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One Dimensional Spectral Analysis and Curie Depth Isotherm of Eastern Chad Basin, Nigeria

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Abstract
One dimensional spectral analysis was applied to aeromagnetic data in order to determine the sedimentary thickness variations, depths to the Curie-temperature isotherm and heat flow measurements within the eastern part of the Nigerian Chad Basin. Two depths sources were interpreted in the area namely; the shallower sources have a mean value of 2.21 km while the deeper ones have an average value of 14.07 km. The result of the analysis shows that depths to the centriod and magnetic bodies (sedimentary thicknesses) range from 11.55 to 18.32 km and 1.65 to 5.12 km respectively. The depth to the Curie temperature isotherm in the area varies between 21.45 km at Mafa-Bama area and 31.52 km at Maiduguri-Gwoza area below sea level. The result also shows that the Curie temperature isotherm within the basin is not a horizontal level surface, but is undulating, and the geothermal gradients associated with it range between 17.45 and 25.64°C/km while the corresponding mantle heat flow is about 46.00 mWm^{-2} and 67.60 mWm^{-2}. It is good to note that areas of high heat flow correspond to high geothermal gradient within the study area. An inverse relationship exists between calculated Curie depths and heat flow within the study area such that high-heat-flow regions correspond to low Curie depths regions. These results correspond to the depths inferred by extrapolating geothermal gradient and heat-flow values, suggesting that the Curie point depth analysis is a useful tool in estimating regional thermal structure. Based on the computed sedimentary thicknesses and the high geothermal gradient, some parts of the study area have been demarcated for detail hydrocarbon exploration.
Keywords: Chad Basin, aeromagnetic data, spectral analysis, Curie point depth, geothermal gradient and Hydrocarbon

1.0 Introduction

The study area is bounded by latitudes $11^0\ 00^1$ -$12^0\ 30^1$ N and longitudes $12^0\ 30^1$ -$14^0\ 00^1$ E within the eastern part of the Nigerian sector of the Chad Basin (Fig. 1).The Chad Basin with an area of about 230,000 km^2 is the largest area of inland drainage in Africa (Barber, 1965; Matheis, 1975; Avbovbo *et al*, 1986). It extends into parts of the Republics of Niger, Chad, Cameroon, Nigeria and Central Africa. The Nigerian sector of the Chad Basin is about one-tenth of the basin and is the most explored in Nigeria with the exception of the Niger Delta. Active exploration work started in the Chad Basin in 1977 (Nwazeapu, 1992). Exploration of the subsurface requires innovative techniques and the magnetic method offers an excellent opportunity to map the structure and lithology of the subsurface.

Adequate knowledge of the thermal structure of the lithosphere is required for a wide variety of geodynamic investigations, including rock deformation, mineral phase boundaries, rates of chemical reactions, electrical conductivity, magnetic susceptibility, seismic velocity, and mass density (Chapman and Furlong, 1992). Lithospheric thermal gradients are often estimated from near-surface heat-flow measurements, but high-quality heat-flow measurements are not available globally, are rarely distributed uniformly, and are sometimes contaminated by local thermal anomalies. In places where heat-flow information is inadequate, the depth to the Curie-temperature isotherm may provide a proxy for temperature-at-depth.

So far this study has been the first to determine the Curie temperature isotherm for eastern parts of the Chad Basin, Nigeria. Specifically, the Curie-temperature isotherm corresponds to the temperature at which magnetic minerals lose their ferromagnetism (Ross *et al.*, 2006). This corresponds approximately to 580°C for magnetite at atmospheric pressure. Magnetic minerals warmer than their Curie temperature are paramagnetic and from the perspective of the earth's surface, are essentially nonmagnetic. Thus, the Curie-temperature isotherm corresponds to the basal surface of magnetic crust and can be calculated from the lowest wave-numbers of magnetic anomalies, after removing the appropriate International Geomagnetic Reference Field (IGRF) from the aeromagnetic data (e.g., Spector and Grant, 1970; Connard *et al.*, 1983; Blakely, 1988; Tanaka *et al.*, 1999; Salem *et al.*, 2000).

Nevertheless, various studies have shown correlations between Curie-temperature depths and average crustal temperatures, leading to viable conclusions regarding lithospheric thermal conditions in a number of regions around the world. Kasidi and Nur (2012) estimated Curie depth isotherm deduced from spectral analysis of Magnetic data over Sarti and environs of North-Eastern Nigeria. They determined Curie depth which varies between 26 to 28km and the geothermal gradient varies between 21 and 23 $^oCkm^{-1}$, while the heat flow values range from 53 to 58 mWm^{-2}. They also noted an inverse correlation between estimated Curie depths and heat-flow measurements. Connard *et al.* (1983) conducted a similar study of the Cascade Range of central Oregon,

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which is part of the volcanic arc associated with the Cascadia subduction zone. They found a narrow zone of shallow Curie depths consistent with thermal models of the area. Similarly, Blakely (1988) calculated basal depths for Nevada and noted several areas where shallow basal depths corresponded with high heat flow, historic faulting, high seismicity, and P- and S-wave attenuation, which he interpreted as regions of shallow Curie-temperature isotherms. Likewise, Tanaka *et al*. (1999) used aeromagnetic data from East and Southeast Asia to estimate depths to Curie isotherm. They identified shallow basal depths across back-arc regions and deeper basal depths along the trench axis as expected from heat-flow values, showing relatively high temperatures in arc environments and relatively low temperatures at trenches. Tanaka *et al*. (1999) also noted an inverse correlation between estimated Curie depths and heat-flow measurements.

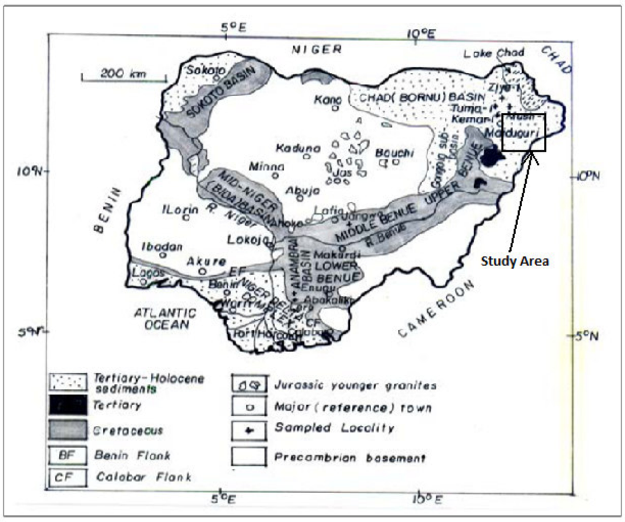


Fig. 1: Geologic map of Nigeria showing the study area (adapted from Obaje *et al*., 2004)

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 parameter that determines the relative depth of the Curie isotherm with respect to sea level is the local thermal gradient that is heat flow. 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 to be expected that geothermically active areas would be associated with shallow Curie point depth (Nuri *et al.,* 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). Thus, this study presents a spectral analysis method applied to magnetic anomalies from the Eastern part of Chad Basin to estimate the depth of the Curie isotherm and heat flow throughout the zone.

However, one major challenge in the discovery of hydrocarbon in the Nigerian sector of the basin has been the presence of intrusive igneous bodies in most of the wells drilled (Nwazeapu, 1992). Furthermore, the presence of Tertiary intrusive that is prevalent in the Southern Chad Basin may be connected with the variation in the geothermal gradient (Nwankwo and Ekine, 2010). There is therefore great need to re-evaluate the geology and hydrocarbon potentials of the basin since the same basin outside Nigeria is productive.

1.1 Regional Geological Setting

The geological history of the Chad Basin in Nigeria (Fig.1) began during the Upper Cretaceous (probably Uppermost Albian) when over 1000 m of continental sediments constituting the Bima Sandstone were deposited uncomfortably on the Precambrian Basement Complex (Barber1965). The basin contains about 4.65 km of marine and continental sediments made up of the Bima Sandstone, Gongila Formation, Fika Shale, Kerri-Kerri and Chad Formations (Okosun, 1995). The basin is rimmed by crystalline basement rocks mainly of granitic and gneissic compositions with some mica schists. Basalts, minor basic and acidic intrusions (particularly of Tertiary age) occur commonly within parts of the basin as sills and plugs. These intrusions could be responsible for the change in the heat flow and temperature and hence influence the geothermal gradient of the Chad Basin (Nwankwo *et al*., 2009). No rocks of Paleozoic age outcrop in the Nigerian sector of the Chad Basin but it is believed that these sediments may be preserved in the lower depressions and grabens, which characterize the basin's floor topography.

During the Turonian, there was an extensive transgression and the Gongila Formation – a mixed limestone/ shale sequence was deposited. These beds are overlain by over 530 m of marine shales belonging to the Fika Formation of Turonian to Senonian age. Towards the end of the Cretaceous (Maestrichtian), an estuarine – deltaic environment prevailed and the Gombe Sandstone was deposited with intercalations of siltstone, shales and ironstones. These sediments probably attain a thickness of over 320 m.

At the end of the Cretaceous there was a period of folding during which the Cretaceous beds were folded into a series of anticlines and synclines that were later partly eroded creating an erosional unconformity at the base of the Tertiary deposits. This has been confirmed by boreholes data from Maiduguri.

2.0 Data and Methodology

The data for this study constitute the aeromagnetic maps of eastern part of the Chad Basin. A total of nine aeromagnetic maps covering the area was collated and digitized. The digitized map formed the input data for separation of both regional and residual magnetic anomaly in the area (Figs. 2 and 3). The residual anomaly formed the basis for spectral analysis, which was then used to determine the depths of magnetic anomalies in the area. The various steps for producing the residual anomaly and determination of depth to magnetic sources have been discussed extensively (Anakwuba *et al*., 2011; Chinwuko, *et al*., 2012; Ikumbur et al., 2013; Spector and Grant, 1970, Onwuemesi, 1997; Stampolidis *et al*., 2005; Abubakar *et al*. 2010; etc). Energy spectral analysis provides a technique for quantitative studies of large and complex aeromagnetic data sets. The logarithm of the radial average of the energy spectrum is plotted against the radial frequency (Fig. 4). The figure was generated from the spectral analysis of the anomalies from five profiles drawn in the residual anomaly map (Fig. 3). The slope of each segment provides information about the depth to the top of an ensemble of magnetic or gravity bodies (Kivior and Boyd, 1998).

To carry out spectral analysis for curie and heat flow assessments, it was ensured that no essential part of the anomaly was cut-off by the profiles, each profiles was filtered to eliminate shallow magnetic sources (short wavelength) and enhance the deep seated magnetic sources. The analysis was carried out using computer program designed for analysis of potential field data. To perform the analysis, the first step according to Bhattacharyya and Leu, (1975) is to estimate the depth to centroid (Z_o) of the magnetic source from the slope of the longest wavelength of the spectrum that is given below:

$$In\left[\frac{\rho(\sqrt{S})}{/S/}\right] = InA \quad 2\pi/S/Z_o \tag{3}$$

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),

$$In\left[\frac{\rho(\sqrt{S})}{/S/}\right] = InB \quad 2\pi/S/Z_t \tag{4}$$

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 of Bhattacharyya and Leu, (1975) as shown below:

$$Z_b = 2Z_o - Z_t \tag{5}$$

The obtained basal depth (Z_b**)** of magnetic sources in the study area is assumed to be the curie point depth according to Bhattacharyya and Leu, (1975) and Okubo *et al*, (1985) and the graphs of the logarithms of the spectral energies for various anomalies using the software were obtained from which table 1 was extracted as shown on Fig. 4 below.

The heat flow and thermal gradient value was calculated in the study area, the calculation was expressed by Fourier's law with the following formula.

$$q=\lambda\frac{dT}{dZ} \tag{6}$$

Where, *q* is the heat flow and λ is the coefficient of thermal conductivity.

In this equation, it is assumed that the direction of the temperature variation is vertical and the temperature gradient dT/dZ is constant. According to Tanaka *et al*, (1999), the Curie temperature (θ) was obtained from the Curie point depth (Z_b) and the thermal gradient dT/dZ using the following equation:

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

Provided that there are no heat sources or heat sinks between the earth's surface and the Curie point depth, the surface temperature is 0°C and dT/dT is constant.

The Curie temperature depends on magnetic mineralogy. Although the curie temperature of magnetite (Fe_2O_4), in view of that, the curie temperature is approximately 580°C, and an increase in Titanium (Ti) content of titanomagnetite (Fe_2-x,$TixO_3$) causes a reduction in curie temperature (Nwankwo *et al.*, 2011).

In addition to that, from Equations (6) and (7) a relationship was determined between the Curie point depth (Z_b) and the heat flow (q) as follows.

$$q = \lambda \left[\frac{\theta}{Z_b}\right] \qquad (8)$$

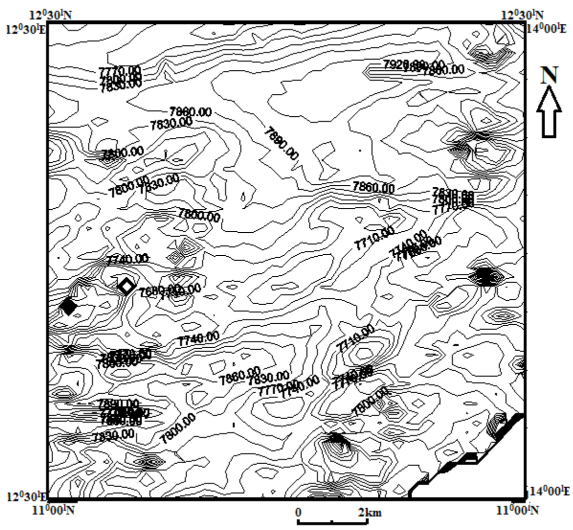
In this equation, the Curie point depth is inversely proportional to the heat flow (Tanaka *et al.* 1999). In this research, the Curie point temperature of 580 °C and thermal conductivity of 2.5Wm^{-1}°C^{-1} as average for igneous rocks was used as standard (Nwankwo *et al.*, 2011) in the study area. In order to compute the thermal gradient and heat flow of the region, equations (7) and (8) were utilised.

3.0 Result Presentation

The maps of the total magnetic field intensity and residual magnetic anomalies of the study area are shown in Figs. 3 and 4. The figures show that the total magnetic field and residual anomalies range from 6900 to 8050 nT and -30 to 390 nT respectively. Thus, the maps show areas with both widely-spaced and closely-spaced contours lines (i.e. area with low and high intensity of magnetization respectively). Total magnetic field intensity map shows that the contour lines of the north-eastern parts are widely spaced indicating that the depth to magnetic basement in this area is relatively high. But, at Gwoza (southeastern part) area, the contour lines are closely spaced signifying that the depth to basement is shallow in this area.

According to Ofor and Udensi (2014), the centriod depth is the depth that relates to the point where magnetism is lost in the crust. Based on this, the depths of the shallowest and deepest sources were obtained using the centroid method and presented in Table 1. The depth to centriod obtained ranges from 11.55 to 18.32 km while the depth to the top of the magnetic bodies ranges from 1.65 to 5.12 km. The regional distribution of the thickness of the magnetized crust is illustrated in Fig. 5. The result shows that the Curie isotherm depth varies between 21.45 km at Mafa - Bama area and 31.52 km at Maiduguri - Gwoza area. The figure also shows that in the north-eastern and south-western portion of the study area the curie depth was found to be less than 32 km while depths of not more than 21.45 km are found in other parts of the study area.

Using curie-point temperature of 580°C and calculated curie-point depths, the geothermal gradient variations in the structural province of Eastern Chad Basin, Nigeria were obtained using equation 7 (Table 1 and Fig. 6). The values of geothermal gradients and thermal conductivity of 2.5 Wm^{-1} $^0C^{-1}$_(Nwankwo *et al.*,2009) were subsequently used to estimate the corresponding heat flow anomalies in the study area (Table 1 and Fig. 7). According to the results obtained, geothermal gradient varies between 17.45 and 25.64°C/km. The corresponding mantle heat flow is about 46.00mWm-2 along Gubio-Gwoza while it is less than 67.60mWm-2 along Mafa-Bama area.



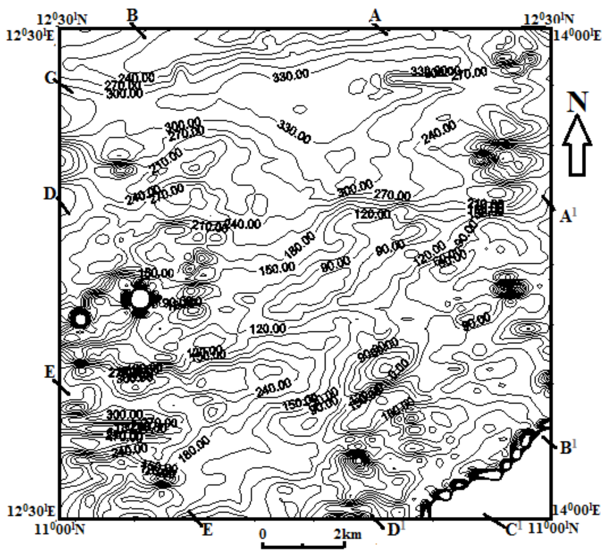


Fig. 2: Total magnetic field intensity map (Contour Interval~30nT)

Fig. 3: Residual anomaly map (Contour Interval~30nT)

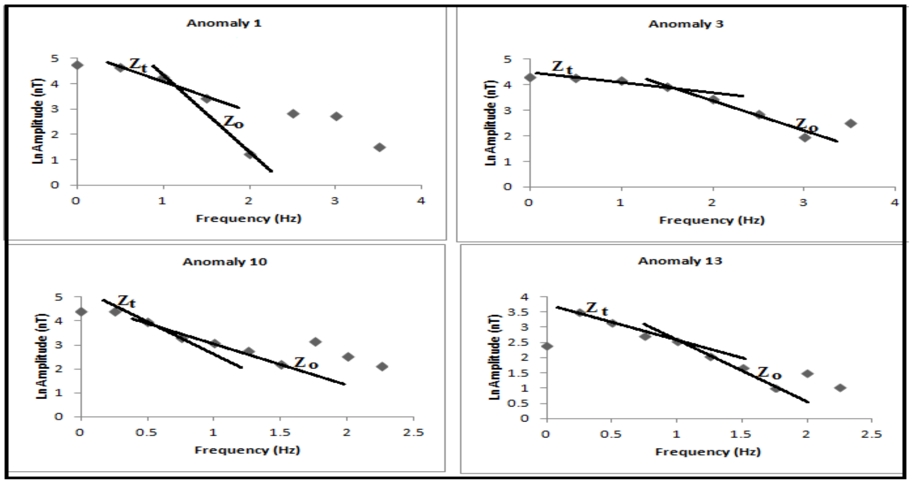


Fig.4: Representative of amplitude spectrum

Table 1: Calculated average Curie point depth and heat flow from spectral analysis

Profile name	Anomaly number	Depth to Centroid (Z_o) in km	Depthto top boundary (Z_t) in km	Curie Depth (Z_b) in km	Geothermal gradient (^oC/km)	Heat flow (q) in mW/m^2
A-A	1	17.13	3.73	30.53	18.0151	47.4942
	2	15.73	3.12	28.34	19.4072	51.1644
	3	16.11	3.49	28.73	19.1438	50.4699
B-B	4	14.76	2.61	26.91	20.4385	53.8833
	5	18.32	5.12	31.52	17.4492	46.0025
	6	15.27	3.08	27.46	20.0291	52.8041
C-C	7	12.58	1.93	23.23	23.6763	62.4193
	8	15.89	3.41	28.37	19.3867	51.1103
	9	11.55	1.65	21.45	25.6411	67.5991
D-D	10	16.62	3.62	29.62	18.5685	48.9534
	11	17.81	4.15	31.47	17.477	46.0756
	12	15.76	3.37	28.15	19.5382	51.5098
E-E	13	12.94	2.06	23.82	23.0898	60.8732
	14	13.81	2.13	25.49	21.5771	56.8851
Average	15	14.07	2.21	25.93	21.211	55.9198

4.0 Discussions

4.1 Curie depth isotherm and Geothermal gradient

The implications of the results are best illustrated by considering the graphs of the logarithms of the spectral energies (Fig. 4) from which Curie isotherm depth was computed. The equivalent curie depth ranges from 21.15 to 31.52 km, these values compares well with what was obtained within and around Upper Benue Trough by Nur *et al*. (1999). The obtained Curie point depth reflects the average local curie depth point values of 27.40 km across the study area. It is also observed that shallower curie point depth of 21.15 km compared to the basement areas such as Gwoza and Mutube; this could be as a result of upwelling of magma chamber on Cameroon Volcanic line (Kasidi and Nur, 2012). The deeper Curie point which trends in NE-SW direction within the study area could be as a result of isostatic compensation in the region (that is the process in which lateral transport at the surface of the earth by erosion or deposition is compensated by lateral movements in a subcrustal layer).

Yamano (1995) made an assertion that, shallow Curie point depths are consistent with high heat flow values as seen in back arc, and young volcanic regions. In view of this, the area of shallow Curie point depth of 21.45 km has a geothermal potential which can be utilized. The geothermal gradient map (Fig. 6) defines region of high geothermal gradient to be south-eastern (SE) part and low geothermal gradient to run from northeastern to southwestern (NE-SW) parts of the study area. This is closely related to the heat flow map (Fig. 7), meaning that most areas of high heat flow correspond to high geothermal gradient. In most part of the study area, heat flows were found to be less than 60 mWm^{-2}, this implies that the heat flows in the study area are not uniform, which possibly indicate that the magma conduits were randomly distributed. Some of the heat flow results obtained compared favourably with that of Nwankwo *et al.* (2009), where they estimated the values of heat flow from 14 wireline logs available in the Nigerian sector of the Chad Basin to range from 63.6 to 105.6mWm^{-2} and a simple average of 80.6mWm^{-2}. The high heat that gives rise to geothermal systems are mostly found in the mantle plumes, subduction and rift zones where for unknown reasons large quantities of heat are transported from mantle to the earth crust. The average heat flow obtained in the study area is 54.375 mWm^{-2}; this may be considered as typical of continental crust (Jessop *et al.,* 1976). Geothermal energy can also occur in areas where basement rocks that have relatively normal heat flow are covered by thick blanket of thermally insulated sediments. It can be inferred that the geothermal prospect areas in this study may be areas where thick layer of thermally insulated sediments cover basement rocks since there is no evidence of volcanic activities in the study area, therefore these areas of high heat flow (Fig. 7) could be geothermal sources and reservoirs and will be of help in identifying the existence of productive reservoirs at attractive temperature and depth in the Chad Basin.

The Curie point parameters obtained from this study were used to construct geological model of the study area (Fig. 8). The model reflects the various depths to curie points which describe the thermal nature of the crust; it shows that materials become ferromagnetic only below their corresponding Curie temperatures and paramagnetic only above their Curie temperature. The result also shows that the Curie temperature isotherm within the basin is undulating rather than being a horizontal flat surface. Meanwhile many authors have shown that the Curie point depth is greatly dependent upon geological conditions (Connard *et al*., 1983; Tanaka *et al*., 1999; Stampolidis *et al*., 2005).

A relationship exists between heat flow and the obtained Curie depths (Fig. 9) such that, the heat flow decreases with increasing Curie depth. That is, Spectral analysis of the data in conjunction with heat flow values revealed an almost inverse linear relationship between heat flow and Curie depths (Fig.9) meaning that an increase in heat flow causes a decrease in Curie isotherm depth within the study area. These can also be used to construct Curie isotherm from the existing data.

4.2 Hydrocarbon Potential

The shallower sources may be as a result of activities in the basement complex of northeastern Nigeria. These tectonic activities account for the complex fracturing in the area with some fractures extending towards northern part. Magnetic lineament map shows major fault trending NE-SW direction with minor fault trending SE-NW direction. These trends are in conformity with the structures of the basement complex of northeastern Nigeria and could have served as a migratory pathway for hydrocarbon or hydrothermal fluid. According to Nwankwo and Ekine, (2010), they revealed that sediments with relatively higher geothermal gradients mature earlier (low oil window) than those with low gradient values. Thus, under normal circumstances a high geothermal gradient enhances the early formation of oil at relatively shallow burial depths, but it causes the depth range of the oil window to be quite narrow, while low geothermal gradient causes the first formation of oil to begin at fairly deep subsurface levels, but makes the oil window to be quite broad.

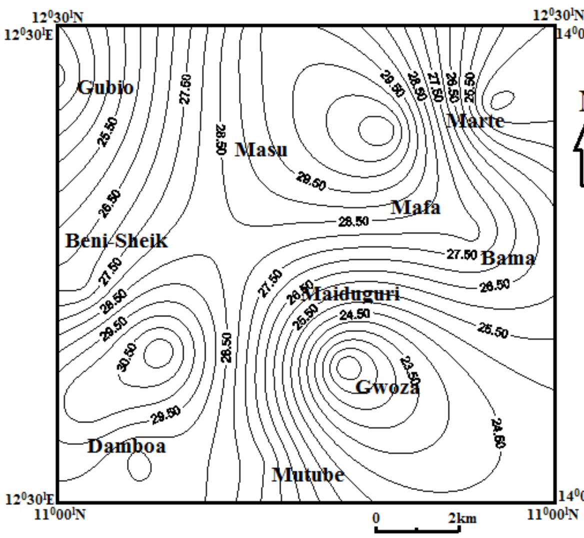


Fig. 5: Map showing the Curie Depth (Contour interval 0.5km)

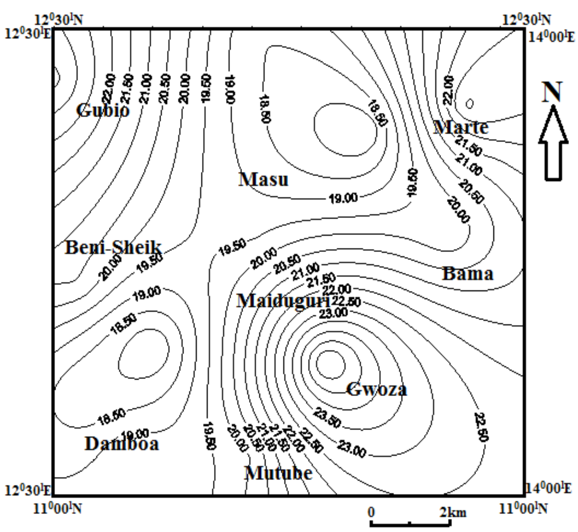


Fig. 6: Map showing Geothermal gradient (Contour interval 0.5 °C/km)

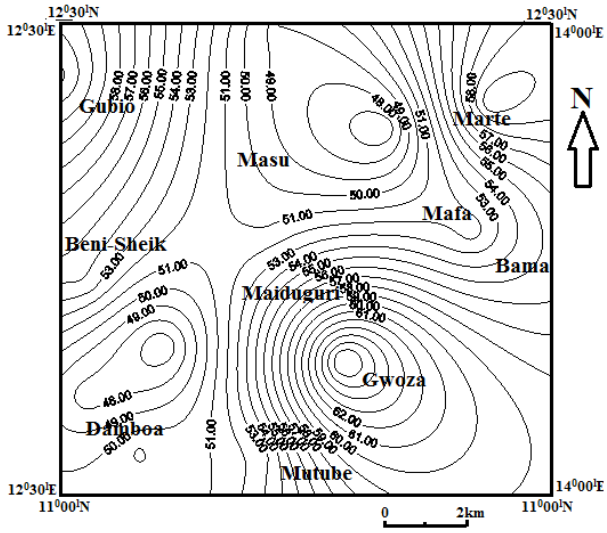


Fig. 7: Map showing Heat Flow (Contour interval 1.0 wM/m^2)

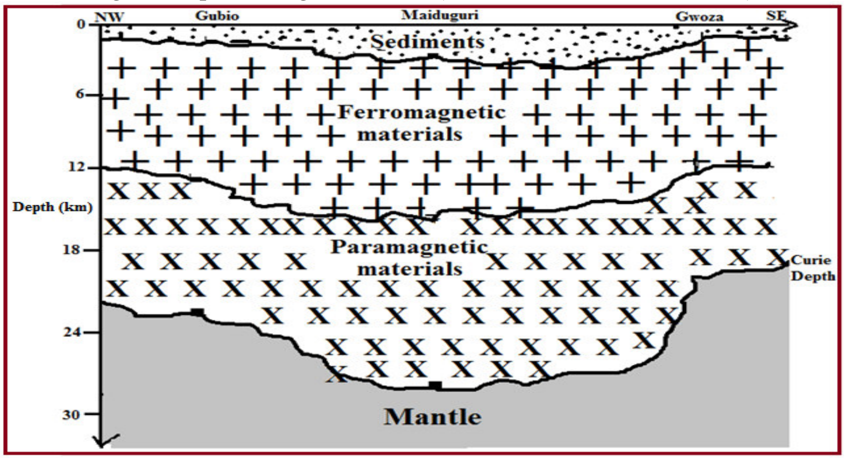


Fig. 8: Geological modelling of the Curie isotherm depth in the study area

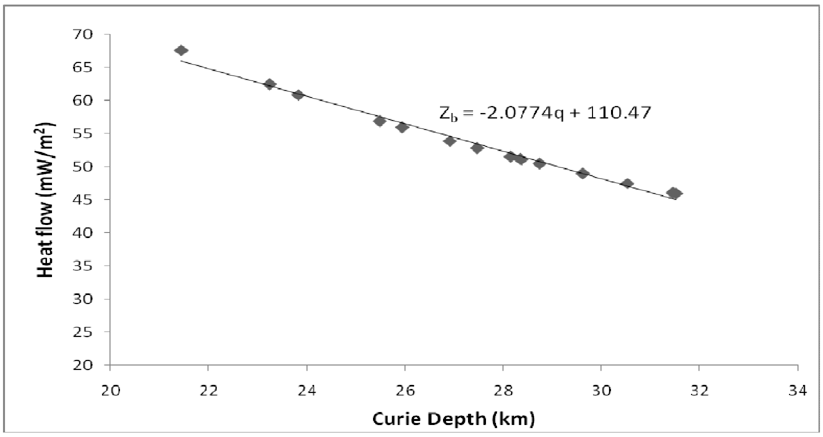


Fig. 9: Relationship between Curie depth and heat flow within the study area

Thus, the sedimentary cover at the southeastern part (Fig.5) is generally low and may not support hydrocarbon formation. Apart from the southeastern part, all the other parts of the study area have sedimentary thickness that is moderately-high. In line with this, for any area to be viable for hydrocarbon formation, the thickness of the sediment must be up to 2.0 km as well as other conditions necessary for hydrocarbon formations (Wright et al, 1985; Oil and Gas Geology, 2010). Also, Nwankwo (2009) said that the Fika and Gongila Shales are the source rocks while the reservoir is the Bima Sandstone in the Chad Basin. Based on the computed sedimentary thicknesses (2.06 - 5.12 km), the geothermal gradient (17.45 and 25.64°C/km.) and the fractures which serve as migratory pathway for hydrocarbon or hydrothermal fluid, then the possibility of hydrocarbon generation in the northern and southwestern parts of the study area is feasible (Fig.10).

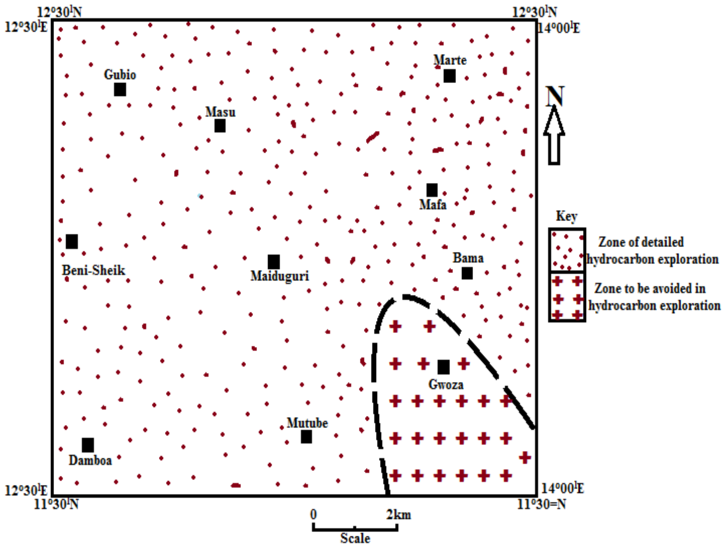


Fig. 9: Isolated area for future hydrocarbon exploration

5.0 Conclusion

A study of Curie-temperature isotherm and heat-flow of eastern part of the Nigerian Chad Basin has been carried out using spectral analysis of aeromagnetic data. The main conclusions of the study are as follows:

i. The maps of the total magnetic field and residual anomalies range from 6900 to 8050 nT and -30 to 390nT respectively. It shows area with low and high intensity of magnetization respectively.
ii. The result shows that the Curie isotherm depth varies between 21.45 km at Mafa-Bama area and 31.52 km at Maiduguri-Gwoza area.
iii. The geothermal gradient obtained varies between 17.45 and 25.64°C/km. Its map defines region of high geothermal gradient to be south-eastern (SE) part and low geothermal gradient to run from northeastern to southwestern (NE-SW) parts of the study area.
iv. The mantle heat flow is about 46.00mWm^{-2} along Gubio-Gwoza while it is less than 67.60mWm^{-2} along Mafa-Bama area.
v. A geological model of the study area shows that the Curie temperature isotherm within the basin is undulating rather than being a horizontal flat surface.
vi. Generally, it was discovered that Curie depths within the Eastern Chad Basin, Nigeria has a negative correlation with both heat flow and geothermal gradient.
vii. The area is intensely fractured with three major regional faults trending in NE-SW direction.
viii. The study has demarcated the areas, where detail hydrocarbon exploration will be concentrated in the future.

6.0 Acknowledgment

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