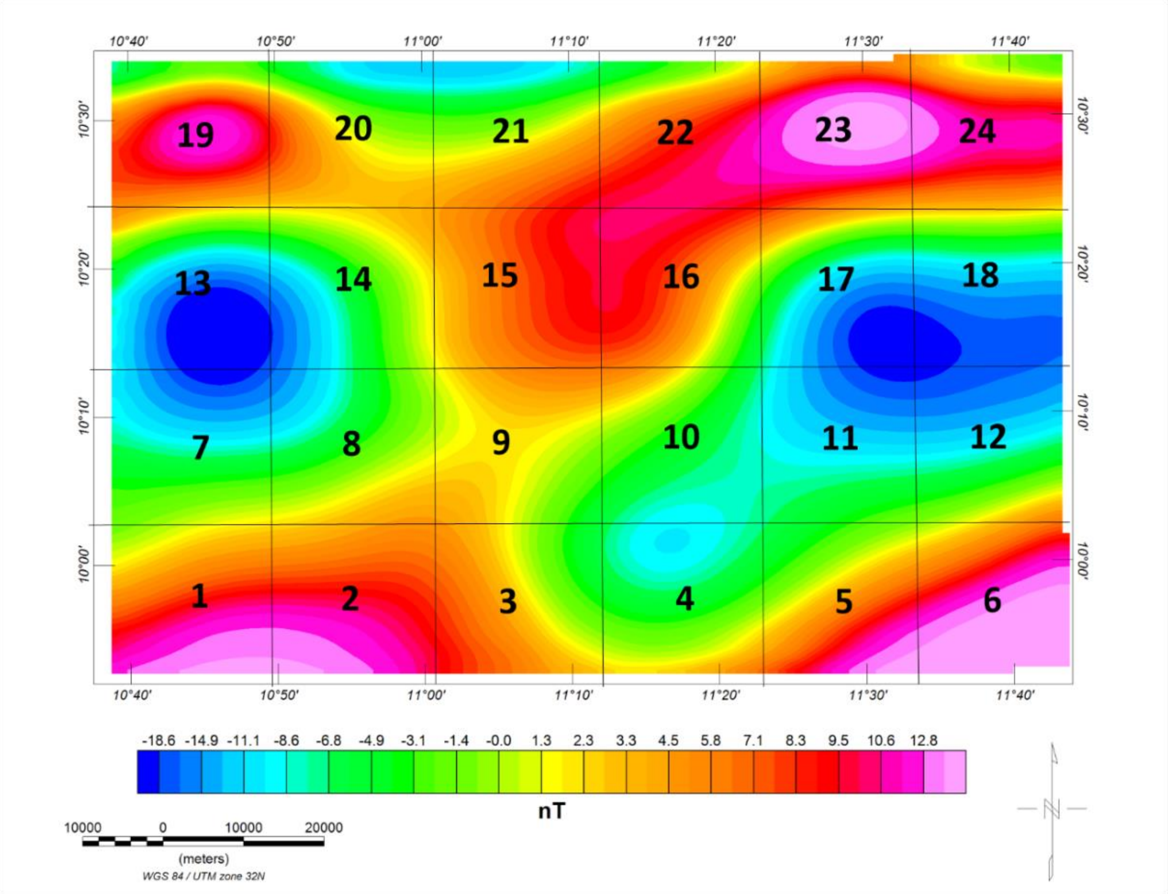

Figure 1: Map showing the 24 blocks for spectral and fractal method analysis

GEOLOGY AND LOCATION OF AREA

The earliest sedimentary rock in the Gongola Basin (Fig. 1) is the Bima Formation. It has a continental shape (braided, lacustrine, or alluvial fan). The formation is composed of sandstones, mudstones, shale, and clay. The transitional (Barrier Island/deltaic) Yolde Formation eventually buried the Bima Formation. The rock is composed of cross-bedded sandstone, shale, and clay stones. when the environment changed from a continental to a marine one. The Northern Benue Trough has two major sub-basins, branches into an E-W trending Yola arm and N-S trending Gongola basin separated by an area shallow basement rocks traversed by four major NE-SW trending sinistral Strike slip faults. The stratigraphic succession which comprises the continental Aptian – Albian Bima Formation, the Cenomanian transitional Yolde Formation.

In the Gongola Basin, the Pindiga Formation was represented by Kanawa Member, Gulani, Dumbulwa and Deba Fulani (Daban Fulani) Members. The Dukul Formation, Jessu Formation, Sekuliye Formation, Numanha Shale and the Lamja Sandstone (all of the Yola Sub-basin) are the facies equivalents of the Pindiga Formation in Gongola Sub-basin. The Gombe Formation, overlies the Campano-Maastrictian Fika Shale. In Upper Benue Trough, the Gongola Basin is an arm that runs from north to south. It is part of the Benue Trough, which runs for 1000 km. The research area lies between the Latitudes 90 52' 55''N and 100 34' 17''N and longitudes 10o 38' 37''E (Fig. 1) and 11o43' 56''E. The proposed area of study lies on the map (Abraham et al., 2015).

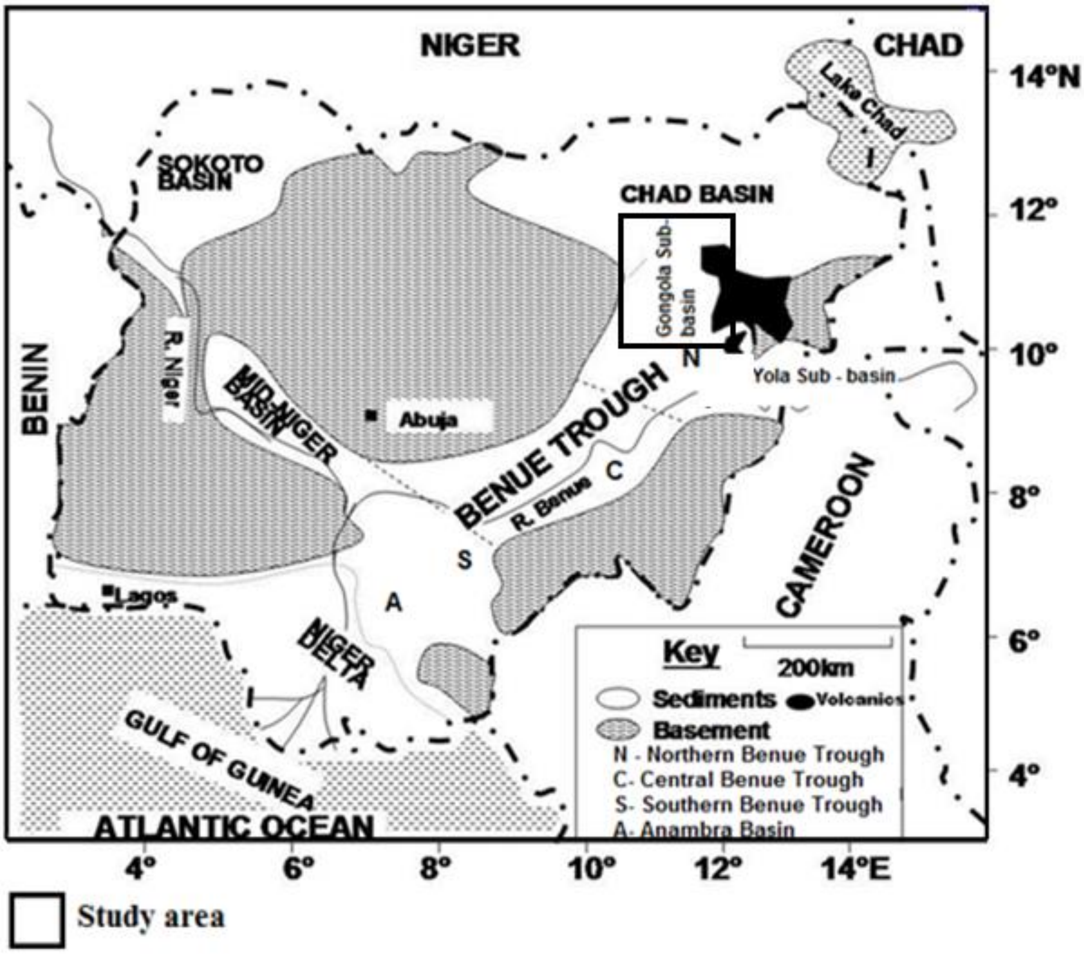

Figure 2: Geological map of Nigeria showing the study area (after Sarki Yandoka, 2015)

MATERIAL AND METHOD

Oasis Montaj is a powerful suite of modeling and analysis tools that can be used to gain a more in-depth understanding of the Earth's subsurface and sub-sea environments, among other things. Everything from ground and airborne survey geophysics to geochemistry to geology can be processed and mapped in a single dynamic 3D environment, which allows the data to be processed faster and effectively.

FRACTAL MAGNETISATION METHOD

The gravitational and magnetic forces exhibit fractal behavior, and a magnetization model was used to estimate the lowest point to the bottom of magnetic sources because magnetic susceptibility and crust magnetization, in particular, exhibit fractal properties that may be detected.(*Quintero et Al. 2019.Pdf*, n.d.). The proposed technique for estimating Curie depth for fractal distributions of sources where scaling exponents are present is based on the assumption that the power spectrum of the magnetic field is used to estimate the top depth and thickness of the magnetic body at the same time.(Bansal et al., 2016). The scaling exponent and depth component of the radial average of the power spectrum are expressed as (Bansal et al., 2016).

$$P(K) = C - 2Kz_t - tK - \beta\ln(K) + \ln\left[\int_0^\infty [\cos h(tK) - \cos(tw)]\left(1 + \frac{w^2}{k^2}\right)^{-1-\beta/2} dw\right] \tag{7}$$

where k is the wavenumber, z_t is the top depth, t is the slab thickness, and β is the source distribution scaling exponent, and w is the wavenumber in vertical plane. For predicting top depth based on the shape of the power spectrum of satellite data, the value of scaling exponents was fixed. For a reliable estimation, manual checking of the calculated parameter is required. For scaling dispersion of sources, a proposed modified centroid approach for estimating Curie depth from aeromagnetic data has been proposed. This method, which is comparable to the standard centroid method for scaling distributions of sources, computes Curie depth in two phases.

Top depth:

$$\ln\left(K^{\beta}P(K)\right) = A_2 - 2Kz_t \tag{8}$$

Centroid depth:

$$\ln\left(k^{\beta}\frac{P(K)}{K^2}\right) = A_3 - 2Kz_0 \tag{9}$$

HEAT FLOW

The essential relation for heat flow conveyance is given by Fourier law, which takes the form (Abraham, Obande, Chukwu, Chukwu, et al., 2015).

$$\boldsymbol{q = \theta\frac{dT}{dZ}} \tag{10}$$

Using the following equation, the Curie temperature (ɵ) can be calculated using the CPD z_b and the thermal gradient dT/dz.

$$\theta = \left(\frac{dT}{dZ}\right)Zb \tag{11}$$

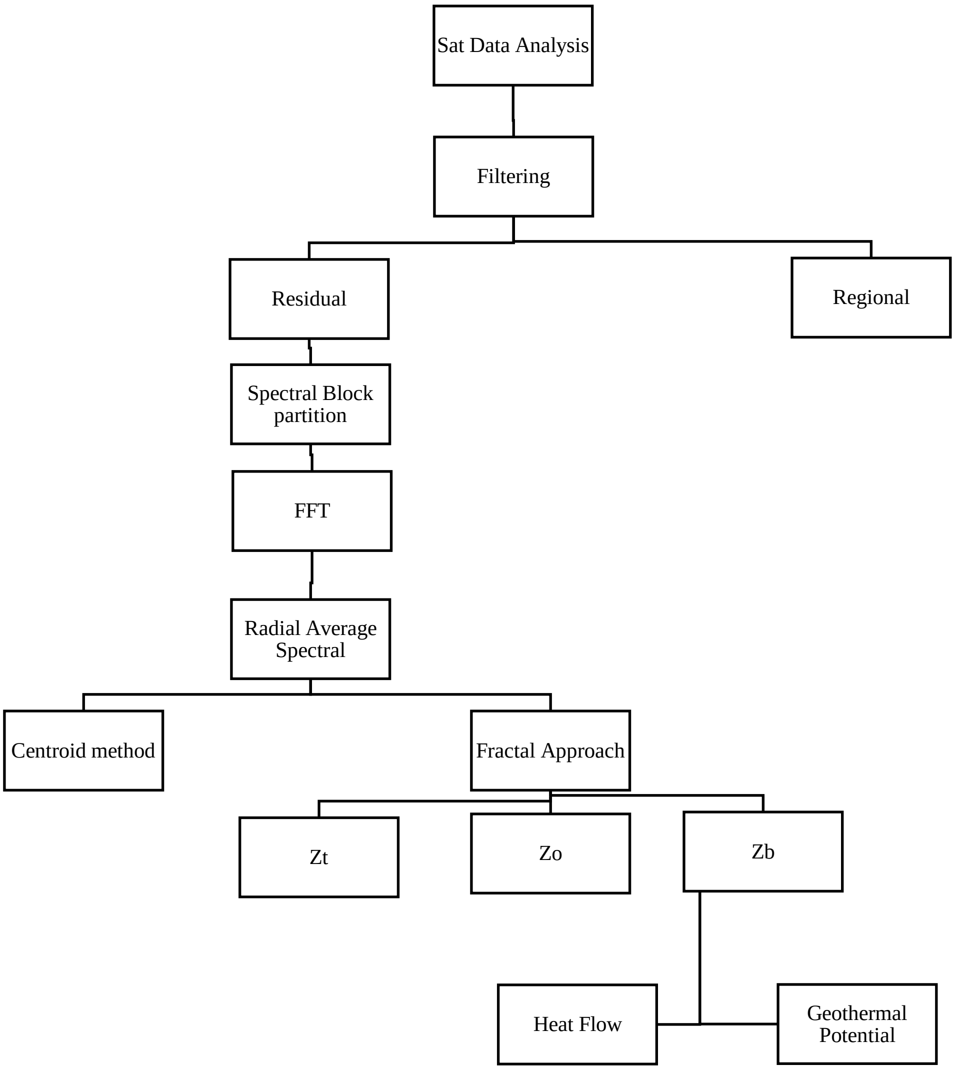

Figure 3: A flow chart

In this equation, the surface temperature is assumed to be zero and the dT/dz (geothermal gradient) constant. This relation implies that regions of high heat flow are associated with shallower sources, whereas regions of lower heat flow are associated with deeper sources

RESULTS AND DISCUSSION

Residual maps were used to emphasize shallower anomalies and demonstrate the geographical distribution of magnetic anomalies caused by shallower source bodies or magnetic anomalous entities that intruded closer to the surface. Following that, using Equation. (6), the depths to the top (Z_t), centroid (Z_0), and bottom (Z_b) of magnetic sources for each block were estimated, and the resulting geothermal gradients and heat flow were calculated using Equation. (10) and (11).

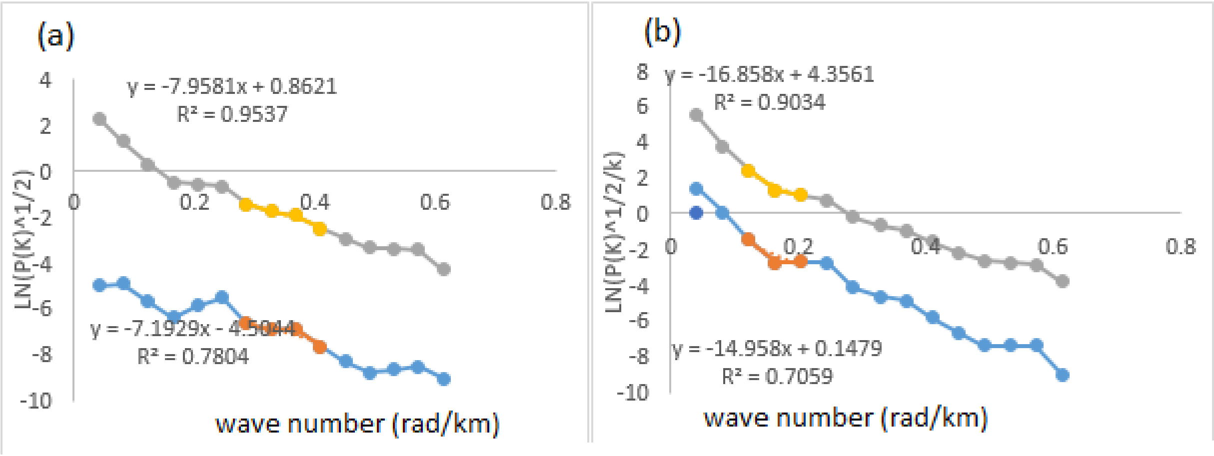

Figure 4: Power spectrum plot for Block 1

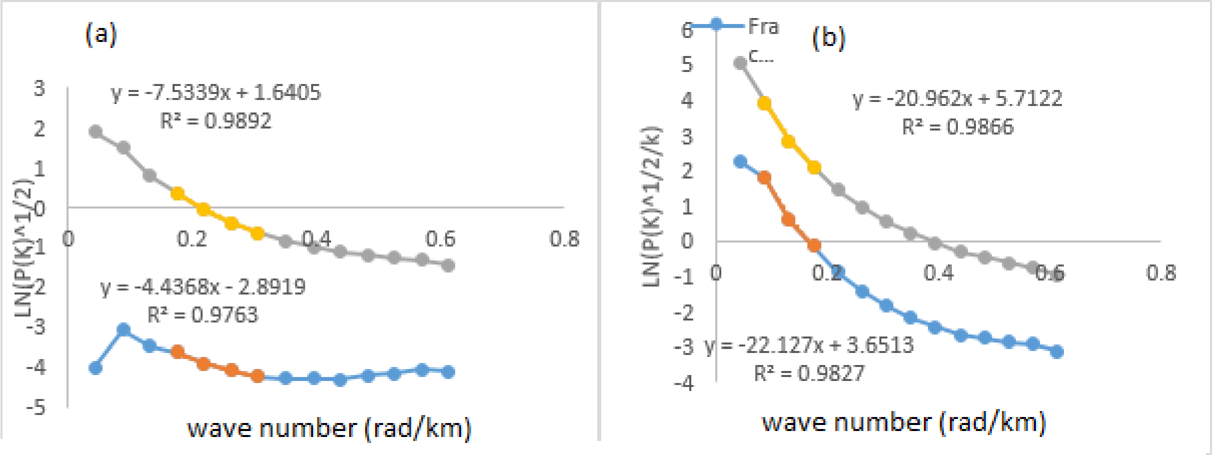

Figure 5: Power spectrum plot for Block 2

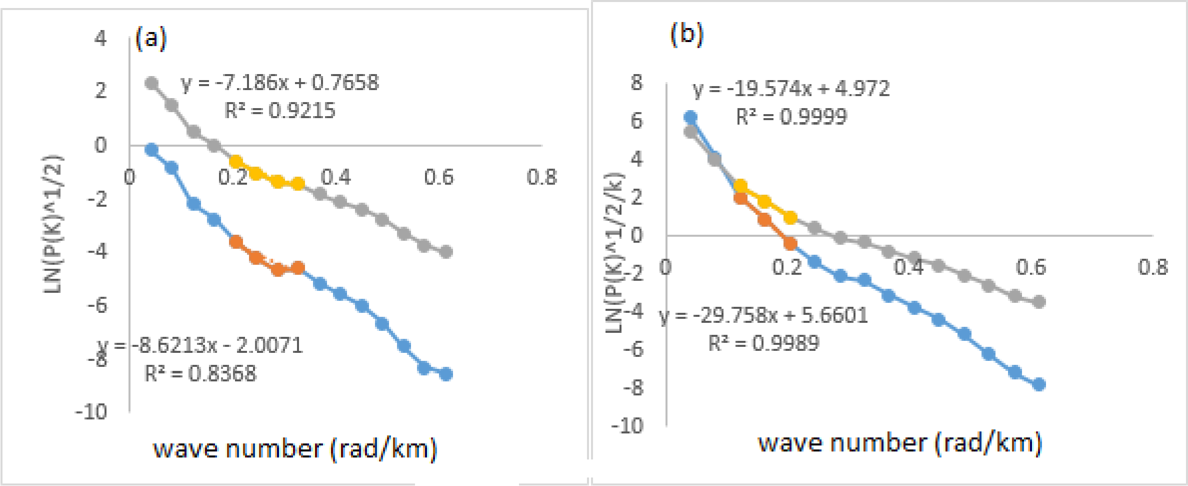

Figure 6: Power spectrum plot for Block 3

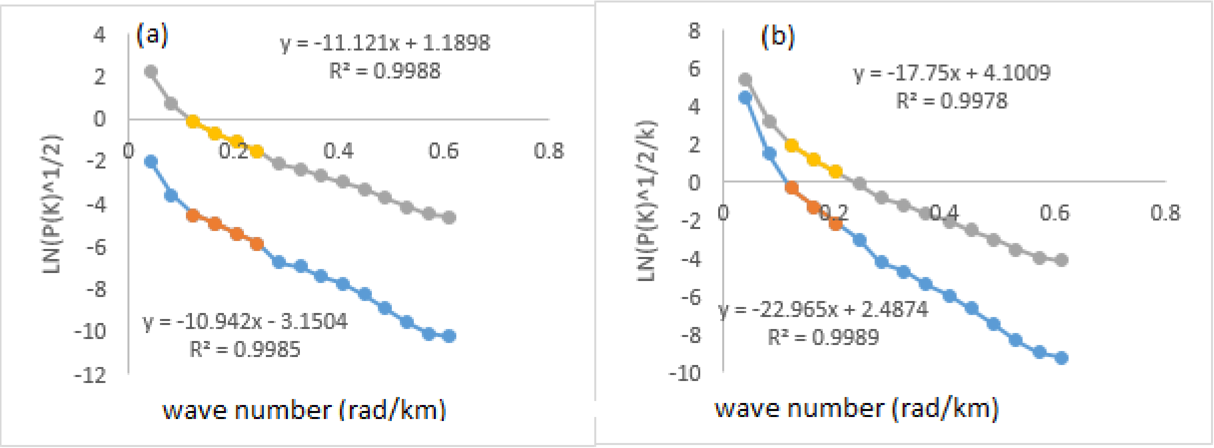

Figure 7: Power spectrum plot for Block 4

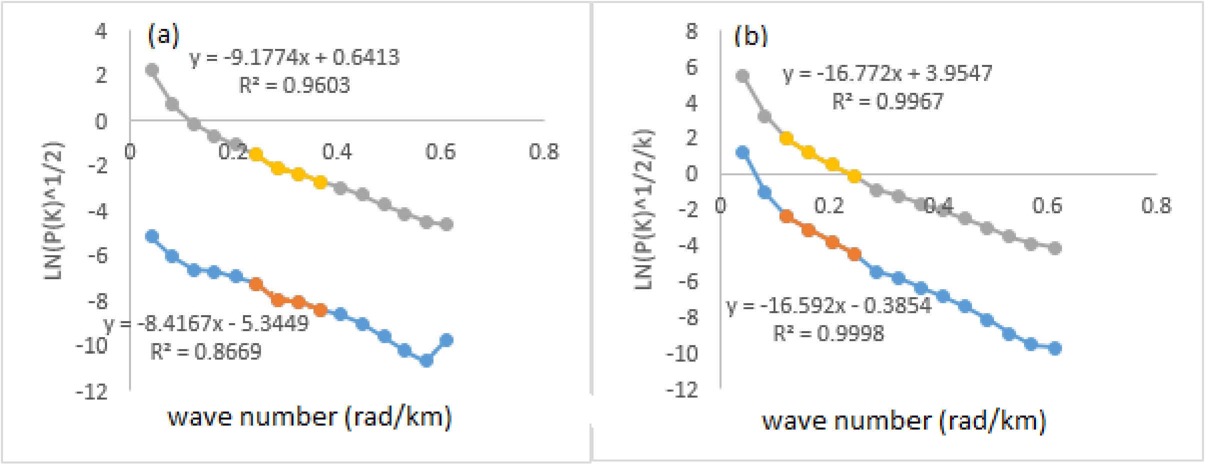

Figure 8: Power spectrum plot for Block 5

To calculate CPD, two plots were created for each of the 24 blocks, i.e., wavenumber-scaled power spectra and power. The group of blocks in the previous figure is a typical illustration. While the slope of the second plot's lower wavenumber section leads to the estimation of centroid depth (Z_0), the slope of the first plot's high-wavenumber portion leads to the estimation of the depth to the top of magnetic sources (Z_t).

Table 1. estimated top depths, centroid depths and curie point depths, and calculated heat flow and geothermal gradients using different values of alpha

Block number	Zt (km)	Zo (km)	Zb (km)	Alpha value	GT °C/km	HEAT FLW mW/m2	LONG	LAT
1	9.662	20.7	31.738	2	18.27462	45.6865587	10.7344461	9.96116818
2	4.4368	22.127	39.8172	2.5	14.56657	36.4164231	10.9133313	9.96116818
3	8.6213	29.758	50.8947	1.5	11.39608	28.4901964	11.0922165	9.96116818
4	10.942	22.965	34.988	2	16.57711	41.4427804	11.2711016	9.96116818
5	8.4167	16.592	24.7673	3	23.41797	58.5449363	11.4499868	9.96116818
6	7.9654	30.954	53.9426	1	10.75217	26.8804247	11.628872	9.96116818
7	7.3174	21.565	35.8126	3	16.19542	40.4885431	10.7344461	10.1313761
8	8.2961	25.339	42.3819	2	13.68509	34.2127182	10.9133313	10.1313761
9	8.5298	26.398	44.2662	2	13.10255	32.7563694	11.0922165	10.1313761
10	5.1483	23.583	42.0177	2.5	13.80371	34.5092663	11.2711016	10.1313761
11	8.0596	20.022	31.9844	2	18.13384	45.3346006	11.4499868	10.1313761
12	9.6329	15.783	21.9331	3	26.44405	66.1101258	11.628872	10.1313761
13	5.1851	27.155	49.1249	2	11.80664	29.5165995	10.7344461	10.3015046
14	3.4465	14.045	24.6435	3	23.53562	58.8390448	10.9133313	10.3015046
15	4.4942	20.107	35.7198	3	16.23749	40.5937323	11.0922165	10.3015046
16	8.5822	20.124	31.6658	2	18.31629	45.7907269	11.2711016	10.3015046
17	8.2501	18.759	29.2679	2	19.81693	49.5423314	11.4499868	10.3015046
18	8.2951	21.036	33.7769	2.5	17.1715	42.9287472	11.628872	10.3015046
19	5.775	24.778	43.781	3	13.24776	33.1193897	10.7344461	10.4717919
20	6.1271	31.338	56.5489	2	10.25661	25.6415244	10.9133313	10.4717919
21	8.4546	27.735	47.0154	1	12.33638	30.8409585	11.0922165	10.4717919
22	7.7499	26.97	46.1901	2.5	12.5568	31.3920082	11.2711016	10.4717919
23	6.073	30.858	55.643	2	10.42359	26.0589832	11.4499868	10.4717919
24	9.662	20.7	31.738	2	18.27462	45.6865587	11.628872	10.4717919

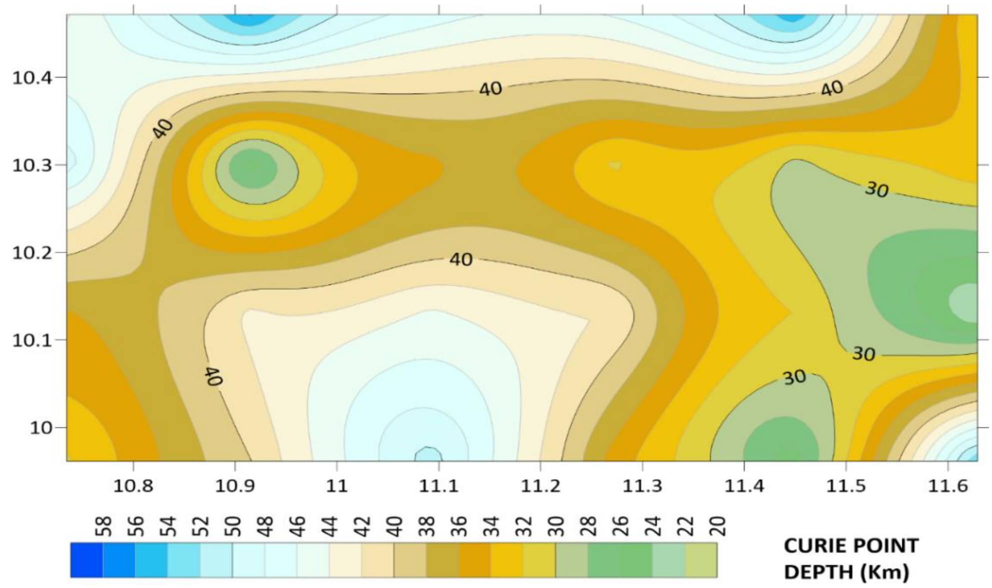

Figure 9: CPD map of the study area

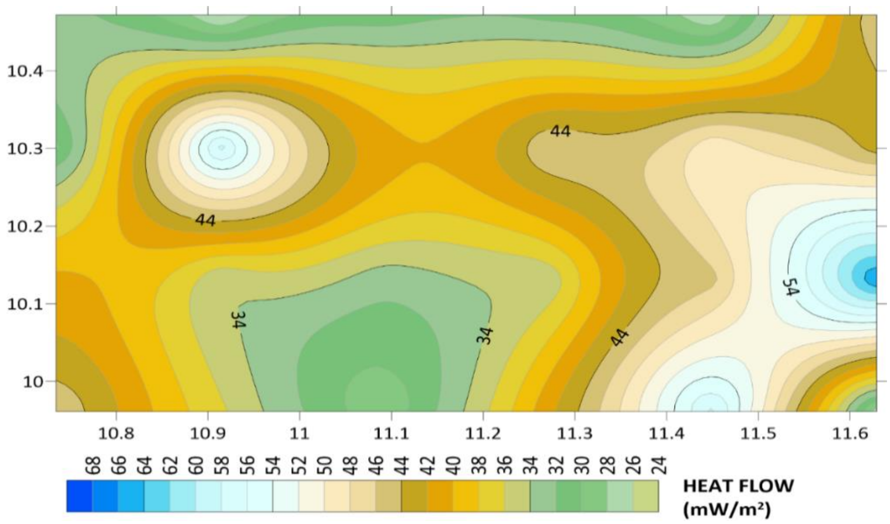

Figure 10: Heat flow map of the study area

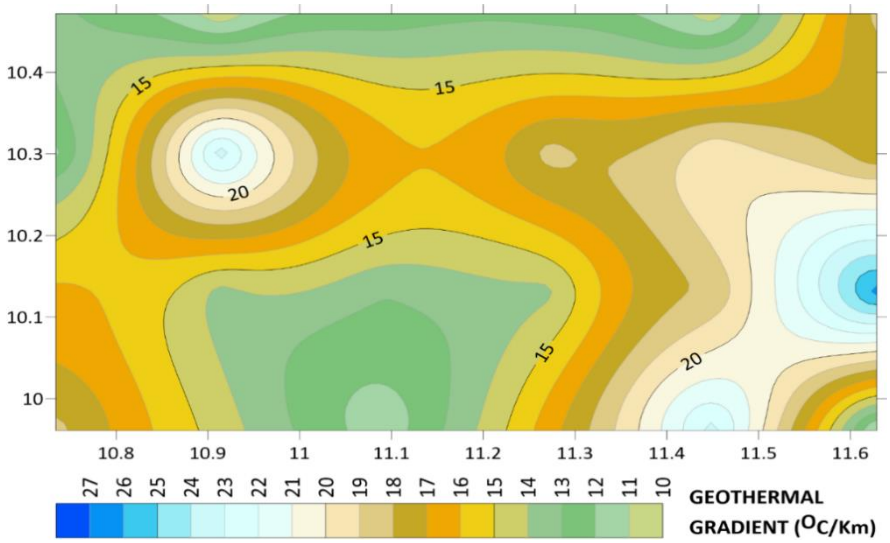

Figure 11: Geothermal gradient map of the study area

According to (landscape evolution,2013), in a normal continental crust, a typical geothermal gradient of the earth surface is about 25^{O}C/km. however this gradient is not sustained but decreases to not more than 16^{O}C/km. and a mean heat flow of 65 mW/m^{2}. The study identify a point (11°63E, 10°12N) with optimal values (26.44^{O}C/km, 66.11mW/m^{2}) at a distance 21.9km which is above the typical optimal values obtained in stable continental craton as obtainable in African plate, which is a potential side for geothermal exploration. Figure 9 depicts a map of the variation in CPD across the research area. A close examination of the map reveals sections or regions within the research area with moderate to high CPD anomalies.

CONCLUSION

The determination of thermal structure of the crust beneath the Gongola Basin with satellite Data using fractal analysis revealed that the centroid method produced CPD estimates with greater percentage differences than its fractal modification. CPD calculations based on centroid fractals were expected to be more accurate. The study found that the Curie-point depths vary between 21.9331 and 56.5489 km, while the basement depths, which are also used as a proxy for sedimentary thickness, vary between 3.4465 and 10.942 km. The resulting heat flow varies between 25.6415 and 58.8390 mW m2. The geothermal gradient varies between 10.25661 and 26.4441 °C/Km. The calculation of the curie depth, geothermal gradient, and heat flow rate across the area found that the average curie depth for the area is 39 km, the average geothermal gradient is 15.8 OC/km, and the average heat flow rate over the area is 39.5 mW/m2. The observed geothermal gradient correlated well with known values for the research location. The centroid-fractal approach could aid with the research of the thermal and geologic structure of the crust, as well as assessing locations with geothermal and oil potential. The minimum CPD value of 21.9331 km was found for block 12 and furthermore, the largest CPD value found in block 20 was 56.5489 km. The presence of shallow CPDs/high heat flow/high temperature gradients in the eastern regions. This result is similar to work of Section, (2022). More so, some fumaroles (Wikki warm spring) near basement areas (Alkaleri areas) in the western part of the study area, as well as the Ruwan-Zafi warm spring near the Lamurde anticlinal area, showed relative conformity with the areas of moderate-high heat flow/moderate-shallow CPDs presented in this study. It also agrees the work of Yusuf, Sani and Abiri (2022) indicating that locations depicting a high magnetic susceptibility contrast from a generated analytic signal map, as well as high temperature gradients, high heat flow, and shallow CPDs are attributed to crustal thinning along the sedimentary basin and magmatic intrusions along basement areas, respectively.

REFERENCES

Abraham, E. M., Obande, E. G., Chukwu, M., & Chukwu, C. G. (2015). *Estimating depth to the bottom of magnetic sources at Wikki Warm Spring region , northeastern Nigeria , using fractal distribution of sources approach Estimating depth to the bottom of magnetic sources at Wikki Warm Spring region , northeastern Nigeria , . April*. https://doi.org/10.3906/yer-1407-12

Abraham, E., Itumoh, O., Chukwu, C. & Rocks, O. 201 9. Geothermal energy reconnaissance of Southeastern Nigeria from analysis of aeromagnetic and gravity data. Journal of Pure and Applied Geophysics 176: 1615-1638.

Bansal, A. R., Dimri, V. P., Kumar, R., & Anand, S. P. (2016). *Curie Depth Estimation from Aeromagnetic for Fractal Distribution of Sources*. 19–31. https://doi.org/10.1007/978-3-319-24675-8_2

Baioumy, H., Nawawi, M., Wagner, K. & Arifi, M.H. 2014. Geochemistry and geothermometry of non-volcanic hot springs in West Malaysia. Journal of Volcanology and Geothermal Research 290: 12-22.

Blakely, R. J. (1996). Potential Theory in Gravity and Magnetic. In *Cambridge University Press*.

Isyaku, A. A. (2018). *Lithostratigraphy and tectonic evolution of the north-eastern Bornu basin , from integrated surface and subsurface interpretation Aminu Abdullahi Isyaku*. *July*.

Likkason, O. K. (2014). Exploring and Using the Magnetic Methods. *Advanced Geoscience Remote Sensing*. https://doi.org/10.5772/57163

Mono, J. A., Ndougsa-Mbarga, T., Bi-Alou, M. B., Ngoh, J. D., & Owono, O. U. (2018). Inferring the Subsurface Basement Depth and the Contact Locations from Aeromagnetic Data over Loum-Minta Area (Centre-East Cameroon). *International Journal of Geosciences*, *09*(07), 435–459. https://doi.org/10.4236/ijg.2018.97028

Nwankwo, L. I., & Shehu, A. T. (2015). Evaluation of Curie-point depths, geothermal gradients and near-surface heat flow from high-resolution aeromagnetic (HRAM) data of the entire Sokoto Basin, Nigeria. *Journal of Volcanology and Geothermal Research*, *305*, 45–55. https://doi.org/10.1016/j.jvolgeores.2015.09.017 *Quintero et al. 2019.pdf*. (n.d.).

Obande, G.E., Lawal, K.M. & Ahmed, L.A. 2014. Spectral analysis of aeromagnetic data for geothermal investigation of Wikki Warm Spring north-east Nigeria. Geothermic 50: 85-90

Saada, S.A. 2016. Curie point depth and heat flw from spectral analysis of aeromagnetic data over the Northern part of Western Desert, Egypt. Journal of Applied Geophysics 134: 11-

100

Section, E. G. (2022). *Curie-point Depths , Geothermal Gradients and Sub-Surface Heat Flow Estimation from Spectral Analysis of High-Resolution Aeromagnetic Data over Gongola Basin and Its Environs , Northeastern Nigeria*. *51*(3), 657–677.

Spring, W. W., Obande, G. E., Lawal, K. M., & Ahmed, L. A. (2014). Geothermics Spectral analysis of aeromagnetic data for geothermal investigation of. *Geothermics*, *50*, 85–90. https://doi.org/10.1016/j.geothermics.2013.08.002

Yusuf A., San, L.H., Abir, I.A., (2022). Curie-point Depths, Geothermal Gradients and Sub-Surface Heat Flow Estimation from Spectral Analysis of High-Resolution Aeromagnetic Data over Gongola Basin and Its Environs, Northeastern Nigeria. Sains Malaysiana 51(3)(2022): 657-677 http://doi.org/10.17576/jsm-2022-5103-03