Determination of Curie Depth, Geothermal Energy and Heat Flow in Chad Basin Northeast Nigeria Using Spectral Analysis of Aeromagnetic Data

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Abstract: ***This study attempts to estimate the Curie point depth (CPD), geothermal energy, and heat flow in the Chad Basin northeast Nigeria. Therefore, the data reduced to the equator were residualized (i.e. remove the regional) by subtracting upward continued data to 3km 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 was divided into eighteen overlapping blocks for the spectral analysis. The blocks were in different sizes. Hence, the investigation of Curie point depth, geothermal gradient as well as heat flow was carried out using spectral analysis. The Curie point depth obtained ranges from 3.22 to 7.16km with an average of 5.19km; the geothermal gradient of the area varies from 81.46 to 180.12^{0}C /km, with an average of 130.79^{0}C /km, while the heat flow ranges from 202.53 to 450.30 mWm^{-2}, with an average of 326.42mWm^{-2}. The 2D contour Curie depth map of the area shows that the deepest Curie depth is located in the northeast, northwest, and southeastern parts, while the shallowest Curie depth is observed in the central part of the area, while the geothermal gradient and heat flow, on the other hand, are highest in the central region and decrease towards the northwest. The high geothermal gradient and heat flow values in the study area are evidence that the area might be capable of geothermal energy generation.***

Keywords: Curie point depth, Aeromagnetic data, Geothermal energy, Heat flow, Spectral analysis, Chad Basin

1. Introduction

The Curie point depth (approximately 580^{0}C for magnetite at atmospheric pressure) is the temperature at which the spontaneous magnetization disappears and magnetic minerals manifest paramagnetic susceptibility. Therefore, the depth at which temperature reaches the Curie-point is assumed to be the bottom of the magnetized bodies in the earth's crust. Curie point temperature changes from one place to another depending on the geology and the mineralogical content of the rocks. Therefore, one can generally expect shallow Curie point depth (CPD) at the areas which have geothermal potential, young volcanisms, and thin-crust [1]. The evaluation of the changes in the Curie depth of an area can contribute valuable information about the regional temperature dispensation at depth and the potential of subsurface geothermal energy [2]. The idea of using aeromagnetic data to evaluate Curie-point depth (CPD) is not new, and it has been greatly applied to several sections of the world. [3] Mapped Curie-point isothermal surface for geothermal reconnaissance of the Yellowstone National Park in the USA. In this region, Curie-point depth (CPD) was evaluated 4–8km. Tselentis's purpose was to confirm the nature and degree of the regional geothermal system at a depth underneath the area of Greece by establishing the Curie isotherms. The results of his research disclosed that the Curie-point depth (CPD) varies significantly underneath Greece, reaching 20km towards western Greece and about 10km underneath the Aegean. In the East and Southeastern parts of Asia, Curie-point depth (CPD) was estimated based on the spectral depth analysis of magnetic anomaly data by [3]. Therefore, the evaluated Curie-point depth (CPD) for this region using the centroid technique varied from 9 to 46km. Furthermore, they forecast Curie point depth (CPD) from heat flow data. The Curie-point depth (CPD) calculated from the heat flow data was indistinguishable from the results of the Curie-point depth (CPD) investigation of magnetic data. [4] Concluded that the investigation of earth crust's thermal structure in southwestern Turkey is helpful to find out the modes of deformation, depths of brittle and ductile deformation areas, and regional heat flow changes. [5] Found the deep origin of the geothermal areas and volcanic centers in central Greece, by amalgamating a travel-time inversion of a micro-seismic dataset together with a Curie-point depth (CPD) research based on the aeromagnetic data. They also found that a feasible magma chamber can be assumed by detecting a low seismic velocity volume at depths below 8km and the Curie-point depth (CPD) evaluation at about 7–8km depth as well.

[6] Calculated the bottom depth of magnetic sources in Germany by using aeromagnetic data. Basically, they suggested a modified centroid technique to evaluate the depth to the bottom of magnetic sources. To appraise the estimated bottom depth of magnetic sources, the outcomes were then compared with the heat flow density data. [7] Calculated Curie-point depth (CPD) and heat flow map for Northern Red Sea rift of Egypt. Their purpose was to portray the Curie-point depth (CPD) based on the spectral depth analysis of the aeromagnetic data. Therefore, the Curie-point depth (CPD) varied between 5 to 20km. The shallowest Curie-point depth (CPD) of 5km (related to the high heat flow) was proposed as

a favorable region for geothermal exploration. [8] Scrutinized the Curie-point depth (CPD) isotherm from the aeromagnetic data to arrange an initial potential map of geothermal resources in the Eastern Sector of Central Nigeria. They revealed that the high prospect regions are situated in the south-west region of the study area. [9] Applied spectral analysis of aeromagnetic data for geothermal exploration in northeast Nigeria. They evaluated the top and the centroid depths of the magnetic source from the power spectrum. The acquired results were subsequently utilized to calculate the bottom depth. In addition, the range of Curie-point depth (CPD) varies between 6 to 12 km based on the heat flow and Curie-point depth (CPD) values of the study area were in the highest heat flow value and the shallowest Curie-point depth (CPD) occurred close the thermal springs. The Wikki warm spring region was found to have a significant energy potential with a shallow Curie-point depth (CPD) and very high heat flow values. The geological and geophysical prove together with the presence of various hot water springs in Ardebil province in the NW of Iran show that the region could have a high geothermal energy potential. Apart from this, the review of the published papers identify that no absolute aeromagnetic data analysis exists to show the geothermal potential of the area. So, any research concerning to detecting geothermal potential areas in such a great area is extremely paramount in the early stage of a geothermal research project. Consequently, this study attempts to apply spectral analysis techniques using aeromagnetic data to determine Curie-point depth (CPD) in the Chad basin. The heat flow values are then evaluated and mapped to appraise further geothermal region.

2. Geological Settings

The study area is located in the Nigerian sector of Chad Basin, which lies within latitude 9.5^0N to 12.5^0N and longitude 9.5^0E to 12.5^0E (Figure 1). Nigerian sector of Chad basin is part of Chad basin which lies within a vast area of central and west Africa at an elevation between 200 and 500m above sea level and covers approximately 230,000km^2 [3]. It is the largest area of inland drainage in Africa and extends into parts of the Republic of Niger, Chad, Cameroon, Nigeria, and Central Africa [7], [8], [18]. The Nigerian Chad Basin is about one-tenth of the basin and has a broad sediment-filled depression spanning northeastern Nigeria and adjoining parts of the Republic of Chad.

Therefore, the region mostly is endowed with rocks mineral base resources such as clay, salt, limestone, kaolin, iron ore, uranium, mica, etc [3]. The sedimentary rocks of the area have a cumulative thickness of over 3.6 km and the rock comprise of thick basal continental series overlaid by transitional beds followed by a thick sequence of quaternary Limnic, fluviatile and eolian sand, clay, etc [26].

The stratigraphic sequence shows that Chad, Kerri-Kerri, and Gombe formations have an average thickness of 130 to 400m. Below these formations is the Fika shale with a dark grey to black in color, with an average thickness of 430m. Others are Gongila and Bima formations with average thicknesses of 320 and 3500 m, respectively [26], [28].

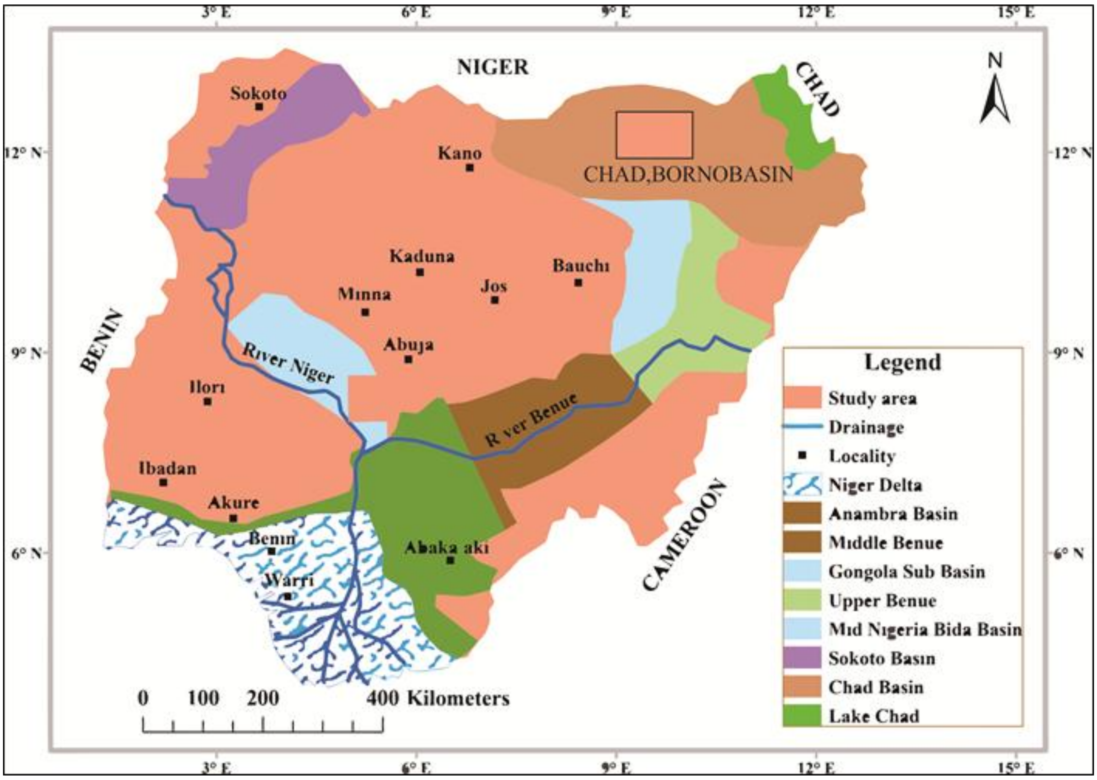

Figure 1: Map of Nigerian's Sedimentary Basin Showing the Study Area [28]

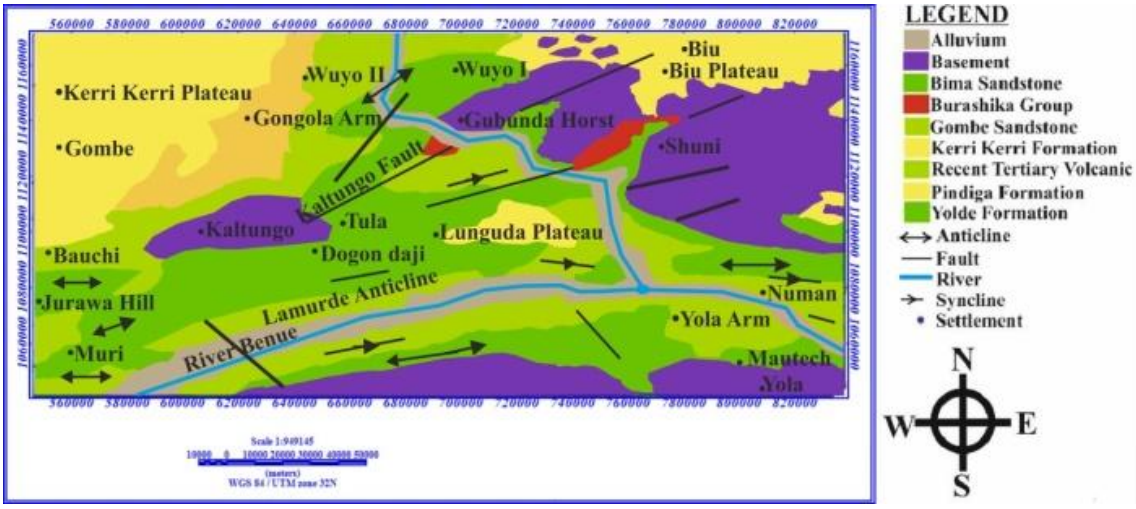

Figure 2: Geologic map of the Chad Basin with location of the studied sections. [28]

3. Source of Data

The aeromagnetic data of Chad Basin north-east, Nigeria were employed for this study. The data were obtained by Fugro Airborne Survey Ltd for the Nigerian Geological Survey Agency (NGSA). The survey was focused on mineral and groundwater development through improved geological mapping. It was acquired on a flight line trend in the NW–SE direction spaced 500m apart with tie lines in the NE-SW direction at a nominal spacing of 2000m. The nominal flight height was 80m above the terrain. The regional geomagnetic field was removed from the data using parameters of the January 2005 International Geomagnetic Reference Field (IGRF) model was used to determined Inclination and Declination as follows: Field Strength = 33129.9632nT; Inclination = -6.87339275; Declination = -2.51357917.

4. Theory of Spectral Analysis

Spectral depth analysis is the technique of estimating and interpretation the spectrum of potential field data. It has been utilized enormously over the years to procure depth to particular geological features or the Curie isotherm [9], [32], [33]. The spectral depth method is based on the principle that a magnetic field measured at the surface can be considered as an integral of magnetic signature from all depths [31]. Therefore, the Discrete Fourier Transform is the mathematical tool for spectral depth analysis and normally applied to regularly spaced data such as the aeromagnetic data. In addition, a Fast Fourier Transform (FFT) algorithm determines the Discrete Fourier Transform (DFT) of a series or its inverse. Moreover, the Fourier Transform is displayed mathematically as [30]:

$$Y_i(x) = \sum_{n=1}^{N}\left[a_n \cos\left(\frac{2\pi n x_i}{L}\right) + b_n \sin\left(\frac{2\pi n x_i}{L}\right)\right] \quad (1)$$

$Y_i(x)$ is the reading at the x_i position, L is the length of the crosssection of the anomaly, n is a harmonic number of the partial wave number, N is a number of data points, a_n is a real part of the amplitude spectrum and b_n is the imaginary part of the amplitude spectrum; for i = 0, 1, 2, 3,…, n.

The logarithms of the energy spectrum (Log E) are normally plotted against the domain frequency. Therefore, two (2) linear sections are drawn from each graph; and their gradients (m) are applied to calculate the centroid depth, (Z_0), the depth to the top boundary, (Z_t), Curie point depth, geothermal gradient (Z_b), and heat flow (q) using the relations as shown in equations 3 – 7 [12], [13], [23], [24], [34],[35], [37].

$$Slope(m_1, m_2) = \frac{\log Energy}{Frequency} \quad (2)$$

$$Z_0 = -\frac{m_1}{2\pi} \quad (3)$$

$$Z_t = -\frac{m_2}{2\pi} \quad (4)$$

$$Z_b = 2Z_0 - Z_t \quad (5)$$

$$\frac{dT}{dZ} = \frac{\theta_c}{Z_b} \quad (6)$$

$$q = \lambda\left[\frac{\theta_c}{Z_b}\right] \quad (7)$$

m_1 and m_2 are slopes, while $Z_0, Z_t, Z_b, \frac{dT}{dZ}$ and q are centroid depth, depths to the top boundary, Curie-point depth, geothermal gradient, and heat flow respectively. λ is given as $2.5Wm^{-1}C^{-1}$ known as the average subsurface thermal conductivity and θ is the Curie temperature, for magnetite, θ = 580^{0}C The negative sign (-) indicates the depth to the subsurface.

5. Methodology

The total magnetic intensity data were imported into Oasis Montaj 8 software and subsequently gridded using minimum curvature. These gridded data were further used to produce the total magnetic intensity maps and reduced to the equator.

Therefore, the data reduced to the equator were residualized (i.e. remove the regional) by subtracting upward continued data to 3000m 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.

6. Curie Point, Geothermal Gradient and Heat Flow Estimations

The residual magnetic map was split into eighteen (18) equal spectral cells with help of the filtering tool of the Microsoft excel software. Therefore, each profile covers a square area of 18 by 18 km. Fast Fourier Transform (FFT) method (equation 1) was employed in Microsoft (MS) Excel software program to convert the magnetic data into the radial energy spectrum for each and every block. The average radial energy spectra were estimated and displayed in a logarithm of energy versus frequency. Therefore, the slopes acquired from equation 2 were replaced into equations 3 and 4 to estimate centroid depth and depth to the top boundary Z_0 and Z_t respectively, for each of the eighteen spectral cells. While these depth values were further replaced into equation 5 to generate Curie point depth. These Curie point depth values were put into equation 6 to generate the geothermal gradient of the area. Ultimately, the heat flow was acquired using equation 7.

7. Results

Figure 3 shows the total magnetic intensity map, while Figure 5 gives the residual magnetic map divided into 18 equal spectra blocks for the estimation of geothermal parameters. On the other hand, Figure 6 gives the spectral plots of the logarithm of energy against frequency for blocks 1-18 respectively. The estimated values of Curie point depth, geothermal gradients, and heat flow of the area are recorded in Table 1. Finally, 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 (i.e. Curie-point depth, CPD), Figure 10 is the contour map of a geothermal gradient, and Figure 11is the contour map of the heat flow of the study area.

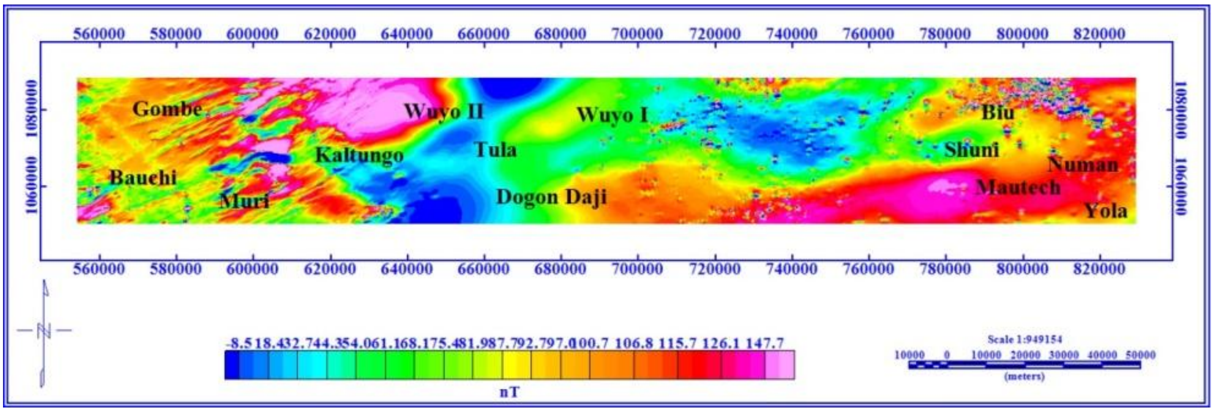

Figure 3: Aeromagnetic Anomaly Map of the Study Area

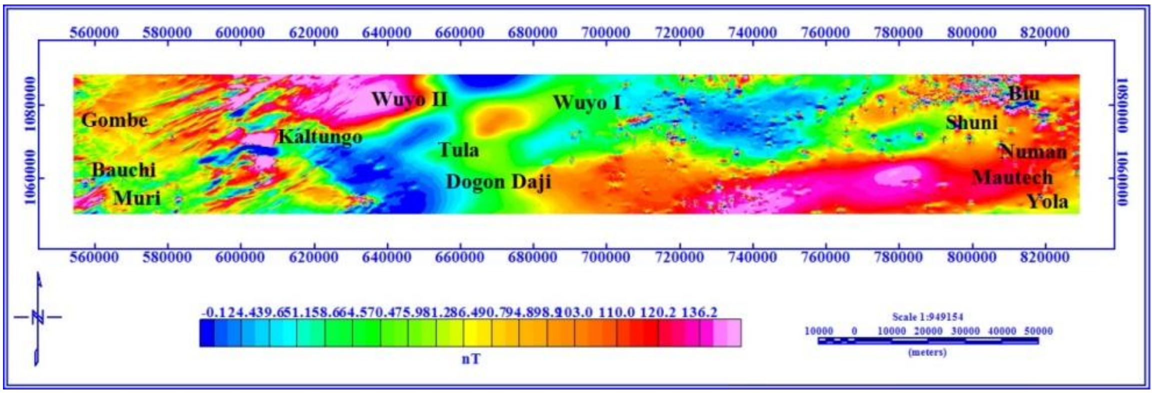

Figure 4: Reduced to Equator (RTE) of Aeromagnetic Map of the Study Area

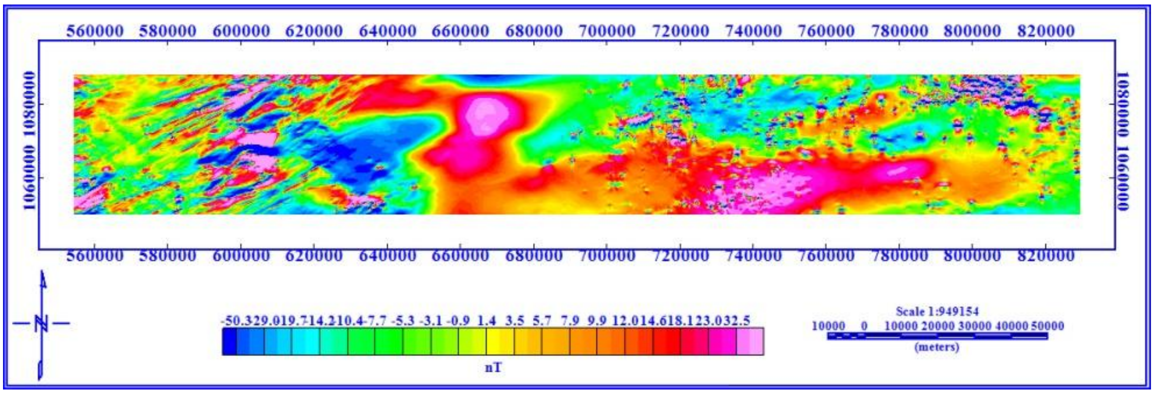

Figure 5: Residual of Upward continuation of aeromagnetic grid to 3000m altitude

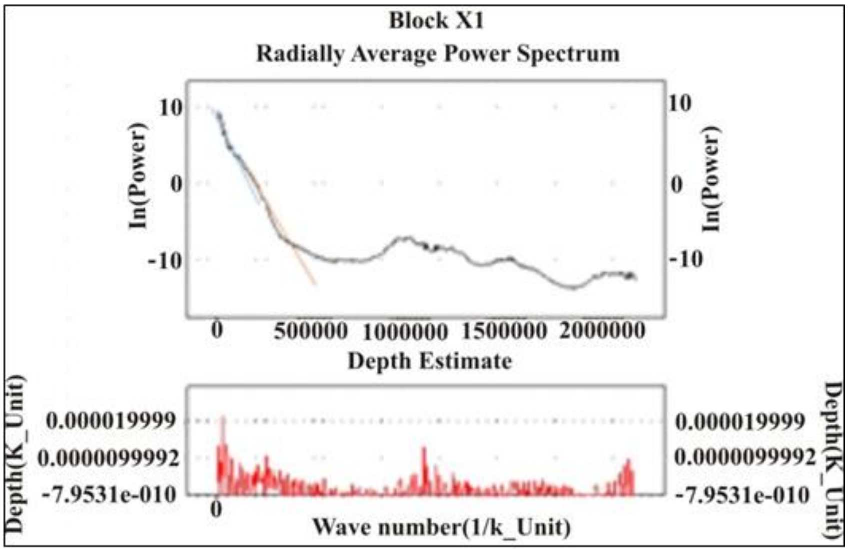

Figure 6: Radially Averaged Power for the 18 Spectral block cells (blocks 1-18) for Estimation of Depth to the bottom of magnetics source using spectral analysis.

Table 1: Calculated Curie depth, geothermal gradient and heat flow of Aeromagnetic data

Block	Lat.	Long.	Deep depth (Z_0)	Shallow depth (Z_t)	Curie depth $Z_b = 2Z_0 - Z_t$	Geothermal gradient $\left(\frac{dT}{dZ}\right) CKm^{-1}$	Heat flow (q) mWm^{-2}
1	9.49	9.98	2.71	0.52	4.90	118.37	295.93
2	9.91	9.98	3.84	0.62	7.06	82.15	205.38
3	10.33	9.98	3.31	0.75	5.87	98.81	247.03
4	10.75	9.98	3.62	0.52	6.72	86.31	215.78
5	11.17	9.98	2.89	0.58	5.20	111.54	278.85
6	11.59	9.98	3.87	0.58	7.16	81.01	202.53
7	9.49	9.86	3.47	0.58	6.36	91.19	227.98
8	9.91	9.86	3.29	0.74	5.84	99.31	248.28
9	10.33	9.86	2.09	0.96	3.22	180.12	450.30
10	10.75	9.86	3.54	0.52	6.56	88.41	221.03
11	11.17	9.86	3.86	0.60	7.12	81.46	203.65
12	11.59	9.86	3.71	0.93	6.49	89.37	223.43
13	9.49	9.75	3.75	0.51	6.99	82.98	207.45
14	9.91	9.75	3.62	0.75	6.49	89.37	223.43
15	10.33	9.75	3.51	0.79	6.23	93.01	232.53
16	10.75	9.75	3.68	0.56	6.80	85.29	213.23
17	11.17	9.75	3.39	0.81	5.97	97.15	242.88
18	11.59	9.75	3.47	0.86	6.08	95.39	238.48
Total average					5.19	130.79	326.42

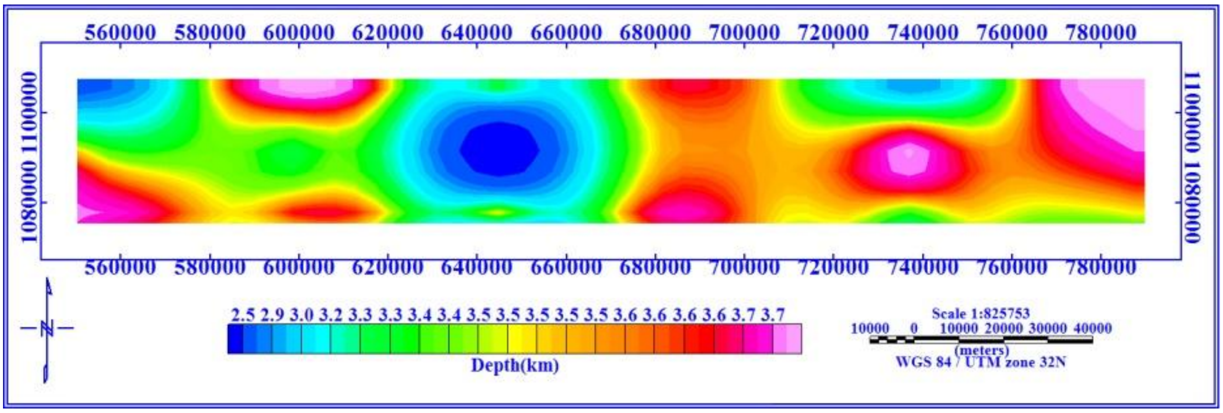

Figure 7: Aeromagnetic Depth to the bottom of magnetized body

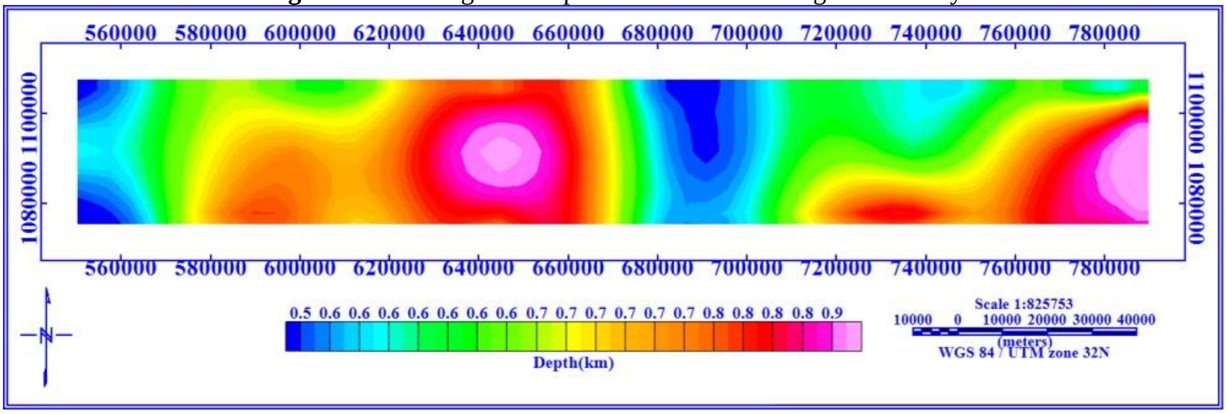

Figure 8: Aeromagnetic Depth to the top magnetic source map

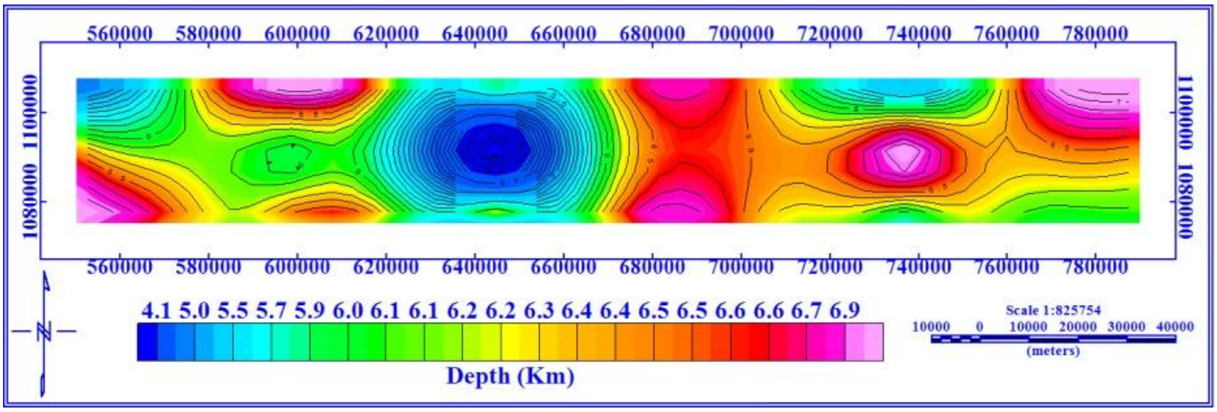

Figure 9: Aeromagnetic curie depth contour map of the study area (Km)

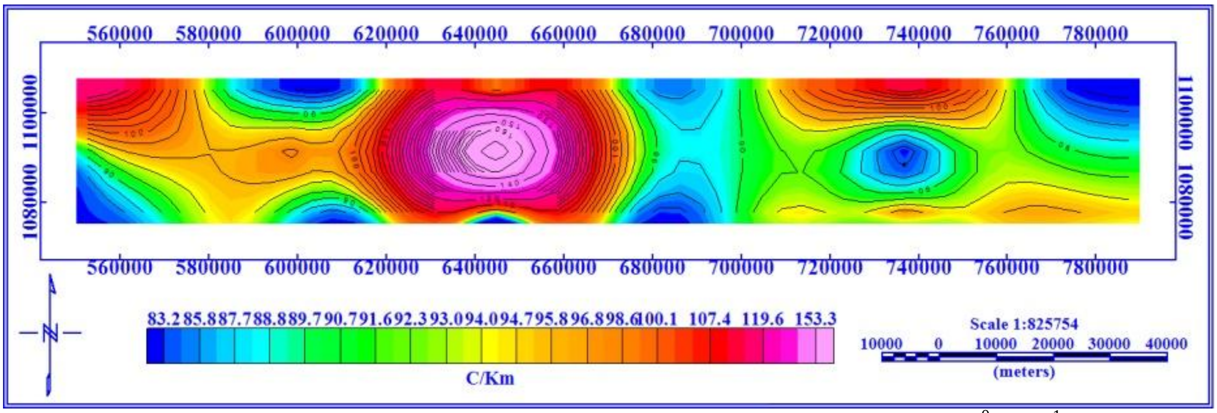

Figure 10: Aeromagnetic geothermal gradient contour map of the study area ($^{0}CKm^{-1}$)

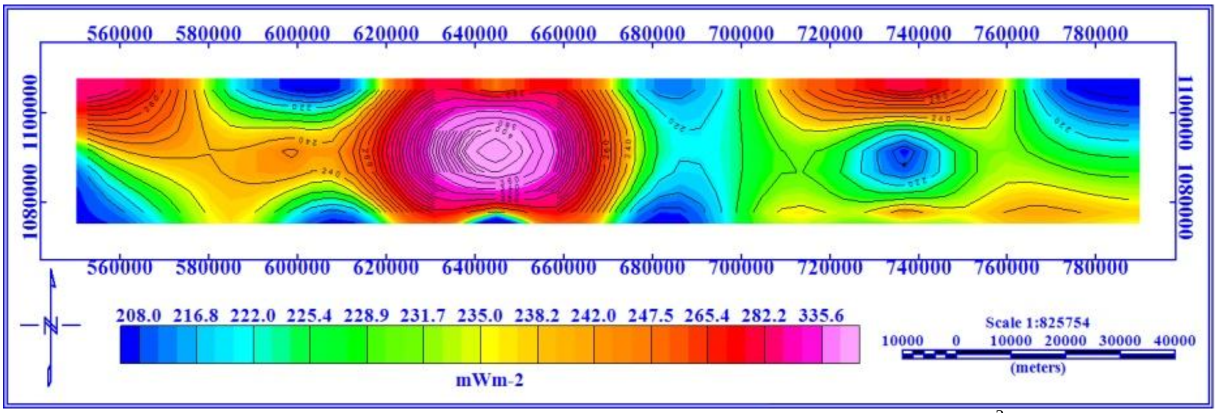

Figure 11: Aeromagnetic heat flow contour map of the study area (mWm^{-2})

8. Discussion

From the qualitative interpretation (Figure 4), it is seen that the magnetic anomalies of the area range between - 0.1 to 136.3nT. The area is noticeable by the high level of (pink and red colors) and low level of (blue color) magnetic signatures. Consequently high magnetic intensity is observed in the northwest and southeastern regions of the study area, while, the northern and southwestern region of the area are marked by low magnetic intensity. The variation in magnetic field intensity could be a result of the degree of the strike, change in depth, and change in magnetic susceptibility, differences in lithology, dip, and plunge [25].

At the same time, observation from Table 1 shows that the calculated Curie point depths in the area range between 3.22 to 7.16 km, with an average depth of about 5.19km. The 2D contour Curie depth map of the area (Figure 9) shows that the deepest Curie depth is located in the northeast, northwest, and southeastern parts of the study area, while the shallowest Curie depth is observed in the central part of the area. The deep Curie-point depth could be as a result of thick sediment, while the shallow Curie-point depth in the region could be on account of the intrusion of igneous rocks or magmatic materials. The geothermal gradient of the area range between 81.46 to 180.12^{0}Ckm^{-1}, with an average of 130.79^{0}Ckm^{-1}. The area with the highest geothermal gradient is observed in the central part of the study area and decreases towards the western region, while the lowest geothermal gradient is located in the north and eastern parts of the area (Figure 10). Table 1 shows that the heat flow in the region varies between 202.53 to 450.30mWm^{-2}, with an average heat flow of 326.42mWm^{-2}. The highest heat flow is located in the central part and decreases towards the western region of the area, while the lowest heat flow is noticed in the north and western parts of the study area (Figure 11).

Critical observations from values in Table 1 reveal that the heat flow and geothermal gradient rise as the Curie depth drop. This trend concurs with the results obtained by other researchers who estimated an average Curie point depth in Wikki Warm Spring, situated in parts of Benue basin, which join up the Chad Basin in the north to be 10.72 km, with an average thermal gradient of 54.11°C/km and average heat flow values of 135.28mWm^{-2} [2]. It was reported that heat flow close to 60mWm^{-2} is required for the considerable generation of geothermal energy, while values ranging from 80 to 100mWm^{-2} and above indicate anomalous geothermal conditions [22]. Region noticed with high heat flow values relate to active volcanic and metamorphic rocks and can also be governed by deep magnetic mass that is yet to complete its cooling in association with young volcanism and faulted structures. Comparably, according to some authors, areas with a high geothermal gradient could lead to the generation of hydrocarbon at shallow depth, while areas with low geothermal gradient may not be feasible for hydrocarbon investigation, except at a significant depth [14]. This is because geothermal gradient plays an important role in hydrocarbon generation; along with various other factors such as the rapid burial of organic debris in oxygen-depleted surroundings.

9. Conclusion

The qualitative and quantitative analysis of aeromagnetic data of Chad Basin northeast, Nigeria has been performed. The qualitative interpretation reveals that the magnetic anomalies of the area range from -8.8 to 147.7nT. Consequently high magnetic intensity is observed in the northwest and southeastern region of the study area, while, the northern and southwestern regions of the area are marked by low magnetic intensity. The Curie point depth obtained varies between 3.22 and 7.16km, with an average of 5.19km. Its map defines a region of deepest curie depth in the northeast, northwest, and southeastern parts of the study area, while the shallowest Curie depth is observed in the central part of the area. The geothermal gradient ranges from 81.46 to 180.12^{0}Ckm^{-1}, with an average of 130.79^{0}Ckm^{-1} and is high in the central region and decreases towards the western region, while the lowest geothermal gradient is located in the northeastern parts of the area. Its corresponding heat flow varies between 202.53 and 450.30mWm^{-2}, with an average of 326.42mWm^{-2}. The highest heat flow is located in the central region and decreases towards the western region of the area, while the lowest heat flow is seen in the northeast and western parts of the area. The heat flow and geothermal gradient increase as the Curie depth decreases, this is equally observed in the previous research works. The high geothermal gradient and heat flow values obtained in the area are indications that the area might be suitable for geothermal energy and hydrocarbon generation.

10. Acknowledgments

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