# Determination of the curie point Depth,geothermal gradient and heatflow of Guzabure and its environs,Chad Basin, Nigeria using Aeromagnetic data

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***Abstract***
The Curie point depth,geothermal gradient and heatflow of Guzabure and its Environs Chad Basin Northeastern,Nigeria was estimated from spectral analysis using Aeromagnetic data.Six aeromagnetic maps covering an area bounded by latitudes12° 00' to 13° 00' North and longitudes12° 30' to 14° 00' East were used as basic data for determining the nature of the of the magnetic anomalies over the area. Regional anomally was removed from the total magnetic intensity field to obtain the residual anomaly field using polynomial fitting. The total magnetic intensity of the study area shows range of magnetic anomalies which vary from -88.4nT to 238.3nT while the residual values are from -169.0nT to 140.5nT. The residual magnetic field was used to bring into focus local features which tend to be obscured by the broad features of the regional field. The areas of strong positive anomalies likely indicate a higher concentration of magnetically susceptible minerals while areas with broad magnetic lows are likely areas of lower susceptibility mineralsThe calculated Curie depths from spectral analysis ranged from 10.220 km to 22.721 km . The result showed that the Curie point depth within the basin is not a horizontal level surface, but is undulating, and the geothermal gradient associated with it ranged from 25.527 °C/km to 56.751 °C/km with an average value of 38.517 °C/km while the corresponding heat flow ranged from 63.818 $mWm^{-2}$ to 141.878 $mWm^{-2}$. Results of Curie point depth in conjunction with heat flow values revealed a distinct inverse linear relationship. The average geothermal gradient of 38.517 °C/km obtained in this work indicates the possibility of hydrocarbon generation in the study area.

***Keywords : Aeromagnetic data,spectral analysis, curie isotherm depth,Geothermal Gradient,Heat flow***

## Introduction

Curie Point Depth (CDP) is known as the depth at which the dominant magnetic mineral in the crust passes from a ferromagnetic state to a paramagnetic state under the effect of increasing temperature (Nagata, 1961). It can also be defined as the depth at which rocks lose their ferromagnetic magnetization as a result of an increase of the temperature in the crust above the Curie temperature.

Thermal structure of the crust involving CPD estimations have been published for various tectonic settings by several authors such as Blakely and Hassan (1981); Connard *et al.*,(1983);

Okubo *et al.*, (1985, 1989); Blakely (1988);Okubo and Matsunaga (1994); Hisarli (1996); Banerjee *et al.*,( 1998); Tanaka *et al.*,( 1999 ); Nur et al., (1999).

The assessment of variations of the Curie isotherm of an area can provide valuable information about the regional temperature distribution at depth and the concentration of subsurface geothermal energy (Tselentis, 1991). One of the important parameters that determine the relative depth of the Curie isotherm with respect to sea level is the local thermal gradient (Hisarli, 1996). Measurements have shown that a region with significant geothermal energy is characterised by an anomalous high temperature gradient and heat flow ((Tselentis, 1991). It is therefore expected that geothermally active areas would be associated with shallow Curie point depth (Nuri et a.,l 2005). It is also a known fact that the temperature inside the earth directly controls most of the geodynamic processes that are visible on the surface (Nwankwo et al., 2011). In this regard, heat flow measurements in several parts of African continent have revealed that the mechanical structure of the African lithosphere is variable (Nur, et al 1999). The technique of using aeromagnetic data to estimate curie point depth is not new and it has been applied to various parts of the world, either by analyzing isolated magnetic anomalies due to discrete sources or employing the frequency domain approach. This research utilizes spectral analysis to estimate the curie point depth of Guzabure and its environs Chad Basin,Norteastern Nigeria.The main aim of this research is to provide clues to likely productive zones for geothermal exploitation. If the geothermal energy is well harnessed, it would help Nigeria to improve on the epileptic power supply issues which has been the situation for quite a while.

## Geology of the Study Area

The Chad Basin lies within a vast area of central and west Africa at an elevation of between 200 and 500m above sea level and covering approximately 230,000km$^2$ (Ajana *et al.*, 2014). It is the largest area of inland drainage in Africa (Barber, 1965; Matheis, 1976; Avbovbo *et al.,* 1986). It extends into parts of the republic of Niger, Chad, Cameroon, Nigeria and Central Africa. The Nigerian Chad Basin (Figure.1) is about one tenth of the Basin (Wright, 1976; Falconer, 1911). This Bornu-Chad Basin is a broad sediment-filled depression spanning northeastern Nigeria and adjoining parts of the Republic of Chad. The stratigraphy of Bornu-Chad Basin has been reported by several workers (Avbovbo *et al.*, 1986; Obaje, 2009; Nwankwo and Ekine, 2009). The stratigraphic sequence shows that Chad, Kerri-kerri and Gombe formations have an average thickness of 130 to 400 m. Below these formations are the Fika shale which is a dark grey to black in color, with an average thickness of 430 m. Others are Gongila and Bima formations with an average thickness of 320 m and 3500m, respectively.

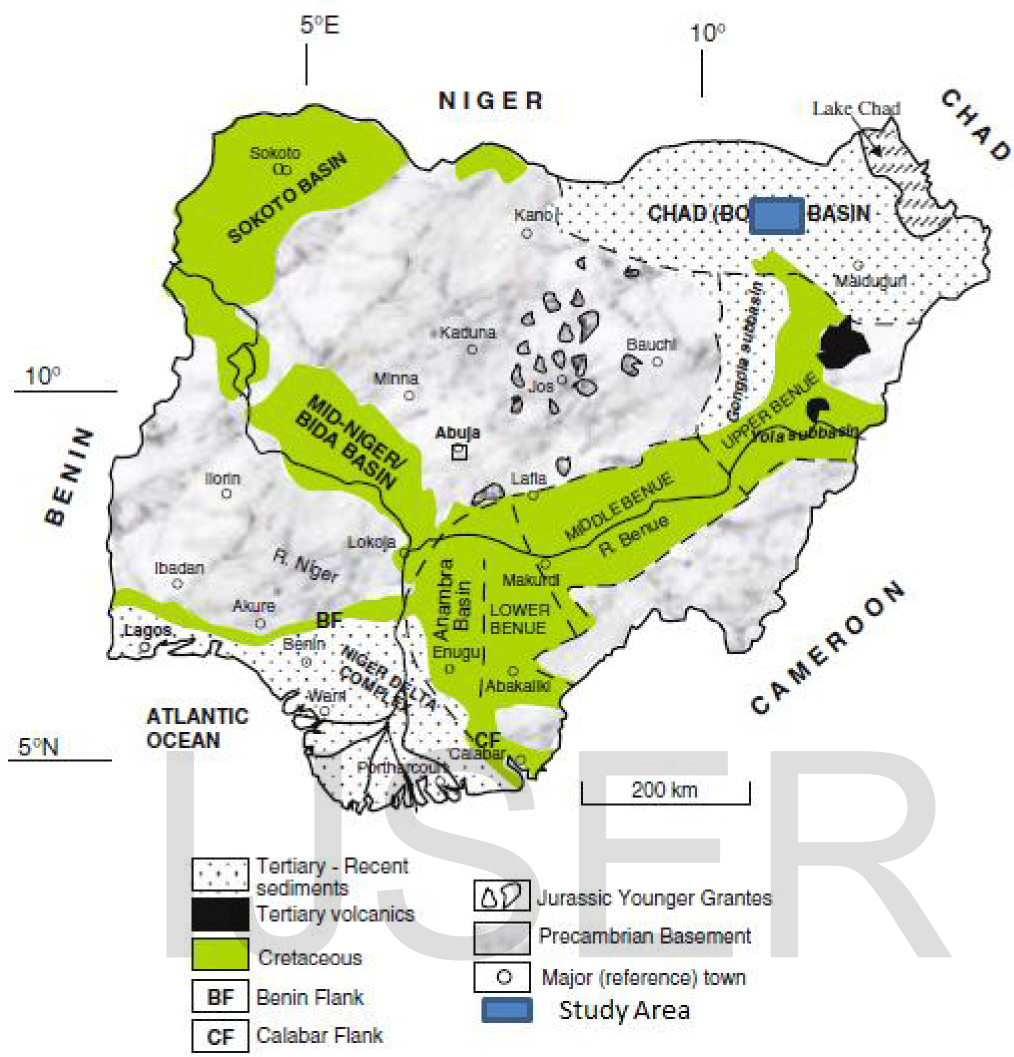


Figure 1. Geological map of Nigeria showing the study area

## Materials and Methods

Six aeromagnetic maps were acquired from National Geological Survey Agency (NGSA), Abuja. These are sheet 44 ( Guzabure), 45 (Gudumbali), 46 (Mungonu),66 ( Gubio), 67 (Masu) and 68 ( Marte).The six sheets were merged together to produce a single composite sheet which formed the study area using Ms Excel software. The data were acquired along a series of NW – SE flight lines with a spacing of 5km and an average flight elevation of about 80m while tie lines occur at about 2km interval. The geomagnetic gradient was removed from the data using the International Geomagnetic Reference Field (IGRF)The regional anomaly was removed from the total magnetic intensity (TMI) field (figure 2) to obtain the residual anomaly field (figure 3.) using first order polynomial fitting.

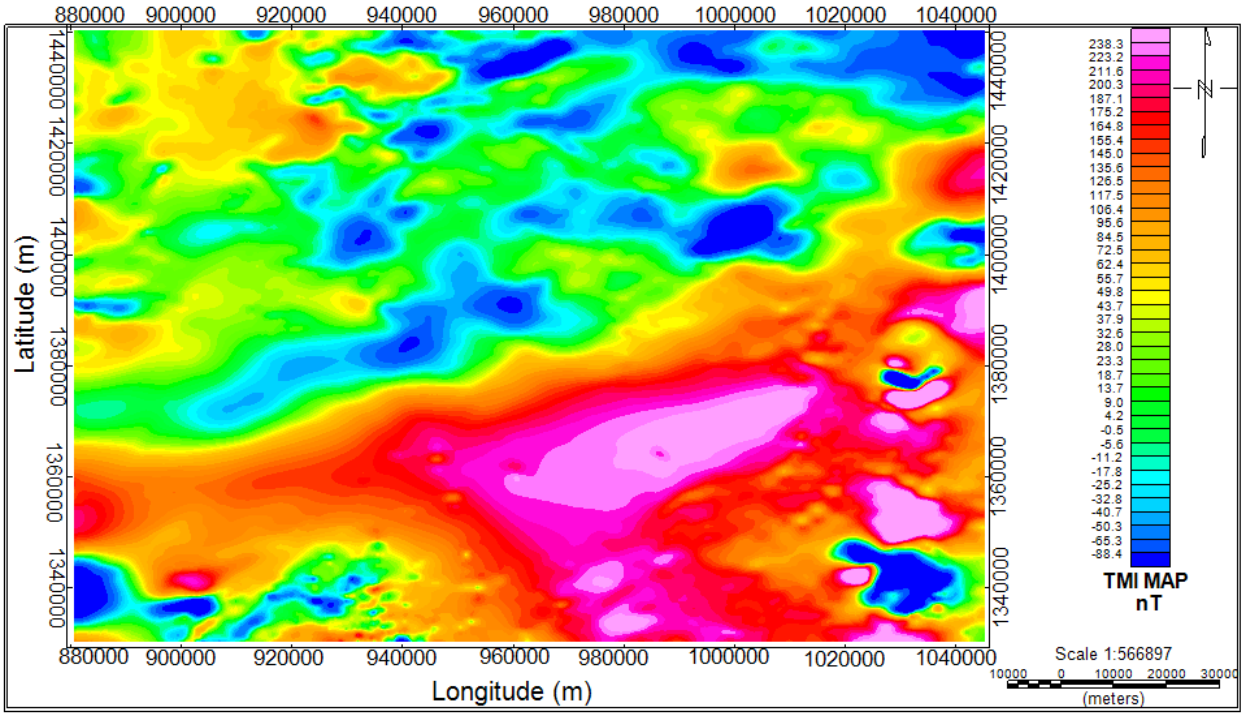


Figure 2: Total magnetic intensity (TMI) map of the study area.

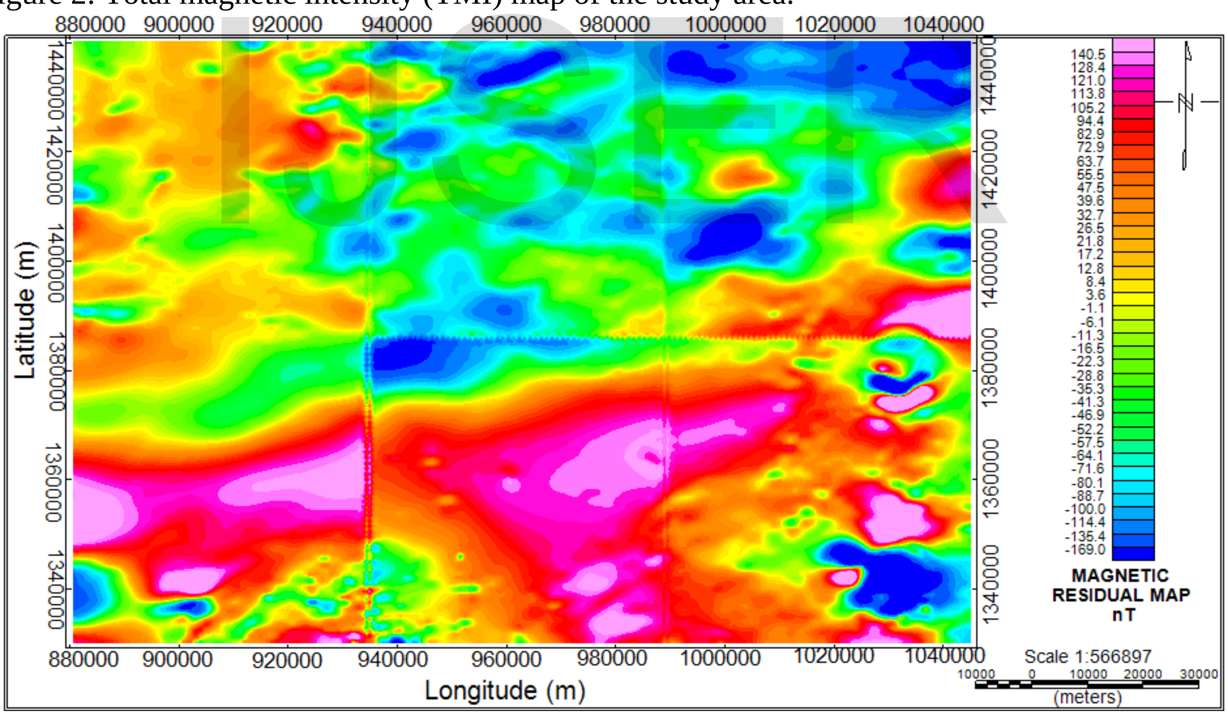


Figure 3: Residual magnetic map of the study area.

**Curie point Depth Estimation**

The methods for estimating the Curie depth have been described by several authors, Bhattacharyya and Leu, (1975); Okubo et al., (1985); Tanaka, *et al*, (1999); Stampolidis, *et al*., (2005); Nwankwo et al.,( 2011) and Kasidi and Nur , (2012) .The methods are classified into two categories: those that examine the shape of isolated magnetic anomalies (Bhattacharyya and Leu, 1975) and those that examine the patterns of the anomalies (Spector and Grant, 1970). However, both methods provide the relationship between the spectrum of the magnetic anomalies and the depth of a magnetic source by transforming the spatial data into frequency domain. In this research, the method adopted is the latter in which case the top boundary and the centroid of magnetic sources were calculated from the spectrum of magnetic anomalies and used to estimate the basal depth of magnetic source.

To compute the depth to Curie point, the residual anomaly data of the study area was divided into twenty four blocks. Each block covers a square area of 27.5km by 27.5 km in order to accommodate longer wavelength so that the deep depth to the basement up to about 7 km could be investigated. The analysis was carried out using computer software FOURPOT.The first step in the analysis is to estimate the depth to centroid ($Z_o$) of the magnetic source from the slope of the longest wavelength part of the spectrum,

$$\ln\left[\frac{P(s)^{1/2}}{/s/}\right]=\ln A - 2\pi/s/\,Z_o \qquad (1)$$

Where P(s) is the radially averaged 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 spectral segment
(Okubo et al, 1985),

$$\ln P(s)^{1/2} = \ln B - 2\pi/s/\,Z_t \qquad (2)$$

Where B, is the sum of constants independent of **/s/.**
Then the basal depth ($Z_b$) of the magnetic source was calculated from the equation 3 (Okubo et al., 1985; Tanaka et al.,1999).

$$Z_b = 2Z_o - Z_t \qquad (3)$$

The obtained basal depth ($Z_b$) of magnetic sources is assumed to be the Curie point depth (Bhattacharyya and Leu, 1975; Okubo et al., 1985) and the graphs of the logarithms of the spectral energies for various blocks are obtained.Six representative plots are shown in figure 4a-f.The curie point depths were then deduced as presented in Table 1

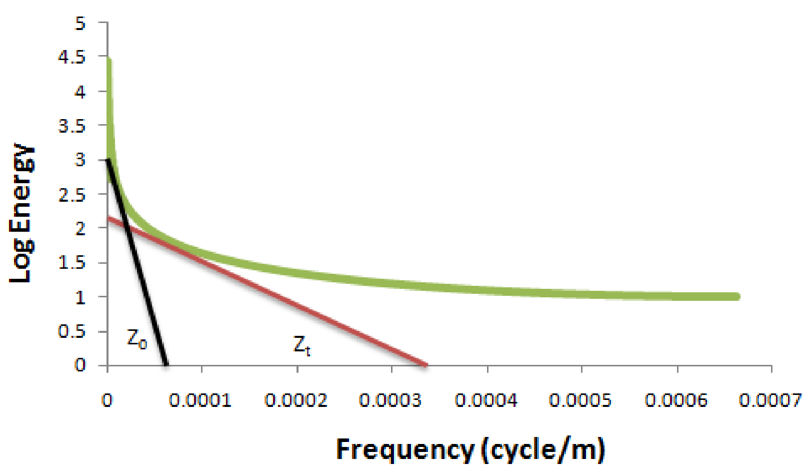


Figure 4(a): Spectral plots of logarithm of Energy against Frequency.

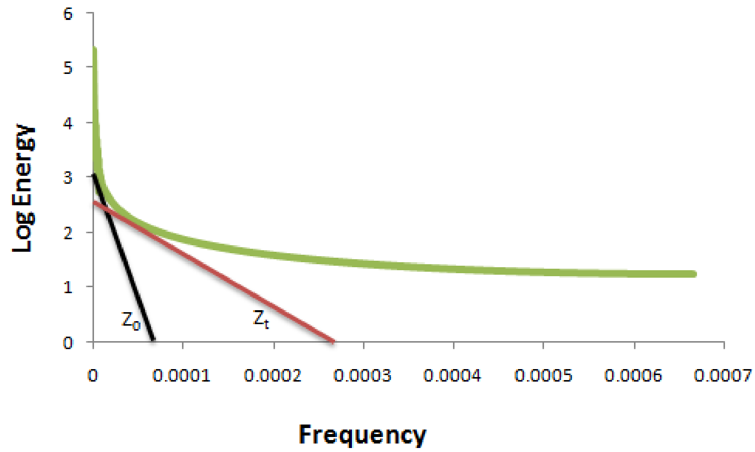


Figure 4(b): Spectral plots of logarithm of Energy against Frequency.

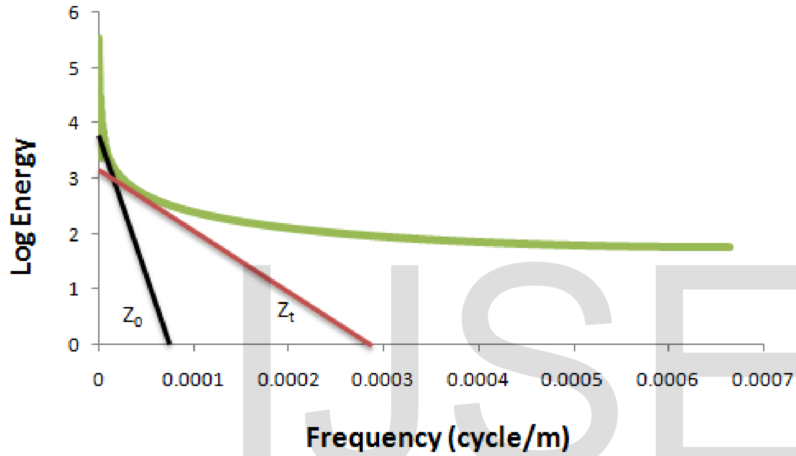


Figure 4(c): Spectral plots of logarithm of Energy against Frequency

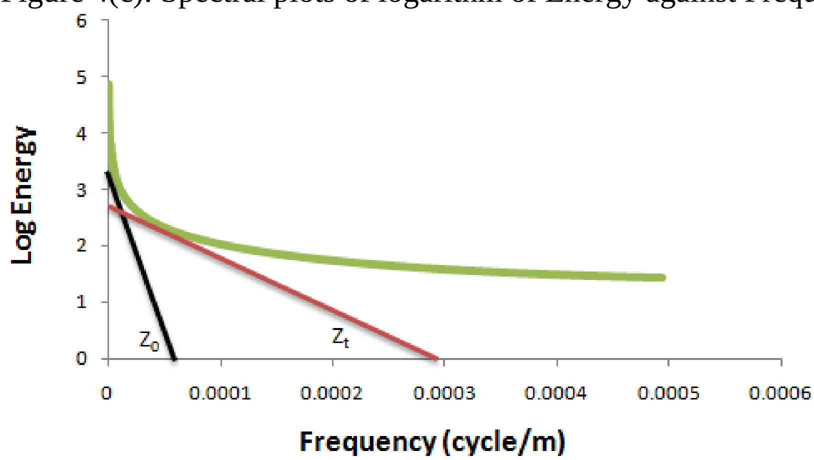


Figure 4(d): Spectral plots of logarithm of Energy against Frequency

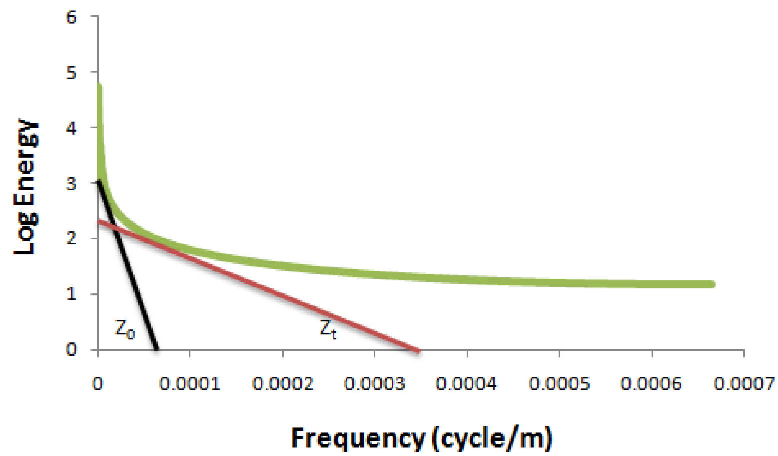


Figure 4(e): Spectral plots of logarithm of Energy against Frequency.

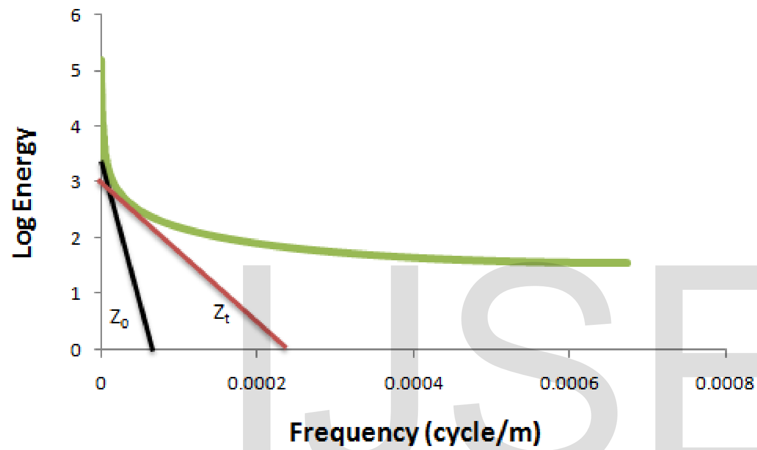


Figure 4(f): Spectral plots of logarithm of Energy against Frequency (cycle per meter).

Table 1.. Calculated Curie depth, Geothermal gradient and Heat flow

| BLOCKS | Depth to Centroid (Z0) in km | Depth to top boundary(Zt) in km | Curie Depth ($Z_b$) in km | Geothermal gradient ($\frac{dT}{dZ}$) in °C/km | Heat Flow(q) in mWm-2 |
|---|---|---|---|---|---|
| 1 | 8.302 | 1.013 | 15.591 | 37.201 | 93.003 |
| 2 | 8.461 | 1.720 | 15.201 | 38.155 | 95.388 |
| 3 | 9.412 | 1.706 | 17.118 | 33.882 | 84.706 |
| 4 | 8.495 | 1.998 | 14.992 | 38.687 | 96.718 |
| 5 | 7.746 | 1.274 | 14.217 | 40.796 | 101.990 |
| 6 | 7.655 | 1.393 | 13.916 | 41.679 | 104.198 |
| 7 | 11.689 | 1.601 | 21.777 | 26.634 | 66.585 |
| 8 | 12.556 | 2.391 | 22.721 | 25.527 | 63.818 |
| 9 | 7.901 | 0.814 | 14.988 | 38.698 | 96.745 |
| 10 | 8.967 | 1.783 | 16.151 | 35.911 | 89.778 |
| 11 | 9.253 | 1.171 | 17.334 | 33.461 | 83.653 |
| 12 | 8.477 | 2.171 | 14.782 | 39.236 | 98.090 |
| 13 | 10.178 | 1.592 | 18.764 | 30.911 | 77.278 |
| 14 | 8.785 | 1.960 | 15.609 | 37.158 | 92.895 |
| 15 | 8.727 | 1.539 | 15.915 | 36.444 | 91.110 |
| 16 | 8.295 | 1.939 | 14.650 | 39.590 | 98.975 |
| 17 | 8.069 | 1.967 | 14.171 | 40.929 | 102.323 |
| 18 | 7.308 | 0.995 | 13.621 | 42.581 | 106.453 |
| 19 | 7.823 | 1.077 | 14.568 | 39.813 | 99.533 |
| 20 | 7.693 | 0.796 | 14.589 | 39.756 | 99.390 |
| 21 | 8.196 | 1.221 | 15.171 | 38. 231 | 95.578 |
| 22 | 8.138 | 0.936 | 15.340 | 37.810 | 94.525 |
| 23 | 7.068 | 3.916 | 10.220 | 56.751 | 141.878 |
| 24 | 7.309 | 3.990 | 10.628 | 54. 573 | 136.433 |
| Average | | | | 38.517 | 96.293 |

ISSN 2229-5518

## Estimation of Heat Flow and Thermal Gradient

In the absence of heat flow data in the study area, we use an empirical relation which is a one-dimensional heat conductive transport model to estimate heat flow and geothermal gradient. The model is based on Fourier's law. In one dimensional case under assumptions, the direction of temperature variation is vertical and the temperature gradient (dT/dz) is assumed constant, Fourier's law then takes the form

$$q = \lambda \left[\frac{dT}{dZ}\right]: \qquad (4)$$

Where *q* is the heat flow and λ is the coefficient of thermal conductivity.
According to Tanaka, *et al*, (1999), the Curie temperature ($\theta_c$) can then be defined as

$$\theta = \left[\frac{dT}{dZ}\right] Z_b \qquad (5)$$

$$\left[\frac{dT}{dZ}\right] = \left[\frac{\theta}{Z_b}\right] \qquad (6)$$

In addition to that, from Equation (4),(5) and Equation (6) a relationship was determined between the Curie point depth ($Z_b$) and the heat flow (*q*) as follows

$$q = \lambda \left[\frac{dT}{dZ}\right] = \lambda \left[\frac{\theta}{Z_b}\right] \qquad (7)$$

From equation 6, it is evident that Curie point depth is inversely proportional to the heat flow we were thus able to estimate the heat flow (q) in the study area using this equation. We also compute the thermal gradient from Equation (6) using a Curie point temperature of 580 °C and thermal conductivity of 2.5$Wm^{-1}$°$C^{-1}$ (Nwankwo, et al., 2011). (Table 1). However, using an average thermal conductivity, value of 2.5$Wm^{-1}$°$C^{-1}$ (Nwankwo, et al 2011; Tanaka et al 1999), we then calculate the value for λ geothermal gradient in the study area using the empirical relation between, curie depth, Temperature and geothermal gradient (equation 6).

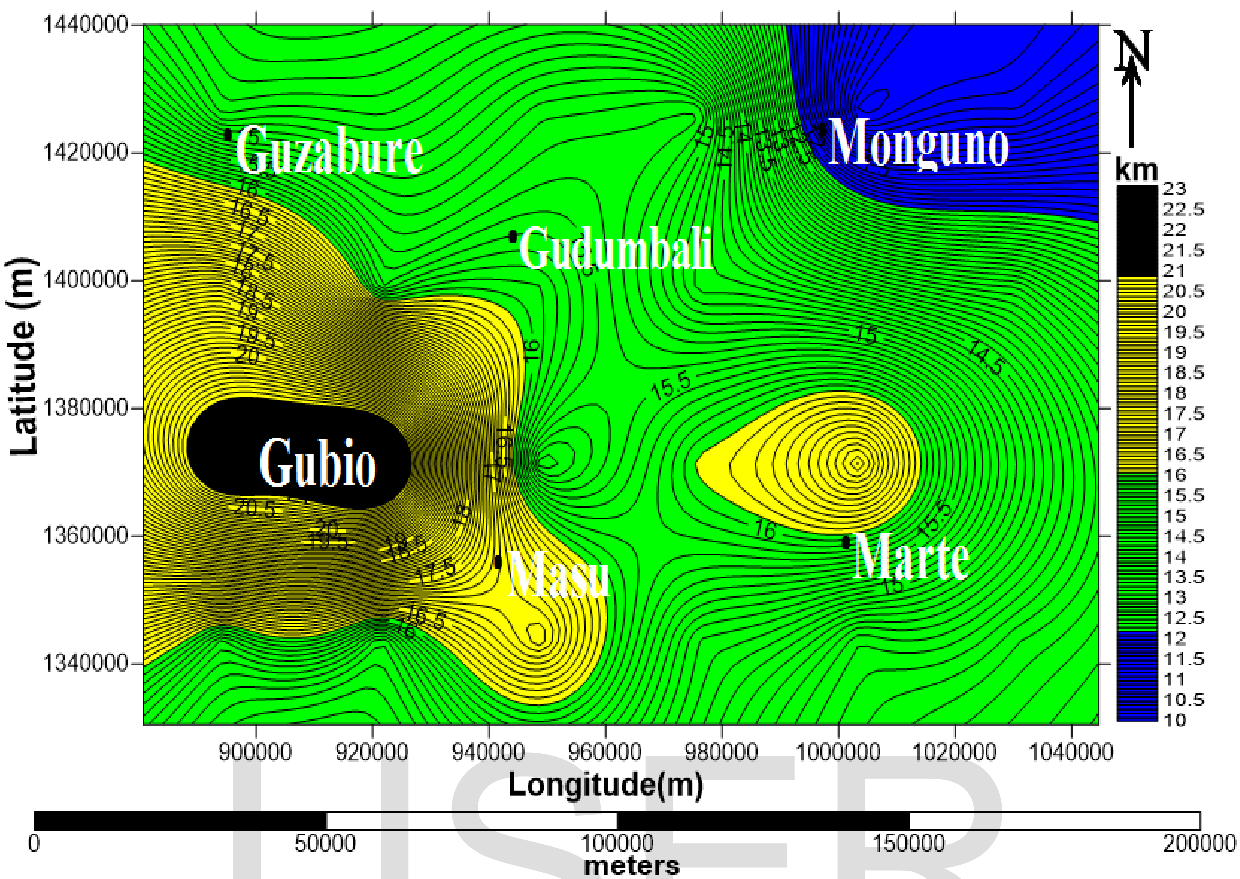


Figure.5 Curie Point Depth Map of the Study Area

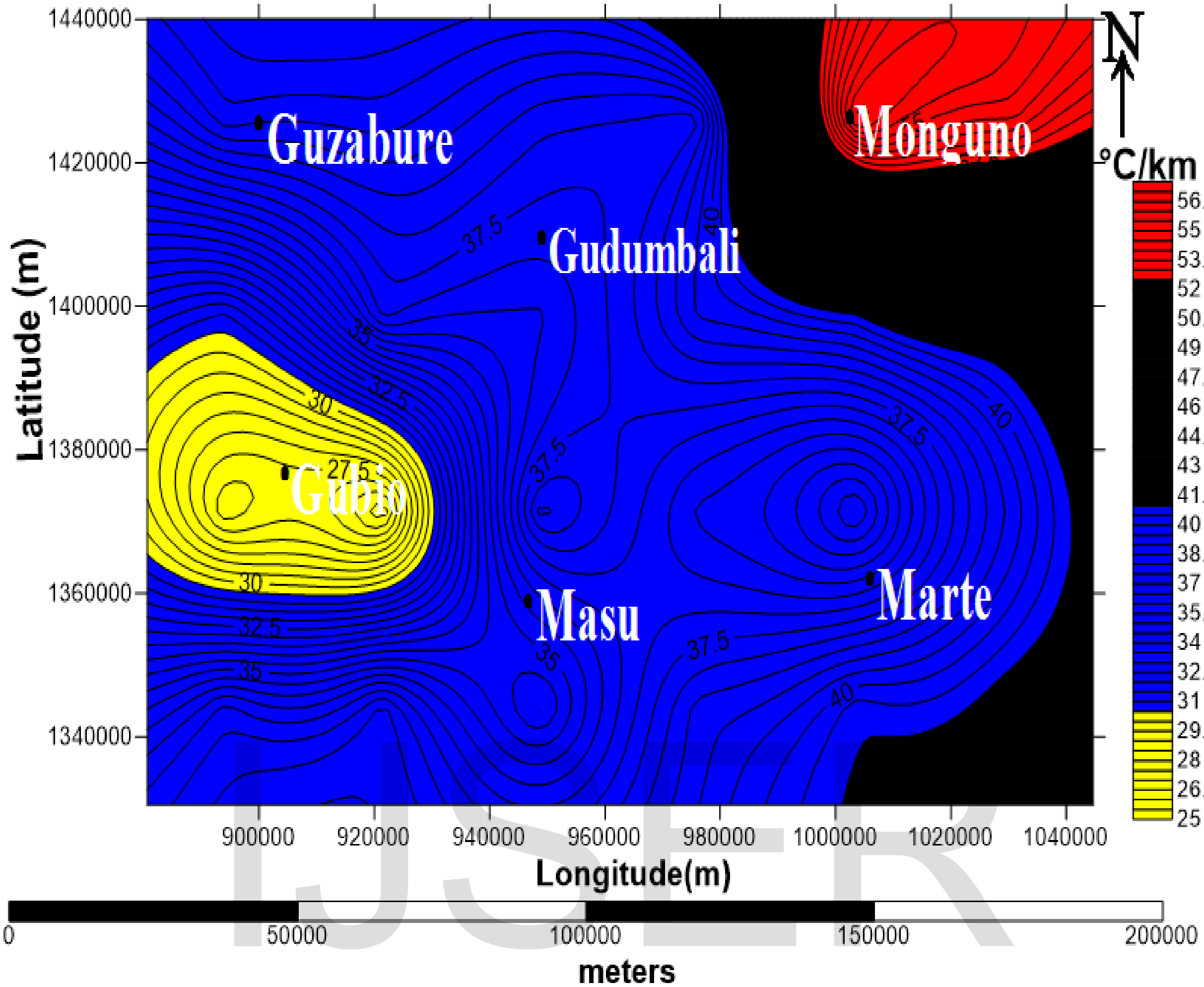


Figure. 6: Geothermal gradient contour map of the study area (Contour interval of 0.5 °C/km).

**Relationship between Curie Depth and Heat Flow**

From Table 1, a plot of the Curie isotherm depth versus heat flow values showed that, the heat flow was inversely proportional to the Curie depth. Therefore, the heat flow in the study area increases with decreasing Curie isotherm depth (Figure 8). The curie depth obtained for the study area (Table1) was used to construct the Curie isotherms surface which are presented in ( Figure 5) likewise the heat flow and geothermal gradient tpresented in a similar way (Figure 7&6 ) These give the direct nature of heat distribution in subsurface of the study area

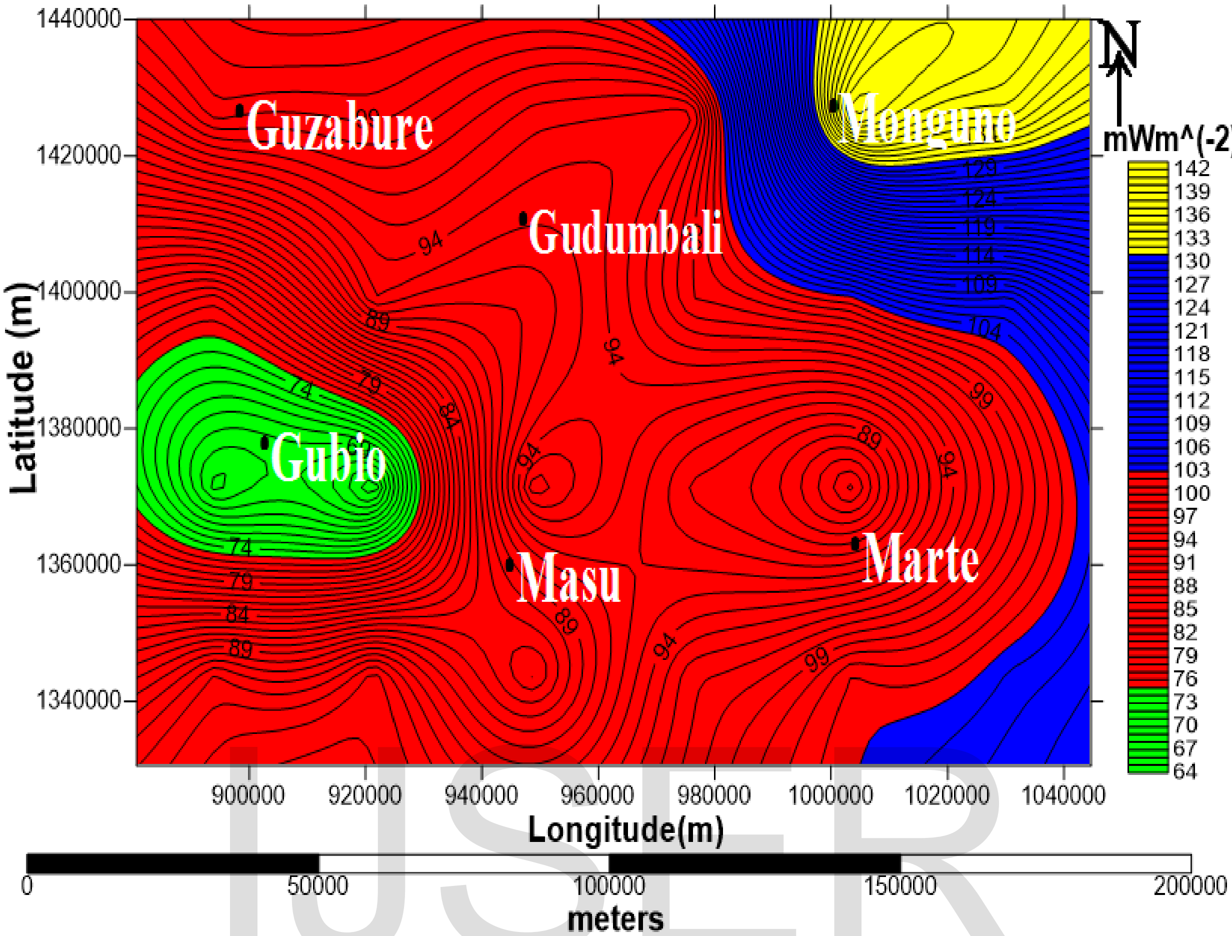




Figure. 7: Heat flow contour map of the study area (Contour interval of 1 $mWm^{-2}$).

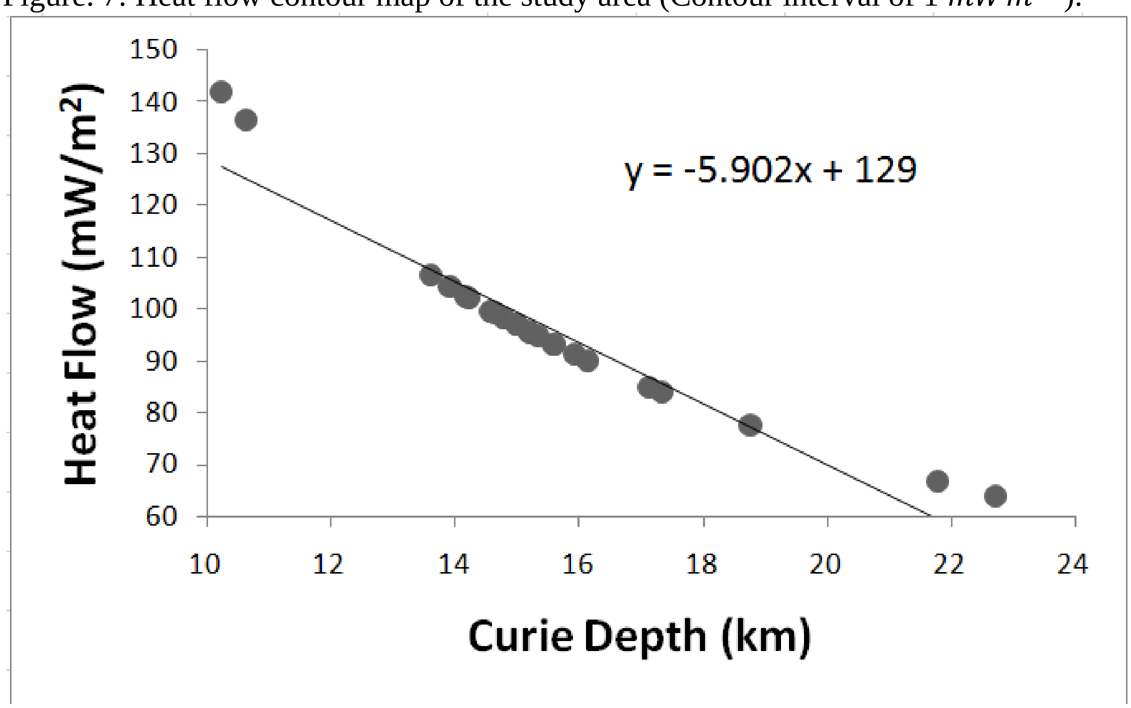


Figure 8: Plot of heat flow against Curie point depth

## Discussion of result

The total magnetic intensity of the study area shows range of magnetic anomalies which vary from -88.4nT to 238.3nT while the residual magnetic anomaly values are from -169.0nT to 140.5nT. The residual magnetic field was used to bring into focus local features which tend to be obscured by the broad features of the regional field. The areas of strong positive anomalies likely indicate a higher concentration of magnetically susceptible minerals while areas with broad magnetic lows are likely areas of lower susceptibility minerals.
Figure 5 shows the result of the investigation of the Curie Point Isotherm of the study area and it reveals the Curie isotherm depth varies between 10 km to 23 km approximately. A closer look at the map reveals that the deepest (black colour) Curie point depth lies at the southwest while the shallowest (blue colour) is observed to be conspicuous in the north eastern part of the study area. The calculated Curie depths from spectral analysis range from 10.220 km to 22.721 km (Table 1). The result shows that the Curie point depth within the basin is not a horizontal level surface, but is undulating, and the geothermal gradient associated with it ranges from 25.527 °C/km to 56.751 °C/km with an average value of 38.517 °C/km (figure 6) while the corresponding heat flow (figure 7) ranges from 63.818 $mWm^{-2}$ to 141.878 $mWm^{-2}$. From figure 8, it was evident that, heat flow increases with decrease in Curie point depth, and vice-versa. This showed that region of high geothermal energy is characterised by an anomalous high temperature gradient and heat flow. It was therefore expected that geothermally active areas will be associated with shallow Curie point depth. This result compared favourably with the results obtained by earlier researchers that worked in Chad Basin. Anakwuba and Chinwuko (2015) obtained a geothermal gradient range between 17.45 and 25.64 $^{o}$C/km and corresponding mantle heat flow of about 46.00 $mWm^{-2}$ and 67.60 $mWm^{-2}$ from one dimensional spectral analysis of aeromagnetic data of eastern part of the Nigerian Chad Basin. Nwankwo and Ekine (2009) got a geothermal gradient of 30 to 44 °C/km and an average geothermal gradient of 34 °C/km from bottom hole temperature logs of Chad Basin, Nigeria. The average geothermal gradient of 38.517 °C/km obtained in this work indicates the possibility of hydrocarbon generation in the study area which agrees with the work of Nwankwo and Ekine (2009) on estimation of geothermal gradients in the Chad Basin, Nigeria. They revealed that sediments with relatively higher geothermal gradients (35 to 44 $^{o}$C/Km) mature earlier (low oil window) than those with low geothermal gradient values.

## Conclusion

The Curie point depth of the study area was estimated from spectral analysis. The inferred Curie point depth obtained ranges from 10.220 km to 22.721km Literatures such as Connard et al., 1983; Tsokas et al., 1998; Tanaka et al., 1999; Stampolidis and Tsokas, 2002; Pamukcu, 2004; Dolmaz et al., 2005 indicate that the Curie point depth is greatly dependent upon geological conditions. Curie point depths are shallower than 15km for volcanic and geothermal fields, between 15 – 25km for island arcs and ridges, and deeper than 20km in plateaus and trenches (Tanaka et al., 1999). Therefore, these areas with variations less than 15km maybe recommended for further investigations for geothermal reconnaissance
studies.

**ACKNOWLEDGEMENTS**
The authors are grateful to the Geological Survey Agency of Nigeria for releasing the aeromagnetic maps.

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