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Evaluation of Sedimentary Thickness and Curie Point Depths in The Eastern Part of Bornu Basin, North-Eastern Nigeria

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Abstract
The Curie point depth is the depths at which subsurface temperature (approximately 580 °C) loses spontaneous magnetization within the rock units and magnetic minerals show features of paramagnetic susceptibility. In this research work sedimentary thickness and Curie point depths of the eastern parts of Bornu basin were investigated. The aeromagnetic data was subdivided into twenty-five (25) overlapping blocks, and each block was analyzed to obtain depth to basement (Z_t) of the magnetic sources and depth to centroid (Z_o). The depth values were then used to estimate CPD and Curie temperature (θ) within the study area. The result shows that the depth to basement (Z_t) varies between 2.55 and 7.4 km, with an average value of 5.96 km, the depth to centroid (Z_o) values varies between 8.4 and 14.15 km with an average value of 11.08 km, the CPD values varies between 15.11 and 19.0 km with an average value of 16.20 km.

Keywords: *Sedimentary thickness, Curie Point Depth (CPD), Spectral Centroid Analysis, Curie temperature, Bornu Basin.*

INTRODUCTION
The Curie point depth is the depths at which subsurface temperature (approximately 580 °C) loses spontaneous magnetization within the rock units and magnetic minerals show features of paramagnetic susceptibility (Khojamli *et al.,* 2016). The depth at which the temperature reaches the Curie point is known as the Curie point depth (Billim, 2017). Curie point temperatures are not the same, the variation of the temperature depends upon the region, geology, and geochemical rock constituents (Khojamli *et al.,* 2016). Understanding sedimentary thickness and CPD variation within a certain location plays an important role in identifying geothermal and hydrocarbon resources. Akbar and Fathianfur, (2017); Nwanko and Sunday (2017) noted that, CPD is less than 10 km in volcanic and geothermal regions, 5

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to 15 km in island arcs and ridges zones, greater than 20 km in plateaus areas, and it is more than 30 km in trenches areas.

Therefore, a good knowledge of thermal conditions is important for a quantitative understanding of different type of geodynamic processes (Bansal *et al.,* 2011). One of the major challenges in subsurface exploration is having direct access to in situ data, mostly due to limited depth and non-uniform distribution of boreholes, and lack of technique to observe undisturbed temperatures from the earth`s surface (Dimri, 2000). Only proxy data are available to derive an idea about the thermal structure of the crust (Bansal *et al.,* 2011). CPD values provides one of the important proxy information (Ross *et al.,* 2006). Despite the important role played by subsurface temperature yet, this parameter is most poorly known. Mapping Curie point isotherm where it forms the base of magnetic susceptibility could be key to understanding the depth boundary condition in the continental crust (Salem *et al.,* 2014). If enough depths can be determined, an isothermal surface at the Curie temperature can be defined (Hsieh *et al.,* 2014)

Recently, statistical models based on spectral analysis received significant attention when it comes to the application of geophysical and geological applications such as estimating average sedimentary and crustal thickness (Eletta and Udensi, 2012). The spectral method is based on the expression of the power spectrum for the total field magnetic anomaly produced by a uniformly magnetized rectangular prism (Bhattacharyya and Leu, 1975). Spector and Grant, (1970) assumed that a number of independent ensembles of rectangular prismatic blocks are responsible for generating anomalies in a magnetic map. Accordingly, Curie point depth can be used to describe the depth to the inferred Curie point transition of magnetite (Selim and Aboud, 2013). Curie point depths provide general information on both regional and local temperature distribution as well as geothermal gradient (Saibi *et al.,* 2015). Curie point depth provide crucial information quantitatively about the thermal structure of the crust by analyzing the differences between short wavelengths and long wavelength anomalies of the magnetic data which will in turn provide a proxy on CPD locations (Eletta and Udensi, 2012).

Very few works had been conducted within the study area, there are very few records pertaining CPD estimation in the eastern parts of Bornu basin with only one record of CPD estimation in the study area, our estimated CPD is not consistent with the CPD results obtained by Anakwuba and Chinwuko (2012, 2015) in the study area. Their CPD values of 21.45 and 31.52 km depicts overestimation considering the method adopted for the interpretation. We realized that the power spectrum was not normalized by the wave number before the implementation of spectral analysis technique, and the power spectrum was taken only along five profiles, this cannot produce reliable and overall picture of the study area, and these could have significantly affected their results. To overcome this challenges, we employ the use of spectral centroid method which normalizes the power spectrum by the wave number instead of using the conventional spectral analysis technique.

LOCATION AND GEOLOGY OF THE STUDY AREA

The study area (i.e Eastern parts of the Bornu Basin) are located between the latitude 11.5^{o} 00′ to 13^{o} 00′ N and longitude 12.5^{o} to 14^{o} 00′ E, North - Eastern Nigeria. The semi-arid climate of Bornu basin is typical of the Sudan region of north central Africa (Miller *et al.,* 1965). The climate is characterized by a long dry season. The Nigerian sector of the Chad Basin constitutes about 6.5% of the entire basin and extends an area of 152,000 km^{2} (Goni *et al.,* 2016).

The geological history of the Bornu basin began during the Upper Cretaceous (probably uppermost Albian) when over 1000 m of continental sediments constituting the Bima sandstones were deposited uncomformably on the Precambrian basement. These beds are mainly restricted to the southwestern margin of the Basin (Cratchley, 1960). During the Turonian, there was an extensive transgression and the Gongila Formation, a mixed limestone/shade sequence was deposited. These sediments probably attain a thickness of over 320 m. They hardly extend Far East in to the Chad Basin. At the end of the cretaceous there was Folding during which the cretaceous beds were folded into a series of anticlines and synclines that were later partly eroded creating and erosional unconformity at the base of the tertiary deposits. This has been confirmed by borehole data from Maiduguri (Cratchely, 1960).

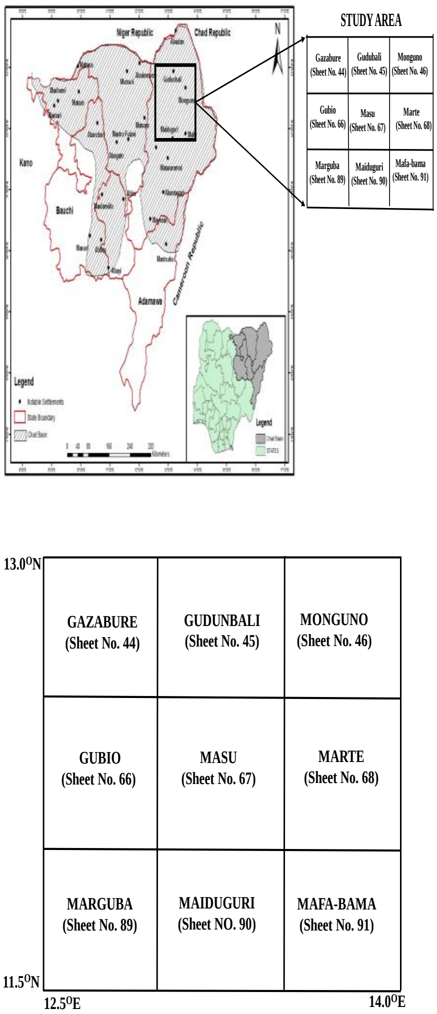


Figure 1: Location Map and aeromagnetic Map sheets number and names of the study area.

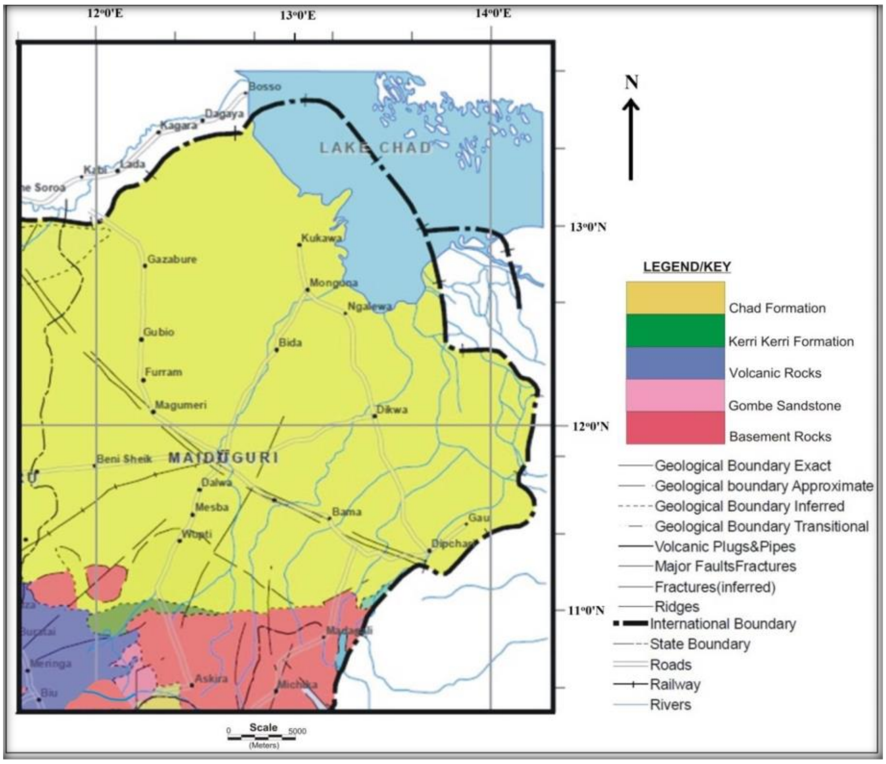


Figure 2: Geologic Map of the Chad basin, modified after Nigerian Geological Survey Agency (NGSA).

METHOLOGY

Method of acquiring data

The study area (Eastern Bornu Basin) is covered by nine (9) aeromagnetic maps of total-field magnetic intensity in half-degree sheets obtained from the Nigerian Geological Survey Agency (NGSA). The magnetic data were presented in form of contour lines at 10 nT (nano Tesla) interval published in the ½ degree aeromagnetic maps on a scale of 1:100,000. The maps are numbered, and names of places and coordinates (longitude and latitudes) written for easy reference and identification. A base value of 25,000 gamma was removed from the TMI values before plotting the contour map. Consequently this value was added back to the digitized values prior to the analysis (Reeves, 2005).

The production of data set and unified aeromagnetic map for the study area

The digitized data extracted from each aeromagnetic map sheet was merged together in a way that is marginable from each columns and rows in order to produce a unified data set. This was in turn used to generate combined aeromagnetic map (unified map).

Filtering and gridding

The data in text format were imported to Oasis Montaj (Version 7.2) software and the TMI map was obtained. Next, filtering was done on the data and various maps were obtained. Filtering is a process of isolating signals that are of interest by identifying the behavior and variations of wavelengths in order to enhance magnetic anomalous features depending on the target thatis aim to be achieved by the interpreter.

Regional and residual magnetic maps

Regional magnetic field data was subtracted from magnetic total magnetic field intensity data using Fortran 77 software, the International Geomagnetic Reference Formula (IGRF) and coordinates of the TMI data values were generated using Fortran 77 computer program. The generated IGRF was then subtracted from the TMI data values. The obtain TMI data values with corresponding coordinates were subsequently exported into Oasis Montaj (Version 7.0) software worksheet environment, in which the regional and residual maps were obtained.

Production of Total Magnetic Intensity (TMI) map

The contour intervals that are contain in the TMI map depicts 25,000 nT magnetic values between each two successive contour intervals, that is to say, 25,000 nT magnetic values were added to the aeromagnetic data while preparing the contour intervals. Solid and hachured contours represent magnetic highs and magnetic lows respectively. Magnetic values of 33,000 nT was approximated to be undisturbed geomagnetic field (Parasnis, 1986).

Blakely (1996) introduced the power density spectra of the total-field anomaly($\Phi_{\Delta T}$) using the following mathematical equations:

$$\Phi_{\Delta T}\left(k_x, k_y\right) = \Phi_M\left(k_x, k_y\right)F\left(k_x, k_y\right)$$

(1)

$$F\left(k_x, k_y\right) = 4\pi^2 C_m^2 \left|\Theta_m\right|^2 \left|\Theta_f\right|^2 e^{-2|K|Z_t}\left(1 - e^{-|k|(Z_b - Z_t)}\right)^2 \quad (2)$$

Φ_M = Power-density spectra of the magnetization

C_m = Proportional constant

Θ_m and Θ_f = Factors for magnetization direction and geomagnetic field direction, respectively

Z_b *and* Z_t = Top and Basal depth of magnetic sources, respectively.

The above equations can be simplified by noting that all terms, except $\left|\Theta_m\right|^2$ and $\left|\Theta_f\right|^2$ are radially symmetric. The average of Θ_m and Θ_f is constant. Hence, the radial average of $\Phi_{\Delta T}$ is:

$$\Phi_{\Delta T}\left(|k|\right) = Ae^{-2|k|Z_t}\left(1 - e^{-|K|(Z_b - Z_t)}\right)^2 \quad (3)$$

Where A is a constant. For wavelengths less than about twice the thickness of the layer, Eqn. (3) can be simplified as:

$$In\left[\Phi_{\Delta T}\left(|k|\right)^{\frac{1}{2}}\right] = InB - |k|Z_t$$

(4)

Where B is a constant.

From the slope of the power spectrum of total field anomaly, Z_t can be estimated. Consequently equation (3.5) can be written as:

$$\Phi_{\Delta T}\left(|k|\right)^{\frac{1}{2}} = Ce^{-|k|Z_0}\left(e^{-|k|(Z_t - Z_0)} - e^{-|k|(Z_b - Z_t)}\right)^{\frac{1}{2}}$$

(5)

Where C is constant. At long wavelength, equation (5) is written as:

$$\Phi_{\Delta T}\left(|k|\right)^{\frac{1}{2}} = Ce^{-|k|Z_0}\left(e^{-|k|(-d)} - e^{-|k|(d)}\right) \approx Ce^{-|k|Z_0}\,2|k|d$$

(6)

$$In\left\{\left[\Phi_{\Delta T}\left(|k|\right)^{\frac{1}{2}}\right]/|k|\right\} = InD - |k|Z_o$$

(7)

Where D is constant.

By fitting a straight line through the high and low wavenumber parts from the radially average power spectrum of $[In\ (\Phi_{\Delta T}(|k|)^{\frac{1}{2}}\ ]$ and $[(\Phi_{\Delta T}(\frac{|k|)^{\frac{1}{2}}}{|k|}\ )]$, $Z_t\ and\ Z_0$ can be estimated. Finally, the basal depth of the magnetic source is:

$$Z_b = 2Z_0 - Z_t$$
(8)

The Curie temperature (θ) was obtained from the Curie point depth (Z_b) and the thermal gradient *dT/dZ* (Tanaka *et al*., 1999). Using the following equation:

$$\theta = \left[\frac{dT}{dZ}\right] Z_b$$
(9)

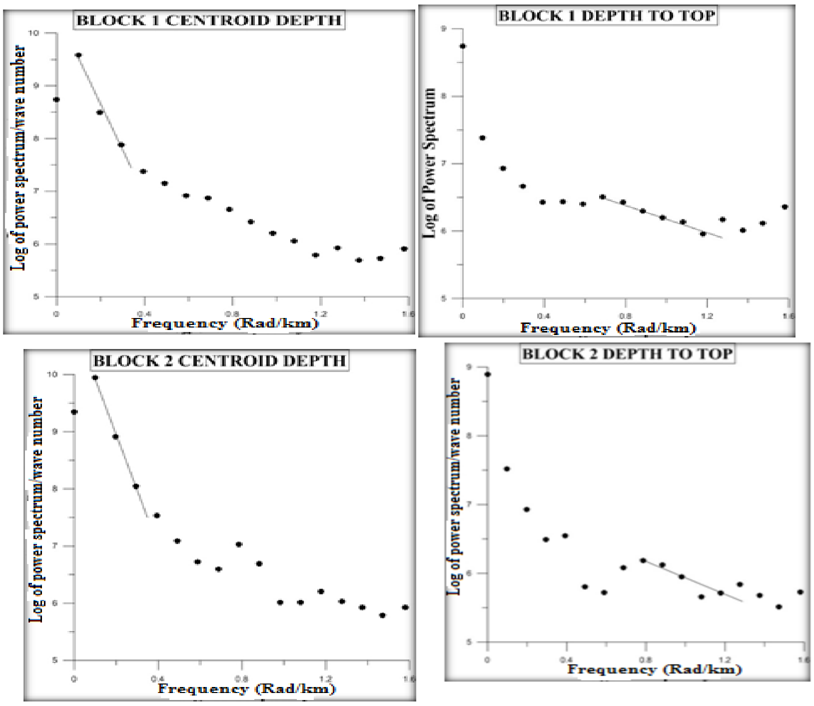


Fig 3: Example of radially average frequency-scaled power spectrum and radially average power spectrum for two blocks and linear fitting to Z_o and Z_t.

RESULTS AND DISCUSSION

Residual maps have been employed to highlight shallower anomalies and provide the spatial distribution of magnetic anomalies resulting as a shallower source bodies or magnetic anomalous bodies that intruded closer to the surface. The construction of residual maps is one of the best methods of interpreting potential field maps qualitatively (Khalil *et al.,* 2016). The residual magnetic intensity map (Figure 4) shows spatial distributions of Green and Blue colours which are depicting negative magnetic field anomalies while Pink and Red colours represent positive magnetic field anomalies. Some of the anomalies have elongated shapes, while some have semicircular shapes, oriented along E-W direction in the study area. Generally, the negative residual magnetic anomalies (Blue and Green) were predominantly observed in the upper northern half and lower southern half of the study area, while positive (Pink and Red coloured) residual magnetic anomalies were predominantly observed in the central part, extreme NW corner and upper southern half of the study area. The RMI map clearly shows four main structural trends, NE-SW, E-W, NW-SE and ENE-WSW directions, in the order of decreasing predominance, and these are related to Pre Pan-African and Pan-African trends.

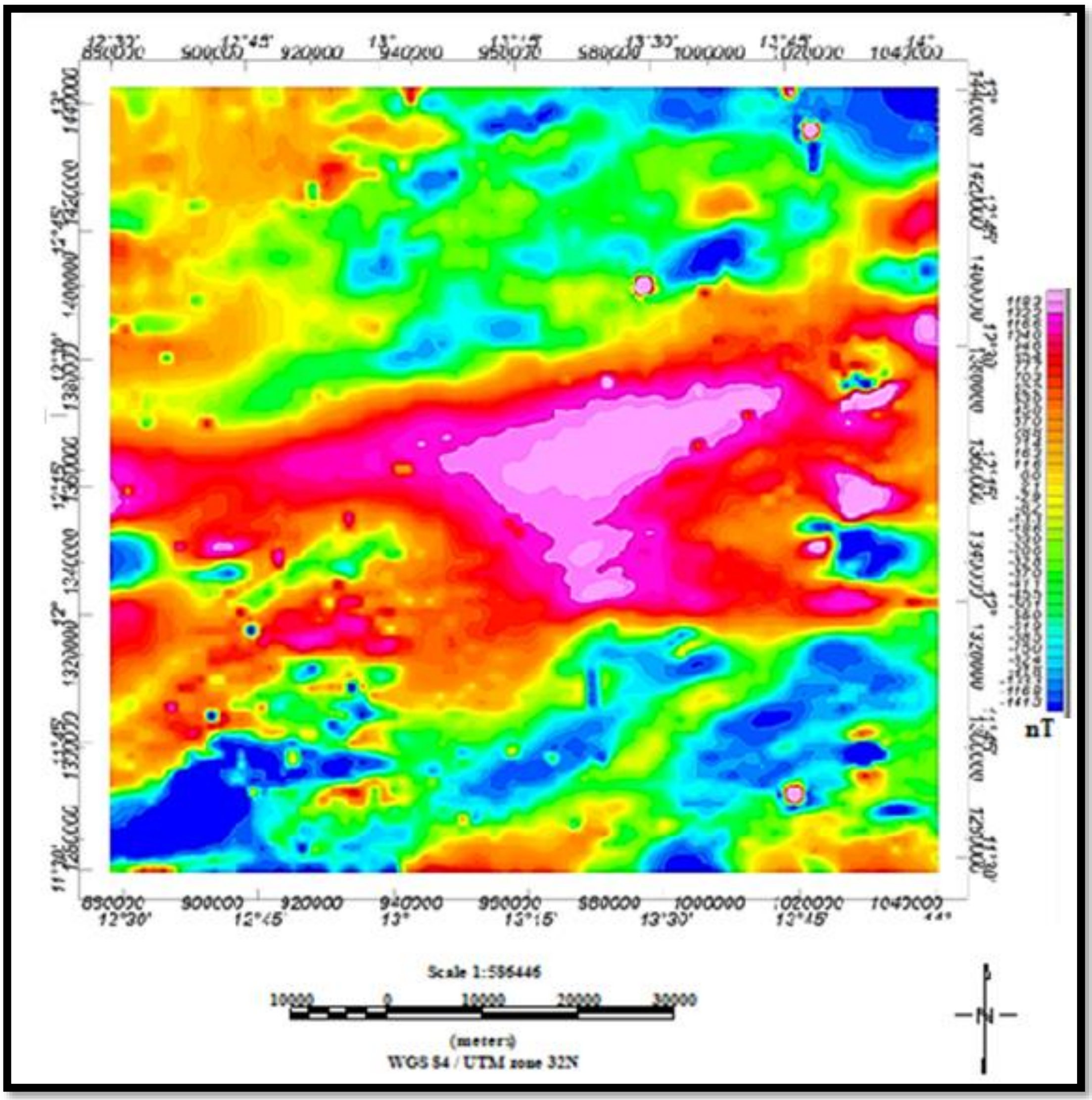


Figure 4: Colour shaded Residual Magnetic Intensity Map. The colour bar situated at the right hand side of the map depicts the residual magnetic intensity values in nT.

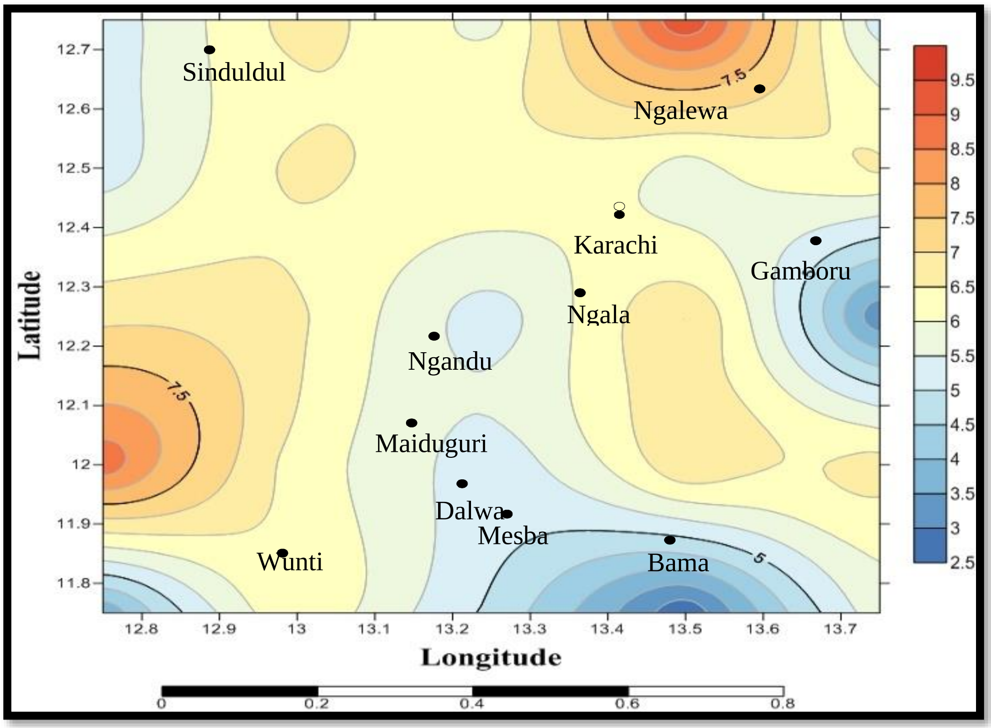
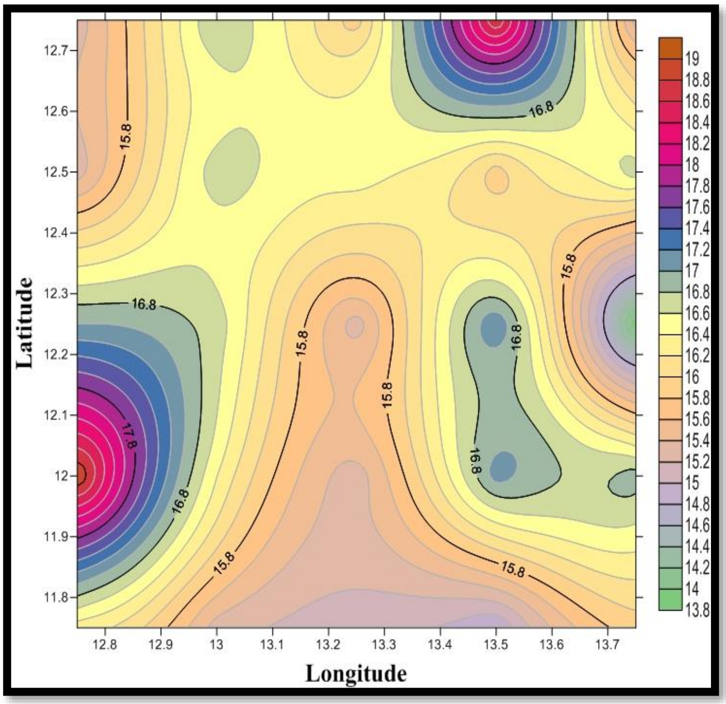


Figure 5: Colour shaded Sedimentary thickness Map. The colour bar situated at the right hand side of the map indicates the Sedimentary thickness values in Km.



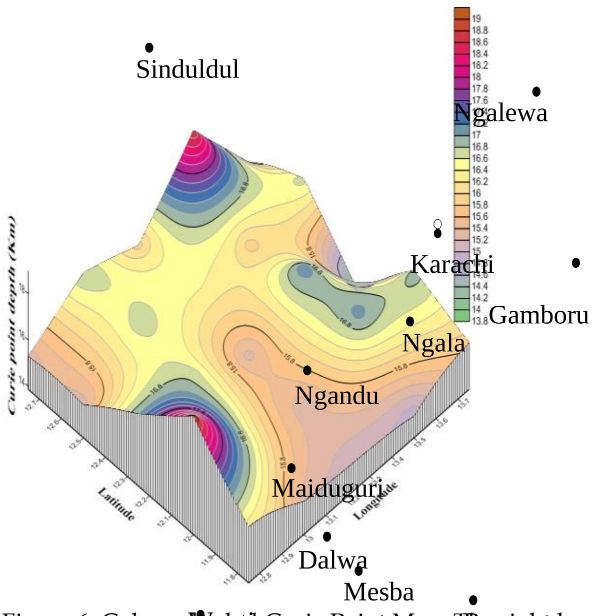


Figure 6: Colour shaded Curie Point Map. The right hand side of the represent the 3-D map of the Curie point depths in km.

Table 1: Estimated results of Sedimentary thickness, depth to centroid, Curie point depth, Curie temperature and their locations.

Number of Block (Km)	Latitude (°E)	Longitude (°N)	Sedimentary thickness (Km)	Centroid depth (Km)	CPD (Km)	Curie temp (°C)
Block 1	12.75	11.75	3.56	9.95	16.3	580.1
Block 2	13.25	11.75	4.89	10.0	15.1	580.1
Block 3	13.75	11.75	5.79	10.8	15.9	579.9
Block 4	12.75	12.25	6.87	11.9	17.0	580.0
Block 5	13.25	12.25	5.20	10.3	15.3	580.0
Block 6	13.75	12.25	3.05	8.40	13.8	579.9
Block 7	12.75	12.75	5.21	10.3	15.3	580.1
Block 8	13.25	12.75	5.81	10.9	15.9	580.0
Block 9	13.75	12.75	5.18	10.2	15.3	580.0
Block 10	13	11.75	6.52	10.9	15.3	580.0
Block 11	13.5	11.75	2.55	8.68	14.8	579.9
Block 12	13	12.25	6.58	11.6	16.7	579.9
Block 13	13.5	12.25	7.03	12.1	17.2	580.0
Block 14	13	12.75	6.71	11.8	16.8	579.9
Block 15	13.5	12.75	9.50	14.2	18.8	579.9
Block 16	12.75	12	8.87	13.9	19.0	579.9
Block 17	13.25	12	5.23	10.3	15.3	579.9
Block 18	13.75	12	6.73	11.8	16.9	579.9
Block 19	12.75	12.5	5.20	10.3	15.3	580.0
Block 20	13.25	12.5	6.38	11.4	16.5	579.9
Block 21	13.75	12.5	6.60	11.7	16.7	580.2

Block 22	13	12	6.26	11.3	16.4	579.9
Block 23	13.5	12	6.98	12.0	17.1	580.0
Block 24	13	12.5	6.61	11.7	16.7	580.0
Block 25	13.5	12.5	5.74	10.9	15.9	580.0
Average		**5.96**	**11.08**	**16.21**	**580**	

According to Billim, (2017); Billim *et al.,* (2016); Khojamli *et al.,* (2016); Khalil *et al.,* (2016) negative anomalies in the residual anomaly (RMI) maps are mostly associated with the low magnetic susceptibility of rocks. Based on this fact, the negative magnetic field anomalies observed in the aforementioned parts of the ditto study area were interpreted as felsic rocks associated with low magnetic susceptibility, while the positive magnetic field anomalies observed in the study area may be interpreted as mafic and ultramafic rocks beneath the sedimentary cover of the central part, north-western half and south-western half at shallow depths. Previous studies (Abubakar, 2004; Lawal *et al.,* 2006; Goni *et al.,* 2016; Sanusi, 2015) have inferred presence of these rocks beneath Bornu basin of Nigeria. Thickness of the sedimentary cover is very crucial in assessing the hydrocarbon prospectivity of the sedimentary basins, as the thicker the sedimentary cover the higher the subsurface temperature, which controls the maturation of potential source rocks, and controls the fluid accumulation and temperature of the geothermal reservoir. Figure 5 revealed that areas around Gubio, Gazubure and Masu sub-basins have average thickness ranging from 5.8 to 6.5 km. These fall above the threshold thickness for an area to be viable for further hydrocarbon generation (Wright *et al.,* 1985). Hence, the estimated sedimentary thickness around Gubio, Gazabure, Munguno, and Masu sub-basins ranging from 5.8 to 6.5 km, is interpreted to be sufficient enough to warrant further hydrocarbon investigations.

Adewumi *et al.* (2017) estimated the sedimentary thickness in some part of the study area between 0.29 and 3.35 km, using conventional spectral analysis of aeromagnetic data. Goni *et al.* (2016) estimated the sedimentary thickness of the basin, using Source Parameter Imaging (SPI) method, three areas were found to have appreciable sedimentary thickness situated around Baga, Gubio and Damboa sub-basins. Maximum depth to basement of over 6 km has been recorded towards western part of the Gubio Sub-basin. Nur (2001) also identified four (4) sub-basins in the basin, based on spectral analysis of gravity data, with sedimentary thickness in excess of 5 km. Nur *et al.* (1999) also estimated the sedimentary thickness in excess of 8 km in the study area. Lawal *et al.* (2006) estimated the sedimentary thickness of the basin between 2.7 and 5.4 km, using fractal analysis of aeromagnetic data. Avbovbo *et al.* (1986) have estimated sedimentary thickness in excess of 10 km based on interpretation of seismic data in the study area. This is very important in the petroleum exploration efforts in the basin.

The shallowest CPD (i.e 13.75 km, Block 6 in Table 1) was observed around southern part of Gamboru and around Mafa-Bama area, while the deepest CPD (i.e 19.0 km, Block 16 in Table 1) was observed around eastern part of Ben Sheik. According to Saibi *et al.* (2015) areas having shallower CPD have been associated with magmatic activity and thin crust, while deeper CPD have been associated with thickened, cooled or old crust. There are minimal records pertaining CPD estimation in Bornu basin with only one record of CPD estimation in the study area, our estimated CPD is not consistent with the CPD results obtained by Anakwuba and Chinwuko (2012, 2015) in the study area. Their CPD values of 21.45 and 31.52 km depicts overestimation considering the method adopted for the interpretation. We realized that the power spectrum was not normalized by the wave number before the implementation of spectral analysis technique, and the power spectrum was taken only along five profiles, this cannot produce reliable and overall picture of the study area, and these could have significantly affected their results.

In comparisons to studies across Nigerian sedimentary basins Nwankwo *et al.* (2009) estimated the CPD of Nupe basin between 12 to 30 km. Ofor and Udensi (2014) estimated the CPD of Sokoto basin to be between 11.36 to 22.30 km while Nwankwo and Shehu (2016) obtained CPD values between 11.13 and 27.83 km for the same basin. Nwankwo and Sunday (2017) estimated the regional CPD of Bida basin from 15.57 to 29.62 km. Ofoegbu (1985) and Nur *et al.* (1999) estimated the CPD of Benue trough north-central Nigeria and came up with CPD values ranging from 18-28 km. Bello *et al.* (2017) estimated CPD values ranging from 14.9 to 23 km, in Anambara basin southern Nigeria. Hence, it was observed that the maximum CPD values obtained from the above mentioned agrees well with each other. Nwankwo and Shehu, (2015) suggested that, it may not be unfounded to also infer that the depth to the deepest boundary between magnetized and non-magnetized crust in Nigeria is roughly 30 km. The estimated lower CPD values in this study area (i.e 13.75-16.0 km) were found to be consistent with those obtained in other Nigerian basins, while higher CPD values (i.e 16.8-19.0 km) were found to be shallower compared to other Nigerian basins, this is an indication that potential source rocks are likely to mature at shallower depths, when compared to other sedimentary basins. There exist a correlation between the CPD values and the sedimentary thickness, it can be seen that areas with higher CPD values correspond to areas with highest sedimentary thickness while areas with lower CPD values correspond to areas associated with shallower sedimentary thickness.

According to Ikpokonte (2009) Bornu basin is underlain by Moho uplift at depth that ranges between 22 and 26 km. Thus, the estimated CPD values are apparently lower than the thickness of the moho in the study area. Billim *et al.* (2016) suggested that areas with CPD shallower than Moho depth are mostly located in the upper crust. Hence, the magnetic sources in the study area are located in the upper crust which agree with earlier assertions of Billim *et al.* (2016); Billim (2017). Based on the current literatures it could be said that the variation of CPD within the Earth crust is largely depending on the geologic settings of an area. Akbar and Faithianfur, (2017) reported that CPD is shallower than 10 km for volcanic region, which are commonly associated with plate boundaries and other geodynamic environments. Nwanko and Sunday (2017) noted that, CPD is less than 10 km in volcanic and geothermal regions, 5 to 15 km in island arcs and ridges zones, greater than 20 km in plateaus areas, and it is more than 30 km in trenches areas.
Based on this fact and considering the results obtained from this study, it could be said that the study area lies within the Island arcs and ridges.

CONCLUSION

The RMI map (Figure 4) in the study area considerably depicts the geology of the surface within the study area. Locations of the geothermal productive zones matched and correlates with lower values of magnetic field intensity (Figure 4). However, areas associated with high hydrocarbon potentials mostly dwelled within the boundary faults in the northern and southern sides of the intrusive rocks located in the central parts of the study area. The estimated sedimentary thickness in the study area ranges between 2.55 and 9.5 km with an average value of 5.9 km, these values suggested that the sedimentary thickness is sufficient enough to reach the threshold temperature which may warrant further hydrocarbon investigations as suggested by Wright *et al.* (1985). The estimated CPD ranges between 13.8 and 19 km, with an average value of 16.21 km. Lower CPD values in this study area (i.e. 13.8-

16.0 km) were found to be consistent with those estimated in other Nigerian basins, while higher CPD values (i.e. 16.8-19.0 km) were found to be shallower compared to other Nigerian basins, this is an indication that potential source rocks are likely to mature at shallower depths compared to other sedimentary basins in Nigeria. It is recommended that locations around Sinduldu, northern part Wunti, and Ngalewa, towns (i.e Eastern part, SW and NW parts of the study area) with thicker sediments and Depth to the Curie points shows attractive and favourable features for hydrocarbon accumulation, the exploratory drilling should extend to these areas to explore more hydrocarbon prospectivity of the area.

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