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Geothermal Energy Potential of the Chad Basin, North-Eastern Nigeria

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ABSTRACT: In this research paper, the sub-surface heat flow of a part of the Chad Basin, in North eastern Nigerian was estimated using spectral analysis. This was obtained from twenty (20) digitized High Resolution Aeromagnetic (HRAM) data sheet covering the study area. Regional-residual separation using first order polynomial fitting method with three coefficients was carried out on the data map before the application of statistical spectral analysis. Result shows that the centroid depth varies between 9.39 km and 18.31 km. The depth to the Curie temperature isotherm varies between 15.14 km and 33.46 km below the mean sea level. It was also found that the Curie temperature isotherm within the basin is not a horizontal level surface but an undulating surface with geothermal gradients and heat flow ranging between 15.77 and 38.31˚C/Km, and 39.41 and 95.77 mWm^{-2} respectively. Thus, the calculated average geothermal gradient and heat flow for this area are 23.39˚C/Km and 58.47mWm^{-2} respectively. Since average heat flow in thermally normal continental region is 60 mWm^{-2} and the values in excess of 80 mWm^{-2} – 100 mWm^{-2} are associated with anomalous geothermal conditions, hence the study area can generally be considered as a thermally normal region. But, the northeastern part of the study area with values in excess of 80 mWm^{-2} is recommended for further investigation.

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Nigeria is a country with insufficient generation of electricity for the consumption of the populace at large despite continue increase in population in Nigeria, the need for more power both for domestic and industrial use. There has never been a more urgent time to look into generation of electric power generation from other sources to complement the ones being used despite the fact that geothermal source of energy has been successively annexed in some countries in Africa and world at large, Nigeria as a country cannot be exempted from the possibility of exploring geothermal energy (Ewa and Kryrowska 2010).Geothermal energy refers to the use of heat energy within the earth where earth's heat engine is driven by cooling of the crust and heating of the lower crust and mantle by thermal decay of radioactive isotopes, therefore the deeper below the surface, the hotter the temperature is (W.E.C, 2016). Some studies have been carried out on geothermal potential in different basins and geological area in Nigeria (Ewa and Kryrowska, 2010;Lawal and Nwankwo, 2017;Nwankwo and Shehu, 2015;and Nwankwo, L.I., 2015).Ewa and Kryrowska (2010) and Nwankwo *et al.,*(2009) reported that geothermal gradient values ranging from 34 ˚C/km to 59 ˚C/km were obtained during a temperature data analysis from wire line logs of 14 shallow water wells which are about 500 m deep in areas covering part of Chad basin. In Sokoto basin located in northwestern part of Nigeria's geothermal gradient of 52.11˚C/km was obtained using magnetic data of the entire basin (Nwankwo and Shehu, 2015).Abraham *et al.,*(2015) estimated a value of 54.11 °C/ 100 K as the average geothermal gradient of the region around Wikki Warm Spring (WWS) using aeromagnetic data of the upper Benue trough. In the Niger-Delta region of the country Adedapo *et al.,*(2009) and Emujakporue and Ekine (2014) reported a result from the analysis of subsurface temperature where a minimum geothermal gradient of 1.2 °C/ 100 m at the central part of the basin and a maximum of 7.62 °C/ 100 m at the northeastern part of the basin were obtained. Chukwu *et al.,* (2017) also carried out an analysis of geothermal energy potential using aeromagnetic data of part of Niger delta and obtain geothermal and heat flow values ranging from 12.26 to 40.19 ºC/km and 25.30 to 84.40 mW/m^2. They concluded that since the heat flow value is below100 mW/m^2, the area may not feasible as a geothermal energy source. In view of the above literature from researchers on geothermal potential in Nigeria and Africa at large, an analysis of aeromagnetic data of part of Chad basin for

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geothermal energy potential was carried out in other to complement the existing work done in the area.

MATERIALS AND METHODS

Location and Geology of the Study Area: The study area which is a part of Chad basin Nigeria is bounded by 11° N - 14° N and longitudes 9° E - 14° E covering states such as Borno, Yobe and Adamawa (Fig. 1). It covers an area of about 59,901 square kilometers. Olugbemiro *et al.,* (1997) reported that the Nigeria sector of Chad basin is bounded to the east by the Mandara Mountains and in the south by the Benue trough and Biu Plateau. It encompasses the southeastern portion of the basin which is situated in a tectonically energetic area with features which spreads northwest to the Air Plateau and Southwest towards the Benue trough, the third and unsuccessful arm of a three-layered rift joint developed as a result of the separation of African and South American plates in early Cretaceous times (Carter *et al.,* 1963). Geologically, the basin, which houses the study area has been described by many authors (Nur 2001; Obaje 2009; Odebode 2010; Lawal and Nwankwo, 2017). This basin is believed to be a broad sediment-filled depression stranding Northeastern Nigeria and adjourning parts of Chad Republic. The sedimentary rocks have a cumulative thickness of over 3.6 km and consist of thick basal continental sequence and transitional calcareous deposit. It combines with the Sokoto Basin in the west of the Damergou gap between the air and Zinder massifs (Wright *et al.,* 1985). The generalized stratigraphy column of the Basin has been described by (Odebode, 2010) to be of sedimentary sequence made up of Chad Formation, Kerri-Kerri Formation, Gombe Formation, Fika Shale, Gongila Formation and Bima Sandstone. Sedimentation began in Chad (Bornu) Basin during Upper Cretaceous (probably Uppermost Albian) when over 1000 m of continental, sparsely fossil ferrous, unwell-organized intermediate to rough grained, Feld spathic sand stone which can be regards to as the Bima Formation were deposited uncomfortably in the Precambrian Basement. Other sedimentary stratigraphy sequences were formed as a result of oceanic intrusion into Chad drainage and extensional deformation that occurred in the basin. The area is marked by two distinct climatic conditions. The rainy season lasts usually from May to September with an average temperature of 30-46 ^{0}C depending on the rainfall pattern for the particular year. The dry season heralded annually by the dry, dusty Harmattan winds which blows off the Sahara desert, occurs between October and April with an average temperature of 30-37 ^{0}C. The mean annual rainfall is 7.8 mm and a relative humidity of an about 50-80%. The vegetation, which is predominantly of the Savannah-type, is divided in to two zones: Sahel Savannah towards the north and Sudan Savannah to the south.

There are different methods of estimating depth to the bottom of magnetic sources, which is also a proxy for Curie Point Depth (CPD) Salk et al (2005). But for this study, Spectral analysis (centroid method) as proposed by Okubo et al., (1985), to estimate for depth to the bottom of magnetic sources(Z_b), was used. According to Ravat et al., (2007), the centroid method is one of the most commonly used methods because it gives better estimates with less depth errors compared to others.

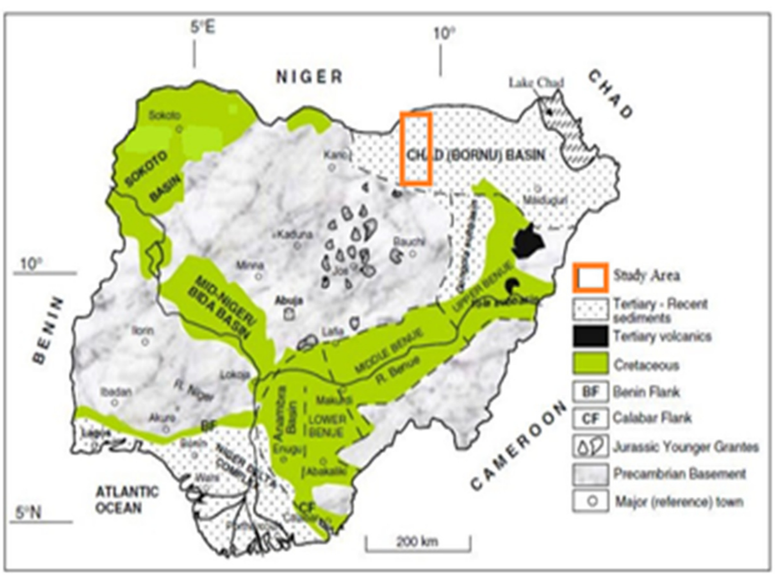

Fig.1: Map of Nigeria showing the study area (Modified after Obaje 2009).

The proposal by Okubo et al., (1985) is based on the spectral analysis method of Spector and Grant (1970) and this method is a 2-D spectral analysis magnetic anomaly data which was used to estimate the depth to the top of magnetized rectangular prisms (Z_t) from the slope of the log power spectrum. Bhattacharyya and Leu (1975); (1977) were able to calculate the depth to the centroid of magnetic sources(Z_o) and the mathematical models of centroid method used in this study are based on the examination of the shape of isolated magnetic anomalies as introduced by (Bhattacharyya and Leu 1975; 1977). Blakely, (1995) introduced power spectral density of total magnetic field, from which Tanaka et al., (1999) showed that the basal depth of magnetic sources can be estimated using equation 3 (below) proposed by Okubo et al., (1985) by calculating the top depth and centroid depth of magnetic sources from the power spectrum of magnetic anomalies. Using equation 1 below, the centroid depth can be calculated by fitting a straight line through the low wave number part of the wave number- power spectrum:

$$\ln\left(\frac{P(k)^{\frac{1}{2}}}{K}\right) = A - |K|Z_o \qquad 1$$

Where $P\ (k)$ is the azimuthal average power spectrum, K is the wave number (km^{-1}), A is a constant, and $Z_o$is the basal depth.

Where,$Z_o = \frac{m_o}{2\pi}2$

The depth to the top of magnetic sources is obtained by fitting a straight line through the high wave number part of the power spectrum.

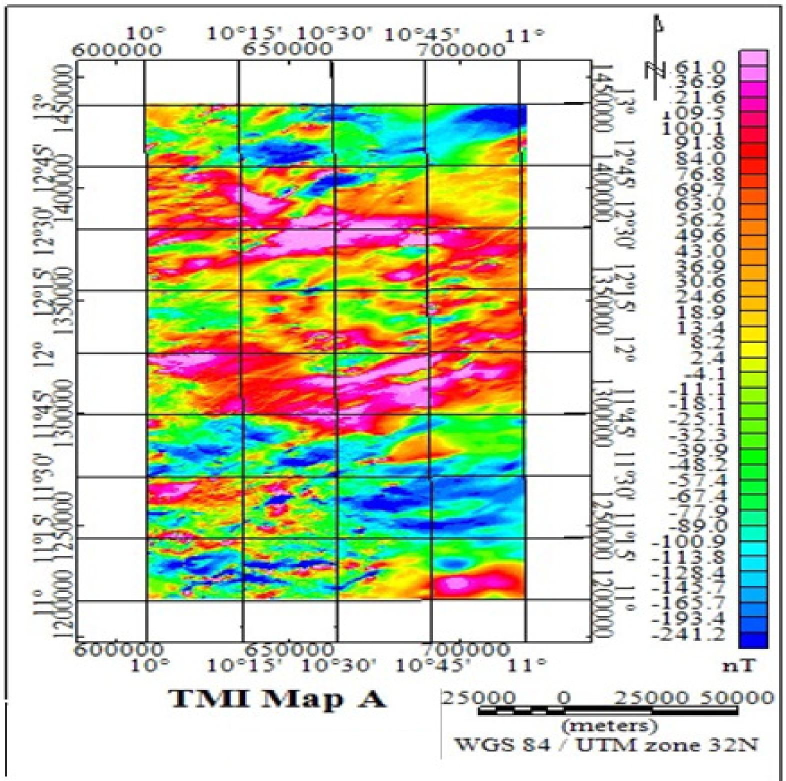

Fig.2. Total Magnetic Intensity (TMI) Map A (First set of obtained aeromagnetic map).

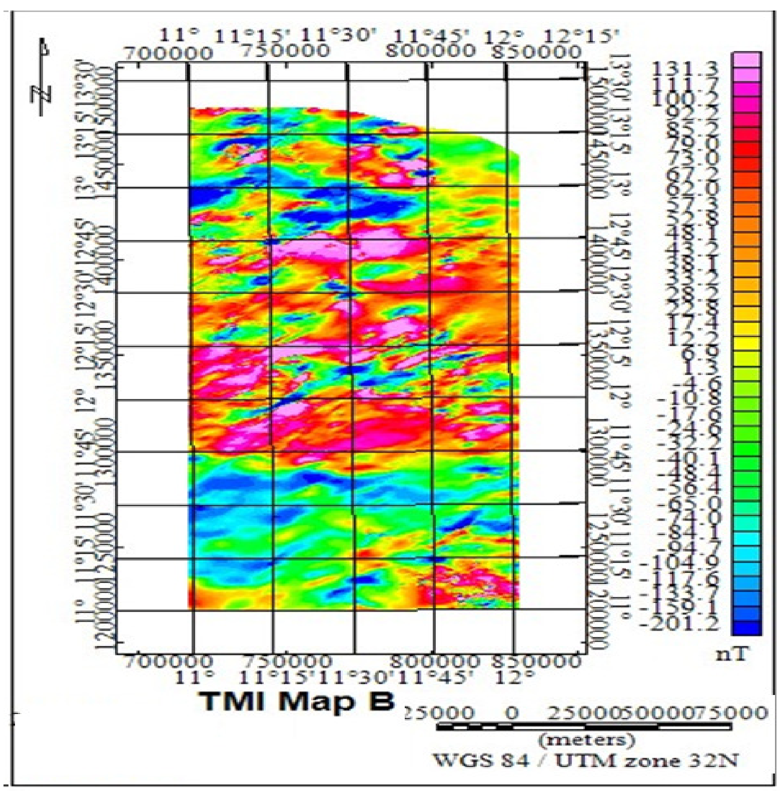

Fig.3. Total Magnetic Intensity (TMI) Map B (Second set of obtained aeromagnetic map).

m_o, is the slope of the plot for the depth to the centroid, Z_o.

$$\ln\left(\mathrm{P(k)}^{\frac{1}{2}}\right) = B - |K|Z_t \quad 3$$

m_o, is the slope of the plot for the depth to the centroid, Z_o.

$$Z_t = \frac{m_t}{2\pi} 4$$

m_t, is the slope of the plot for the depth to the top, Z_t, B is a constant, and Z_t is the depth to the top of magnetic sources.

From the two equations above, the natural logarithm (Ln) of the power spectrum is always plotted against the wave number (K). Where Z_t and Z_o are the slopes of such plot. Consequently the Depth to the Basal or Bottomof Magnetic Sources (DBMS) or Curie Point Depth (CPD) can be estimated using the relation Okubo et al., (1985).

$$Z_b = 2Z_o - Z_t \quad 5$$

To calculate the geothermal gradient, $\frac{\mathrm{dT}}{\mathrm{dZ}}$it is assumed that: (i) the surface temperature is 0 ˚C i.e. no heat sources exit at the surface. (ii) The direction of temperature variation is vertical and the temperature gradient $\frac{\mathrm{dT}}{\mathrm{dZ}}$ is constant and (iii) there is no magnetic source at the CPD.

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

Where, θ_c is the Curie temperature to be 580^{0}C and $\frac{\mathrm{dT}}{\mathrm{dZ}}$ is the geothermal gradient which could only be obtained if the above assumptions 1 – 3 are true (Bansal et al. 2011; Nwankwo and Shehu 2015).The heat flow(q_z) , can be

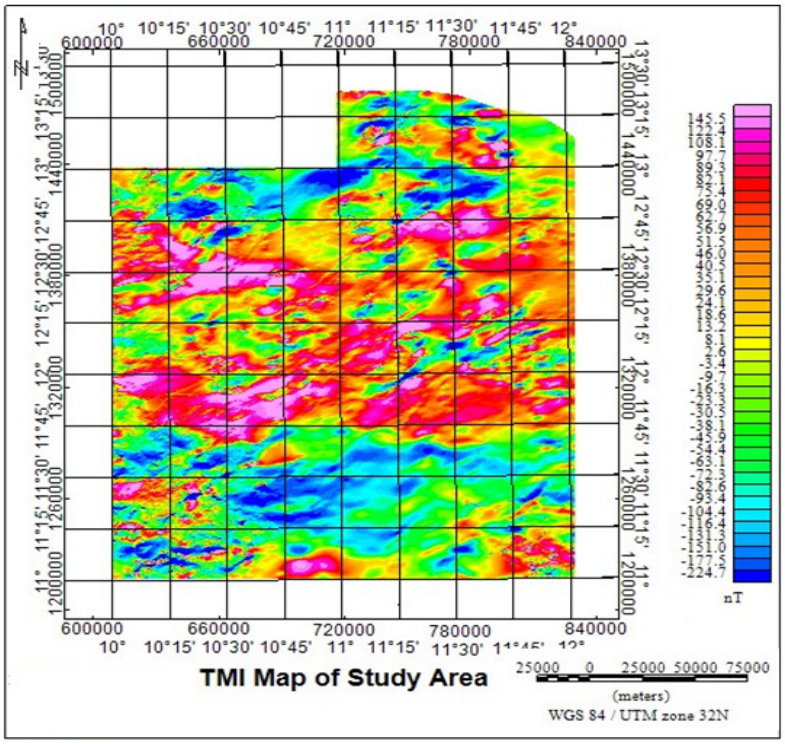

Fig.4. Composite Total Magnetic Intensity (TMI) map of the study area (After Knitting)

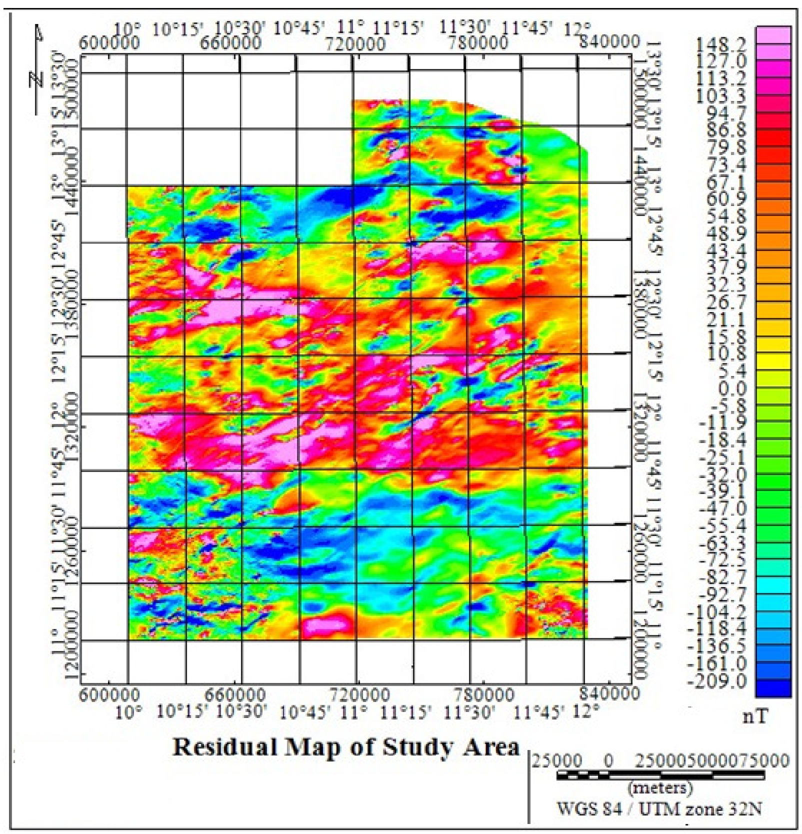

Fig.5.Residual Field Aeromagnetic Map of the study area.

calculated from the temperature gradient using the Fourier's (1995) Law

$$q_z = -k\frac{\theta_c}{Z_b} = -k\frac{\mathrm{dT}}{\mathrm{dZ}} \qquad 7$$

Where, K is the thermal conductivity and it is assumed be 2.5 $Wm^{-1}{}^{\circ}C^{-1}$ (Nwankwo, and Shehu, 2015).

Application to the Magnetic data set: High Resolution Aeromagnetic (HRAM) data covering the study area and published in a map form on a scale of 1:100,000 were procured from Nigerian Geological Survey Agency (NGSA) in two sets of ten sheets each making a total of twenty (20) aeromagnetic maps.

The two data set were then knitted together with the aid of Oasis Montaj software using the blending method. The two data sets and the composite Total Magnetic Intensity (TMI) map obtained after knitting are shown in Fig. 2, 3 and 4 respectively. In order to obtain an accurate DBMS, a regional trend map (Fig.6) was removed from the TMI map (Fig. 4) using a first orderpolynomial equation so that effect of topography and shallow magnetic sources present in the data would be resolved (Saada, 2016) and presented as a residual map (Fig.5).

The residual field data of the study area was divided into ten (10) 50 by 50 overlapping blocks for the purpose of spectral and geothermal analysis (Abraham *et al.,* 2015). The blocks were overlapped to ensure that no data was left out. The average power spectrum of each block was then obtained.Two plots of natural logarithm of the spectral power against their corresponding wave number were made for each block, with the aid of Matlab using a moving average of three points in order to obtain a smoothed plot. Taking the ground surface as a reference zero kilometer, the depth to the top (Z_t), centroid (Z_o), and bottom (Z_b), of magnetic sources for each block were obtained using equations (1) – (5).The obtained depths for each block is presented in Table 1.In other to calculate the geothermal gradient and heat flow of the study area, equation 6 and 7 were used. The obtained depth for each block is presented in Table 2 and their contour plots are shown in Figs. 9 and 10 respectively.

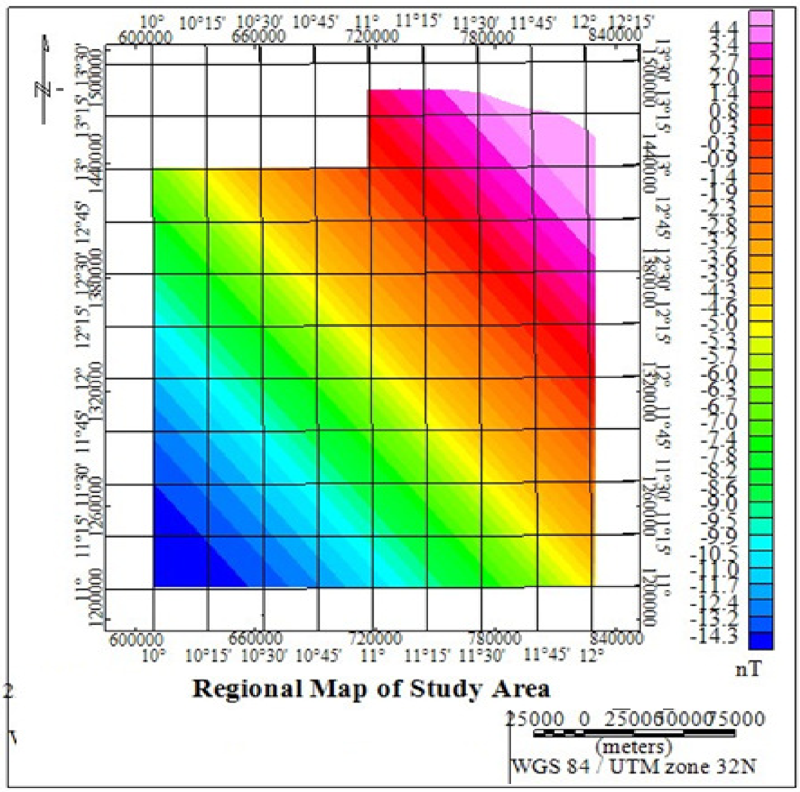

Fig.6. Regional Field Aeromagnetic Map of the study Area.

RESULTS AND DISCUSSION

The results of the estimated depths for the ten blocks as shown in Table 1, ranges between 1.48 to5.00 km with an average value 3.33 km, the centroid depth ranges between 9.39 to 20.52 km, with an average of 15 km. The depth to the base of magnetic sources (CPD) varies between15.14 km to 36.79 km with an average depth of 26.68 km. Furthermore, the geothermal gradient was found to vary between 15.77 and 38.31˚C/km, with an average of 23.39˚C/km, while the heat flow parameter vary between 39.41 and 95.77mWm^{-2}, having an average of 58.47mWm^{-2}. In the exploration of sedimentary basins, the general assumption is that intrusive rocks within the crystalline basement complex are truncated by erosion at their surface. Hence, the variation in the depth to the top of magnetic sources obtained from the study area shows a spatial relationship between the sediments overlying the Precambrian basement complex which is characterized by elevations and depressions. The sedimentary thickness obtained is in agreement with previous research work in the study area (Anakwuba and Chinwuko, 2012; Chinwuko et al., 2012; Lawal et al., 2015).

Table 1: Estimations of Depth to top (Z_t), centroid (Z_o), and bottom (CPD) (Z_b), of magnetic sources from spectral analysis

Blocks	Long(˚E)	Lat. (˚N)	Depth totheTop (Z_t) (km)	Depth to the centroid (Z_o) (km)	Depth tothe Bottom (Z_b) (km)
1	10.50	12.50	2.91	12.83	22.75
2	11.00	12.50	3.12	14.76	26.52
3	11.50	12.50	3.64	9.39	15.14
4	11.50	12.88	4.99	11.34	17.69
5	10.50	12.00	1.48	13.82	26.16
6	11.00	12.00	3.47	16.92	30.33
7	11.50	12.00	2.72	16.75	30.78
8	10.50	11.50	3.59	14.25	24.91
9	11.00	11.50	4.25	20.52	36.79
10	11.50	11.50	3.15	19.43	35.71
Average			3.33	15.00	26.68

The depth increases from the central part to the northeast and southern part of the study area. According to Wright (1985), the minimum sedimentary thickness required to attaining a threshold temperature for the beginning of hydrocarbon maturation is 2.3 km. Hence, hydrocarbon exploration is feasible in all parts of the study area except the west-central part, where a depth is lesser than 2.3 km.For the Curie-point isotherm map (Fig.8), the values trend NE–SW with the shallowest (15 km) at the northeastern part of the study area, while the deepest (> 30 km) is noticeable at the southeastern part of the study area, this deeper part of the study area extends into the Republic of Chad and Upper Benue trough where similar results have been obtained (Lawal and Nwankwo, 2017; Nur et al., 1999). Lawal and Nwankwo (2017) obtained a depth to base of magnetic sources value ranging between 18.18 and 43.64 km, with an average of 28.70 km.

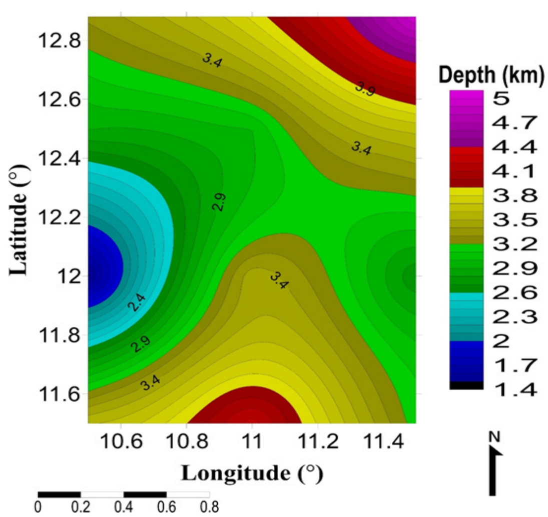

Fig. 7 Depth to the top (Z_t) of magnetic sources contour map (Sedimentary thickness). (Contour interval of 0.1km)

It can also be observed from the map that shallow depth to the base of magnetic sources are associated with negative magnetization which corresponds to low magnetic values of the residual map (Salk et al., 2005).

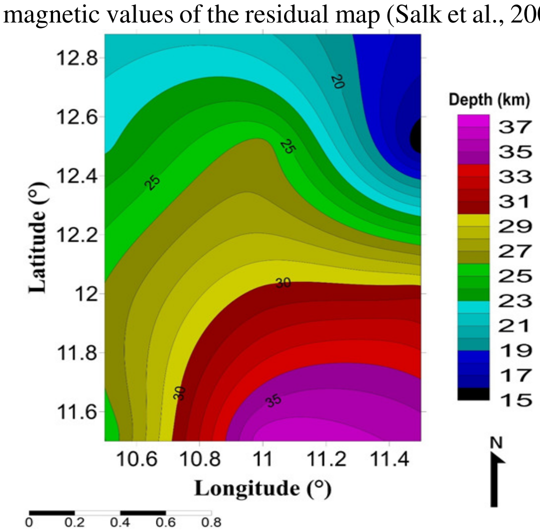

Fig.8. Curie point depth(Z_b) contour map of the study area (CI – 1km).

Table 2: Geothermal gradient and respective heat flow values of block

Blocks	Long (°E)	Lat (°N)	Depth to the bottom(km)	Geothermal gradient (°C/km)	Heat flow (m/Wm^2)
1	10.50	12.50	22.75	25.50	63.74
2	11.00	12.50	26.52	21.87	54.68
3	11.50	12.50	15.14	38.31	95.77
4	11.50	12.88	17.69	32.79	81.97
5	10.50	12.00	26.16	22.17	55.43
6	11.00	12.00	30.33	19.12	47.81
7	11.50	12.00	30.78	18.84	47.11
8	10.50	11.50	24.91	23.28	58.21
9	11.00	11.50	36.79	15.77	39.41
10	11.50	11.50	35.71	16.24	40.61
Average			26.68	23.39	58.47

Figure 10 shows the heat flow map of the study area, with the high heat flow (>83 mWm^{-2}) corresponding to high geothermal gradient (> 33˚C/km) (Fig. 9) and the shallow DBMS at the northeastern part of the study area . While the low heat flow (<47 mWm^{-2}) corresponds to the low geothermal gradient (< 18 ˚C/km) and high DBMS at the southeastern part of the study area. Jones (1975) reported that regions of high geothermal gradient could lead to hydrocarbon generation at shallow depth, while regions of low geothermal gradient may not be viable for hydrocarbon exploration except at greater depth. Hence, the northeastern part of the study area with high geothermal gradient and sedimentary thickness would be more feasible for hydrocarbon exploration at a shallow depth. In addition the average value for heat flow obtained ($58.47 mWm^{-2}$) is consistent with that of Anakwuba et al., (2015) who obtained a value of $54.375 m/Wm^2$ for an adjoining area.

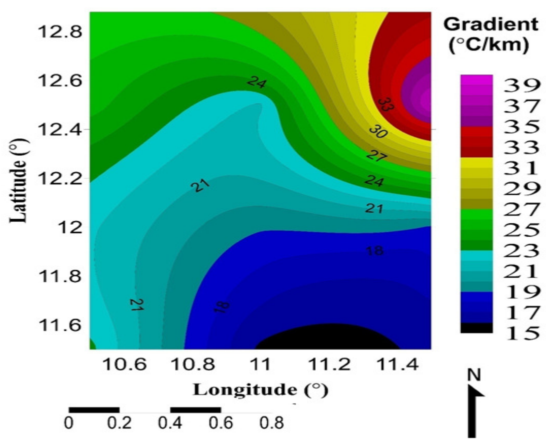

Fig. 9.Geothermal gradient contour map of the study area (CI - 1˚C/km)

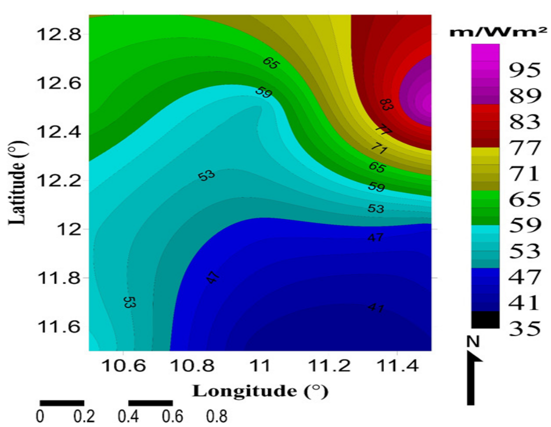

Fig. 10.Surface heat flow map of the study area (Contour interval of $2m/Wm^2$).

Lawal and Nwankwo (2017) obtained an average of $54.93 m/Wm^2$. It is believed that the estimated geothermal gradient and heat flow values in this study differs from the estimated values from previous works using Borehole data from oil wells in Chad (Bornu)basin (Nwankwo et al., 2009a; 2009b)due to lack of any of such boreholes being located in our study area. In addition, changes in groundwater movement, thermal conductivity of rocks, and endothermic reaction during diagenesis (this increase in thermal energy can be due to pressure) with the added effect of uneven presence of intrusives in the basin can cause the estimated difference.

*Conclusion:*Evaluation of geothermal energy potential of part of Chad Basin, North-Eastern Nigeria has been carried out. The study has given mathematical information about the geothermal structures of the area. The basis of this study is to contribute to the body of work on geothermal energy potential in the Chad Basin section of Nigeria with the hope that it will lead to energy sufficiency in the country at large. From the results obtained, it is believed that the northeastern part of the study area is a good prospect for geothermal energy exploration. Jessop et al., 1976 proposed a minimum heat flow of 60 m/Wm^2 for considerable generation of geothermal energy values ranging from 80 – 100 $m/Wm^2$and above indicates anomalous geothermal conditions. Since there are values greater than 60 m/Wm^2 in the northeastern part of the map, A more detailed geothermal investigations is required in this part of the area.

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