

# Evaluation of Curie Point Depth and Heat Flow over Part of Bida Basin, North Central Nigeria using Aeromagnetic Data

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**Abstract**-An estimation of Curie-point depth, geothermal gradient, and heat flow has been executed from the spectral analysis of the recently obtained high resolution aeromagnetic (HRAM) data of the Bida Basin in north-central Nigeria. The high resolution aeromagnetic (HRAM) data was divided into sixteen overlapping blocks and each block was analyzed using the spectral analysis technique to acquired depth to the top, centroid, and bottom of the magnetic source. The depth values were subsequently utilized to determine the Curie-point depth (CPD), geothermal gradient, and heat flow in the study area. The result shows that the Curie-point depths (CPD) varies between 3.543 and 5.848 km with an average of 4.610km, the geothermal gradient varies between 51.295 and 84.663°C/Km with an average of 67.979°C/Km and the heat flow result varies between 92.30 and 152.40mWm<sup>-2</sup> with an average of 122.35mWm<sup>-2</sup>. Therefore such heat flow results indicated that the study area might be a good indicator of geothermal energy potential with minimum CPD, maximum geothermal gradient, and heat flow since demagnetized rocks confirm a hot rock quantity in the crust that can be harnessed for geothermal energy exploitation in the basin.

**Keywords:** Aeromagnetic data; Curie-point depth; geothermal energy; Heat flow; Bida basin, Nigeria

## 1. INTRODUCTION

The high-resolution aeromagnetic data over part of Bida Basin has been analyzed and interpreted quantitatively with the purpose of determination of the Curie-point depth and the heat flow of the study area based on investigation for geothermal energy. The Curie-point (bottom of magnetic source) is the point in the earth's crust at about the temperature of 580°C for magnetite under atmospheric pressure where magnetic properties of rocks vanish and magnetic mineral revealed paramagnetic susceptibility [1]. The deepness at which temperature reach the Curie points are presumed to be the bottom of the magnetized bodies within the earth's crust. Depending on the geology and rocks mineral content, Curie-point temperature change from region to re-

gion. It is therefore normal to expect minimum Curie point depth (CPD) at the regions which have geothermal potential, young volcanisms, and a thin crust [2]. The assessment of the disparities in the Curie point depth (CPD) of a particular region can give preliminary and appreciated information about the area temperature distribution at depth and the geothermal energy potentials beneath the earth's surface [3].

In some parts of Nigeria, there are geological and geophysical evidence and the presence of warm spring in the southwest (Ikogosi) and hot spring in the Northcentral (Wikki) which have a good indicator for geothermal potential energy. It is therefore requisite for this present study to be executed with the help of the aeromagnetic data of part of Bida Basin based

on a reconnaissance survey to estimate the geothermal energy potential from the result of CPD and heat flow acquired from the area.

## 2. LOCATION OF THE STUDY AREA

The study area Figure1 is part of the Bida Basin bounded by latitude 8°N and 9°N and longitude 6°E and 7°E with an estimated total area of 18,150 km<sup>2</sup>. The Bida Basin is an intracratonic sedimentary basin that trends NW-SE direction and spreads from Niger State to areas to some extent beyond Kogi State in the southern part.

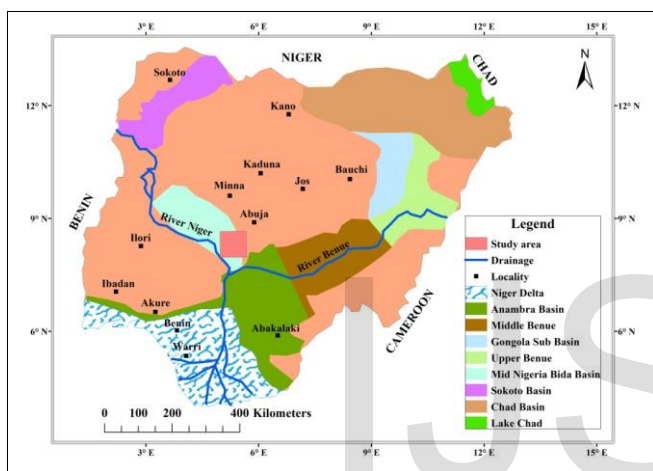


Figure 1: Map of Nigeria showing the location of the study area [4].

## 3. Geology of the Study Area

The study area (Bida basin) is one of the seven inland basins of Nigeria accommodating sediment-fills of Cretaceous to Tertiary age. Therefore the remaining basins are Sokoto, Anambra, Benue Trough, Chad, Niger Delta, and the Dahomey (Benue) Embayment [5]. Figure 2 is the geological map of the study area showing the various geologic structures. The basin composed of the Bida and Lokoja formation which generate throughout the course of the Campanian, the Sakpe, Enagi, Batati, Patti, and Agbaja formations were which generated during the Maastrichtian. The Bida Formation is divided into the Doko Member and the Jima Member with the Doko Member situated 16km south of Bida and having a basal unit that composed of 80m massive and flat bedded arkoses and coarse to medium sandstone with breccia horizon [6]. The sandstone

of the Jima Member, according to [7], is mainly quartzose, non-arkosic, and brownish. Thin intercalation of poorly sort, hard, whitish, argillaceous sandstone is locally present in the lower section of the Jima surfaces.

The Lithologic unit in Lokoja Formation ranges from conglomerates, coarse to fine-grained sandstone, siltstone, and claystone in the Lokoja regions [8]. Subangular to subrounded cobble, pebbles, and granule sized quartz grains in the units are routinely spread in a clay matrix. The Sakpe Formation consists mostly of oolitic and pisolitic ironstone with sandy claystone locally, at the base, followed by mainly oolitic ironstone which manifests quick facies change across the basin at the top [9]. The Enagi Formation as disclosing by [10], on the other hand, comprises mostly of siltstones and relates with the Patti Formation in the Lokoja sub-Basin. Other subsidiary lithologies comprise sandstone-siltstone with some claystone. Fossil leaf impressions and rootlets have been discovered in the formation. The formation range in thickness between 30m to 60m. The mineral assemblage comprises mostly quartz, feldspars, and clay.

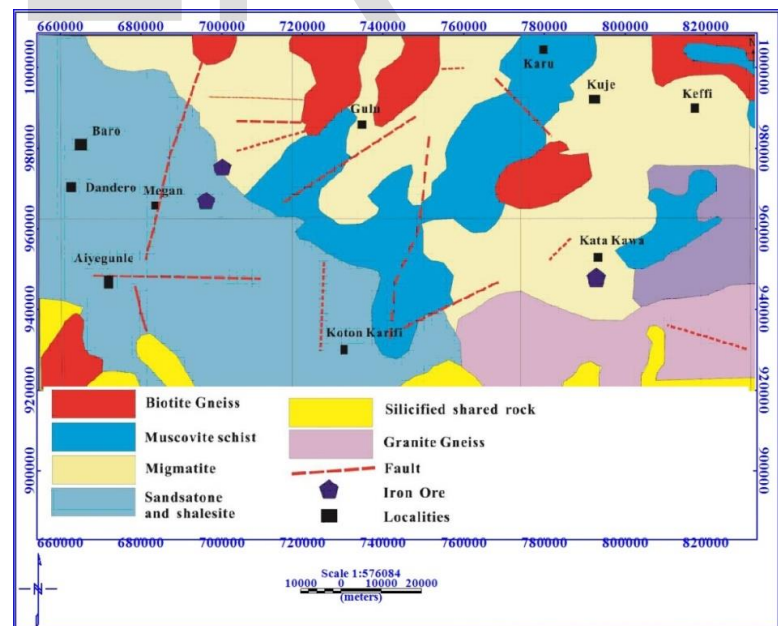


Figure 2: Geological map of the study area (Nigeria Geological Survey Agency, NGSA).

The Batati formation comprises the uppermost unit in the sedimentary sequence of the Bida Basin. It composes, according to

[11], argillaceous, oolitic, and goethite ironstones with ferruginous claystone and siltstone intercalation and shaly beds which arise in a small proportion of which have yielded near-shore shallow marine to freshwater fauna. The outcrops of the Patti Formation arise between Koton-Karfi and Abaji. This formation comprises sandstone, siltstone, claystone, and shale interbedded with bioturbated ironstone with the argillaceous units predominating in the central sections of the basin. The Agbaja Formation forms a persistent cap for the Campanian - Maastrichtian sediments in the Southern Bida Basin as a lateral equivalent of the Batati Formation on the northern parts of the basin. It comprises of sandstone and claystone interbedded with oolitic, concretionary, and massive ironstone beds in this area.

#### 4. Source of Data

The aeromagnetic data utilized in this study was acquired from Nigeria Geological Survey Agency. The data was part of the high-resolution aeromagnetic data acquired from the nationwide airborne survey executed between the years 1974 to 1980. Fugro Airborne Survey Limited executed this survey out for Nigeria Geological Survey Agency (NGSA). They performed the survey out with the following details;

- Terrain clearance = 50-200 m
- Line spacing = 500 m
- Tie line spacing: < 500m.
- Flight line spacing: 50-200m
- Nominal flight altitude 152.4m

#### 5. Methodology

This research makes use of the spectral depth analysis of the aeromagnetic data to evaluate the Curie point depth (CPD) of the study area. [12] elucidated the spectral depth analysis method they employed to estimate the depth to the top of the magnetic four-sided prism ( $Z_t$ ) from the gradient of the log of the power spectrum. [13], [14], from the view of [15] estimate the depth to the centroid of the magnetized source

rock ( $Z_0$ ). [16] combined and expanded the view from [17], [18], [19], to advance the method to determine the bottom depth of magnetized bodies ( $Z_b$ ). If the degree at which a magnetic body of 2D bodies is completely random and unrelated, the circular average of the power density spectral of the total field anomaly,  $p(k)$ , could be expressed as follows [20], [12]:

$$P(k) = A_1 e^{-2|k|Z_t (1 - e^{-k(Z_0 - Z_t)})^2} \quad 1$$

Where  $A_1$  is a constant and  $Z_t$  and  $Z_b$  denote the depths to the top and bottom of the magnetic body, respectively.  $k$  shows the wavenumber of the magnetic field.

According to [22], Curie point depth (CPD) ( $Z_b$ ) can be achieved in two stages. First of all, the centroid depth ( $Z_0$ ) of the inmost magnetic source is appraised from the gradient of the lengthiest wavelength part of the spectrum divided by the wavenumber using the following equation [23]:

$$\ln(P(k)^{1/2}) - B - |k|Z_t \quad 2$$

where  $B$  is a constant.

The depth to the bottom of the magnetized body is therefore giving as follows;

$$Z_b = 2Z_0 - Z_t \quad 3$$

Where  $Z_b$  the depth to the bottom of the magnetized body is,  $Z_0$  is the centroid depth and  $Z_t$  is the depth to the top of the magnetized body.

As analyzed in the method above, the Curie point depth (CPD) is evaluated in three stages: (i) dividing the residual of the TMI map into overlapping blocks, (ii) computing the logarithm of the power spectrum for each block, the centroid depth and depth to the top of the magnetized body is obtained and (iii) using  $Z_b = 2Z_0 - Z_t$  the basal depth is calculated. Having calculated the Curie point depth (CPD), the heat flow is therefore calculated from the equation as follow;

$$q = k \frac{\partial T}{\partial Z} \quad 4$$

Where  $q$  is the heat flow,  $k$  is the thermal conductivity and  $\frac{\partial T}{\partial Z}$  is the thermal gradient.

According to [24], [25], the Curie-depth is connected with the Curie temperature ( $580^{\circ}\text{C}$ ); the vertical direction of temperature variation and the constant thermal gradient were assumed. The geothermal gradient  $\left(\frac{dT}{dZ}\right)$  between the Earth's surface and the Curie-point depth ( $Z_b$ ) is defined using the formula as follow;

$$\frac{dT}{dZ} = \frac{\theta_c}{Z_b} \quad 5$$

$\frac{dT}{dZ}$  is the thermal gradient,  $\theta_c$  ( $580^{\circ}$ ) is the Curie temperature and  $Z_b$  is the Curie depth.

## 6. DATA PROCESSING AND ANALYSIS

The total magnetic intensity map Figure 3 was subjected to regional/residual separation. Therefore, the data reduced to the equator were residualized (i.e. remove the regional) by subtracting upward continued data to 30km from the reduced to the equator data so as to obtain a magnetic response from the upper-crust of the earth consisting of the basement and the sedimentary units. The residual map Figure 5 shows magnetic anomalies slightly different from that of the reduced to equator (RTE) map Figure 4. The residual map was divided into sixteen overlapping blocks for the spectral analysis. The blocks were in different sizes. It is generally admitted that the utilization of a small window width may be a fundamental error in the application of spectral methods for aeromagnetic interpre-

ting blocks. The data acquired from the spectral in CSV format were exported into Microsoft Excel where the data for wavenumber and log of energy spectrum were extracted for plotting. The data were plotted using a program written in Matlab to deduce the centroid depth from the slope of the long-wavelength ( $Z_0$ ) and the depth to the top of the magnetized body ( $Z_t$ ).

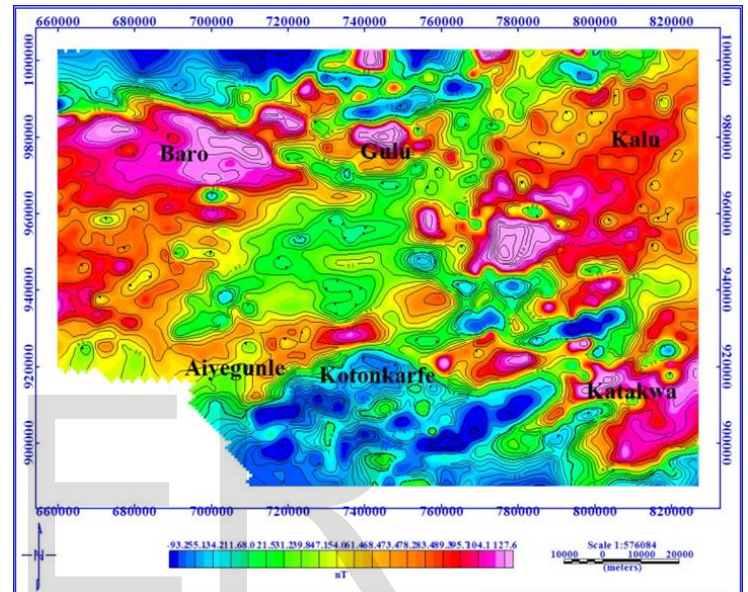


Figure 3: Total magnetic intensity map of the study area

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tation [26]. Spectral analysis was performed on each overlap-

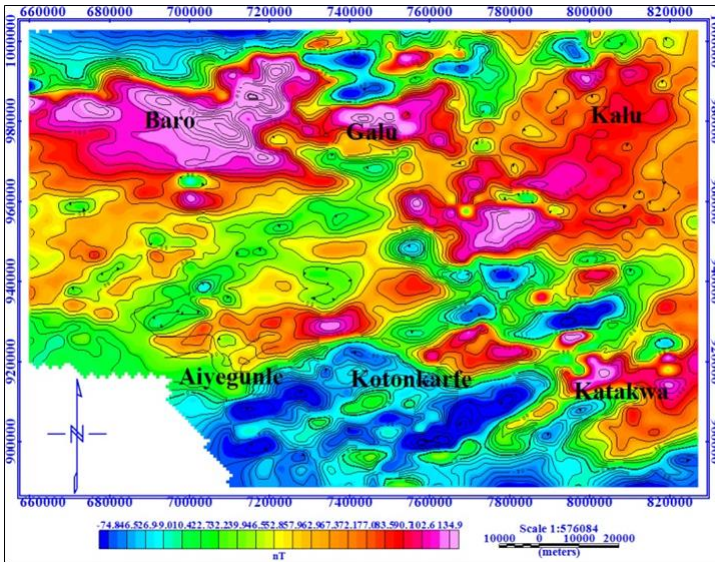


Figure 4: Reduce to Equator map of the study area.

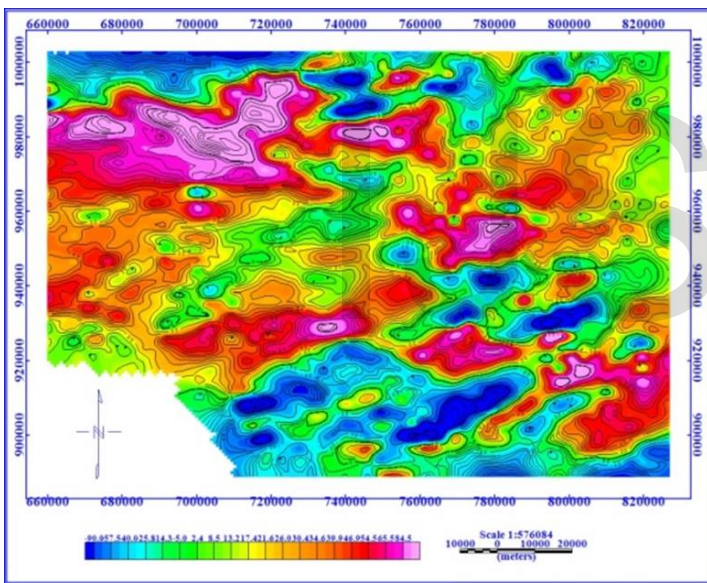


Figure 5: Residual of the total magnetic intensity Map

For the purpose of this study, depths to the top of magnetic anomalies only because the study was based on depth to basement and its thermal properties. The map was broken into 16 blocks as shown below.

Table 1: The table showing the sixteen (16) broken blocks.

7.46	A	B	C	D	
7.09	E	F	G	H	
6.71	I	J	K	L	
6.33	M	N	O	P	
5.96					
	12.53	12.75	13.00	13.26	13.51

The spectral blocks were plotted as log power against wave-number. The slope of each spectral curve was determined and divided by  $4\pi$  to obtain the estimated depth to the top of the magnetic source. The result indicated a two depth source model. The spectral plots are shown below:

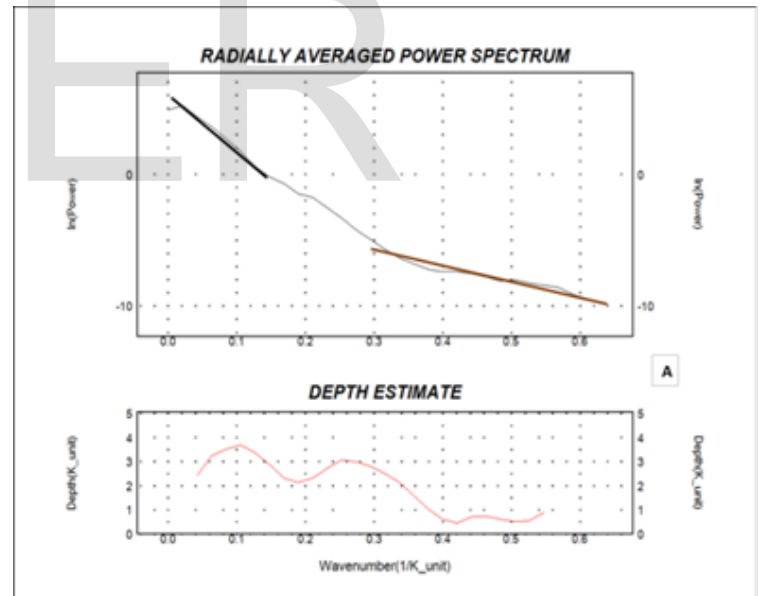


Figure 6A: Average power spectral plots for sixteen (16) A-P blocks.

Table 2: Estimated Curie-point depth (CPD), geothermal gradients.

Block Identity	Longitude		Latitude		Deep Depth, $Z_c$ (Km)
	Max	Min	Max	Min	
A	12.75	12.53	7.46	7.09	2.905

B	13.00	12.79	7.09	6.71	2.217
C	13.26	13.05	6.71	6.33	2.345
D	13.51	13.31	6.33	5.96	2.483
E	12.75	12.53	7.46	7.09	2.635
F	13.00	12.79	7.09	6.71	2.715
G	13.26	13.05	6.71	6.33	2.491
H	13.51	13.31	6.33	5.96	2.961
I	12.75	12.53	7.46	7.09	2.854
J	13.00	12.79	7.09	6.71	2.564
K	13.26	13.05	6.71	6.33	2.682
L	13.51	13.31	6.33	5.96	3.259
M	12.75	12.53	7.46	7.09	2.420
N	13.00	12.79	7.09	6.71	2.560
O	13.26	13.05	6.71	6.33	2.201
P	13.51	13.31	6.33	5.96	2.579
Shallow Depth, $z_t$ (Km)	Curie Depth $z_b = 2z_0 - z_t$	Geothermal Gradient, °C/Km	Heat Flow mW/m <sup>2</sup>		
0.796	5.014	115.676	107.7		
0.624	3.810	152.231	141.8		
0.733	3.957	146.576	136.5		
0.656	4.310	134.571	125.3		
0.666	4.604	125.977	117.3		
0.725	4.705	123.273	114.8		
0.697	4.285	135.356	126.0		
0.730	5.192	111.710	104.0		
0.863	4.845	119.711	111.4		
0.884	4.244	136.664	127.2		
0.762	4.602	126.032	117.3		
0.670	5.848	99.179	92.3		
1.297	3.543	163.703	152.4		
0.779	4.341	133.601	124.4		
0.748	3.654	158.730	147.8		
0.618	4.540	127.753	119.0		

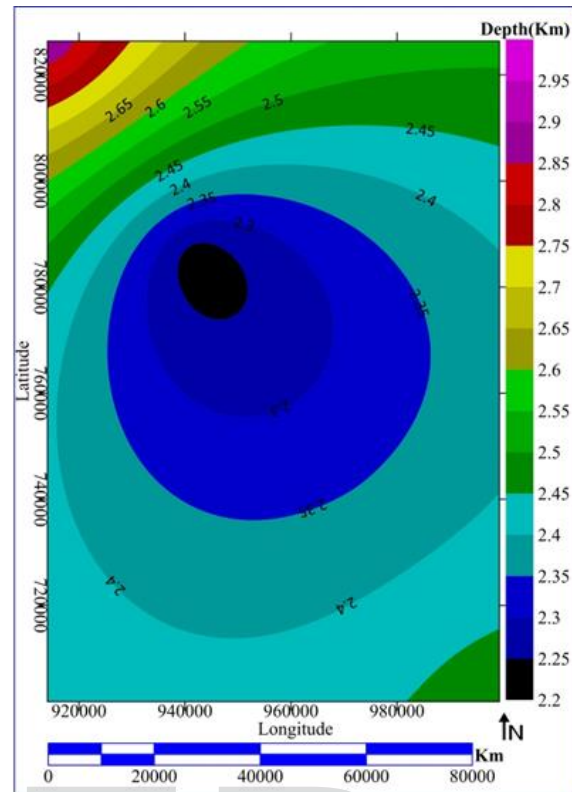


Figure 7: Depth to the bottom of magnetized body.

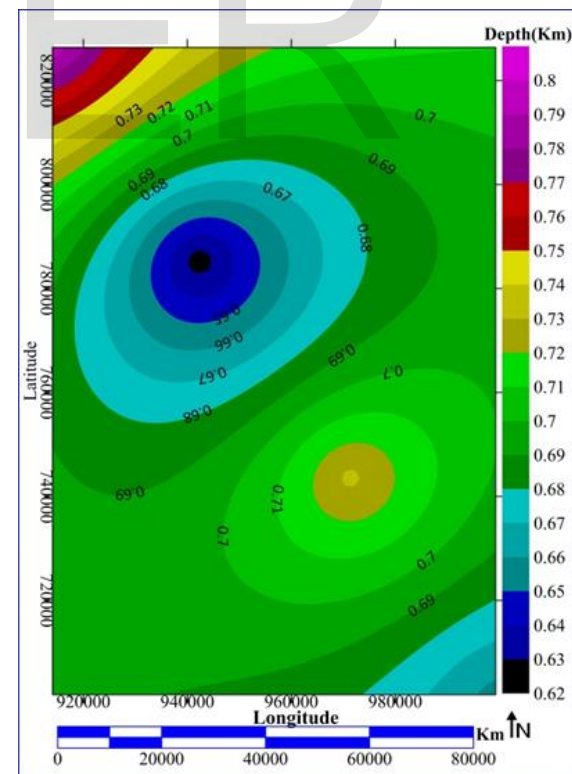


Figure 8: Depth to the top magnetic source map

The Curie temperature approximately 580°C was divided by the estimated Curie point depth (CPDs) to give the geothermal gradients for the sixteen blocks which range from 99.1790Ckm<sup>-1</sup> at the center of the southern region of the area to 158.7300Ckm<sup>-1</sup> at the northeastern and northwestern region of the study area with an average of 128.9550Ckm<sup>-1</sup> Figure 10. Table 1 gives the heat flow to range from 92.3mWm<sup>-1</sup> to 152.4mWm<sup>-1</sup> with an average value of 122.35mWm<sup>-2</sup>. The heat flow was estimated by multiplying the geothermal gradient estimated by the coefficient of the thermal gradient of 1.8Wm<sup>-1</sup>C<sup>-1</sup>. The CPD, geothermal gradient and heat flow estimated from this present study agree with [27].

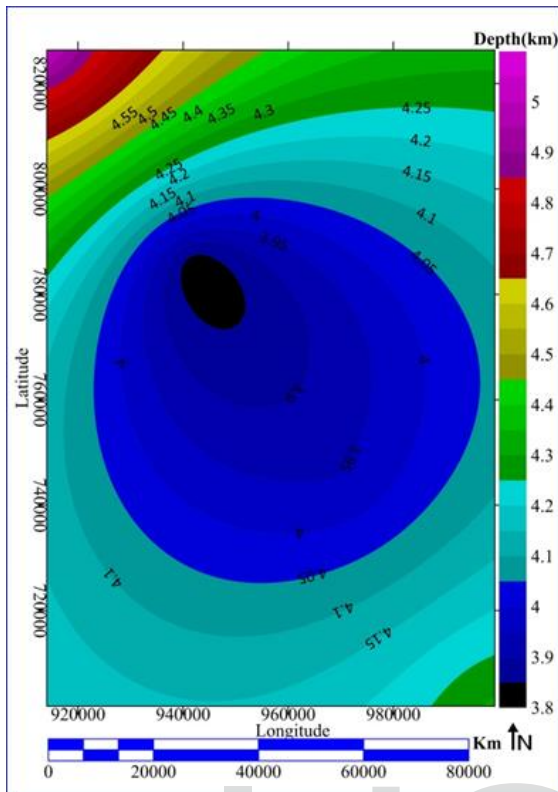


Figure 9: Curie-point depth (CPD) map of the study area

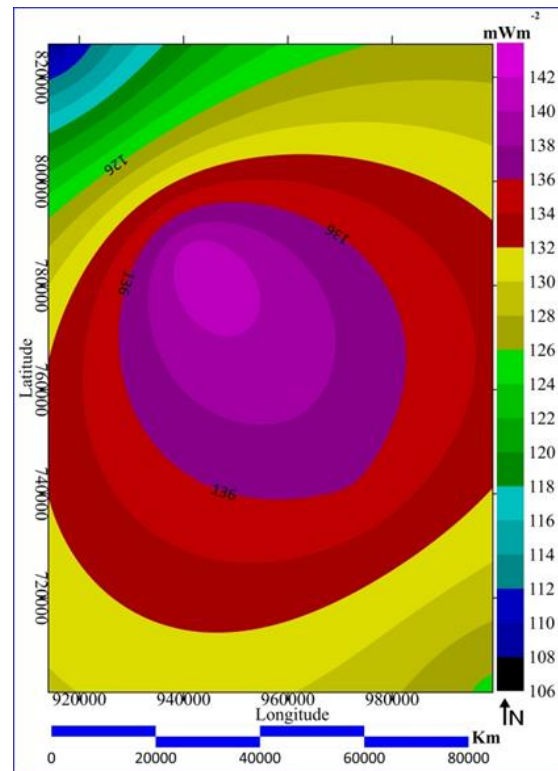


Figure 11: Heat flow contour map

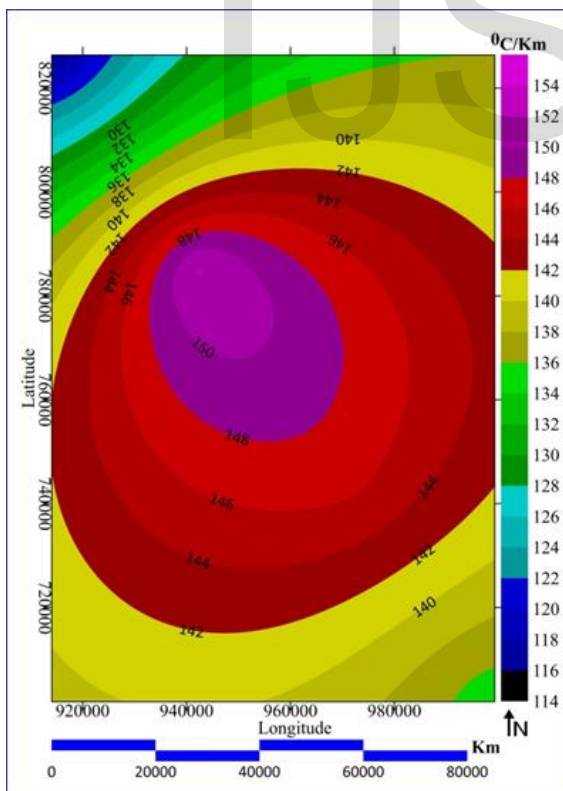


Figure 10: Geothermal gradient contour map

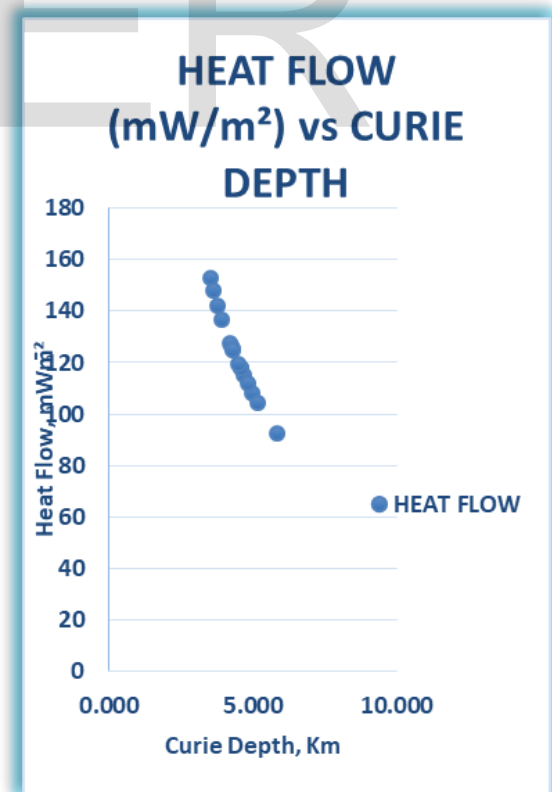


Figure 12: Map of Heat flow versus Curie depth.

Figure 7 is the contour map of the depth to the centroid of the

magnetized body in km, Figure 8 the contour map of depth to the top of the magnetic boundary in km, Figure 9 is the depth to the bottom of the magnetized body (CPD) in km, Figure 10 the contour map of a geothermal gradient in  $^{\circ}\text{Ckm}^{-1}$ , Figure 11 the contour map of the heat flow of the study area in  $\text{mWm}^{-2}$  and Figure 12 is the map of heat flow versus curie depth.

## 7. RESULT/DISCUSSION

The power and wavenumber-scaled power spectra were made for each of the sixteen (16) overlapping blocks for the purpose of estimating Curie-point depth (CPD). The ordinary example for block 6a is shown in Figure 6. In the first plot, the slope of the high-wavenumber portion leads to the estimation of the depth to the top of magnetic sources ( $Z_t$ ) while the slope of the lower-wavenumber part of the second plot leads to the estimation of centroid depth ( $Z_0$ ) [28].

Table 1 shows the results of estimated depth extents for the 16 blocks. The range of the depths to the top of magnetic sources is range from 0.618 to 1.297 km with an average of 0.960 km, while the centroid depth  $Z_b$  of the inmost magnetic source is range from 2.201km to 3.259km with an average of 2.730km. Therefore the depths to the bottom ( $Z_b$ ) that is Curie-point depth (CPD) range from 3.543km to 5.848km with an average depth of 4.610km. This depth information was subsequently used to generate basement depth and Curie-point depth (CPD) maps of Figures 7 and 8 for the Bida basin. The variation of basement depths (also regarded as sedimentary thickness) in the basin as inferred from Figure 7 is found to be consistent with those of other workers [29], [30]. Likewise, Figure 7 shows that the north-western portion has the thickest sedimentary layer of about 2.95 km in the basin. The lowest values of sedimentary thickness are found at the central part of the basin with a southward trend of thickness' increase resulting in maximum values in the north-western part. The medium value sedimentary thickness is found at the south-eastern of the basin. The Niger-Delta basin in southern Nigeria

has been explored for hydrocarbon for several decades with considerable success [31] and for political reasons; the government has encouraged extensive hydrocarbon exploration in inland basins, especially in the northern part of the country. However, [32] revealed that the minimum thickness of sediments needed to accomplish a threshold temperature for the commencement of hydrocarbon formation is 2.3km. Therefore, hydrocarbon exploration may be feasible in the Bida Basin.

Current literature state that Curie-point depth (CPD) varies greatly with geological settings [33]. They reported that Curie-point depth (CPD) is shallower than 10km for geothermal energy attributable to volcanic activity, which is commonly associated with plate boundaries and other geodynamic environments. On the other hand, Curie-point depth (CPDs) ranging between 15 and 25 km are as a result of island arcs and ridges, and deeper than 20km in plateaus and trenches. Figure 9 shows that the Curie-point depth (CPD) values trend NE - SW with the shallowest portion (less than 5km) located in the north-central part of the basin, and extends southward while becoming deeper with its deepest (about 5 km) at the north-western part. The central portion with very low Curie-point depth (CPD) values is found to be consistent with earlier work done in this part of the basin by [34].

Furthermore (Table 1) also reveals that the geothermal gradients in the area vary between 99.179 to 158.730 $^{\circ}\text{C}/\text{Km}$  with an average of 128.955 $^{\circ}\text{C}/\text{Km}$ . The contour basement plot for the geothermal gradient is shown in Figure 10. The geothermal gradient map Figure 10 also exhibits NE - SW trending. The lowest values of the geothermal gradient were found in the northwestern part of the basin. The trend of gradient increase was found resulting in a maximum value of 154 $^{\circ}\text{C}/\text{km}$  in the central area.

Moreover, the derived heat flow presented in Table 2 varies between 92.30 to 152 $\text{mWm}^{-2}$  with an average of 122.35 $\text{mW}/\text{m}^2$ . The minimum heat flow value required for the considerable generation of geothermal energy is about 60 $\text{mWm}^{-2}$ . Values ranging from 80 to 100 $\text{mWm}^{-2}$  and above indicate the anomalous geothermal condition [35]. Subsurface



heat flow in the basin exhibits NE – SW trending Figure 11, while the derived amounts increase from the south towards the central part with values higher than  $140\text{mWm}^{-2}$  observed in the central portion. This same high heat flow portion corresponds to a high geothermal gradient (above  $150^{\circ}\text{C}/\text{km}$ ) and shallow CPD values (below 5km) in the area such as depicted in Figures 9 and 10. Commonly, areas with high flow values agree with volcanic and metamorphic rocks [36]. In addition Figure 12 shows the relationship between heat flow and Curie-point depth (CPD). It is also probable that the high heat flow portion might be governed by a deep magmatic mass that has not completed its cooling in association with young volcanism and faulted structure as witnessed in Gazamna by [37]. This suggests an abundance of geothermal resources in the area and is therefore recommended for further geothermal investigation for plausible harnessing.

## 8. CONCLUSION

This study demonstrates the estimation of the basement and Curie-point depths, geothermal gradients, and near-surface heat flow from the spectral analysis of the high resolution aeromagnetic (HRAM) data of the part of Bida Basin in north-central Nigeria. The study revealed that the basement depths, also regarded as a proxy for sedimentary thickness, varies between 0.618 and 1.297km with an average of 0.960km, while the Curie-point depths vary between 3.543 and 5.848km with an average of 4.610km. The geothermal gradients vary between  $51.295$  and  $84.100^{\circ}\text{C}/\text{Km}$  with an average of  $67.979^{\circ}\text{C}/\text{Km}$ , and the resulting heat flow vary between  $92.3$  and  $152.4\text{mWm}^{-2}$  with an average of  $122.350\text{mWm}^{-2}$ . These findings have been explained the maximum sedimentary thickness in the basin is 2.730km. However, it has been argued that the minimum thickness for hydrocarbon formation is 2.3km [38]. Consequently, hydrocarbon exploration in the Bida basin may be plausible. Furthermore, the result shows regions with shallow Curie-point depths (below 14km) and corresponding high heat flows (above  $80\text{mWm}^{-2}$ ) exist in the basin, which suggests anomalous geothermal conditions [39].

These anomalous regions are recommended for more detailed study. Repeatedly, direct crustal temperature measurements may not be too feasible for regional studies; hence the derived geothermal gradients be enough or adequate for the study area.

Therefore, this study provides more details on the geothermal and geodynamic rheology in the Bida Basin, which could serve as an index for the thermal exploitability of the basin. In addition, the prospect of employing thermal energy through the development of resorts and allied thermal options exist in the study area, which could be re-confirmed through detailed integrated surveys. Exploration and exploitation of geothermal heat will definitely provide opportunities to increase energy options, energy market flexibility in Nigeria.

## 9. ACKNOWLEDGMENTS

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