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DETERMINATION OF GEOTHERMAL POTENTIAL IN YANKARI GAME RESERVE, BAUCHI STATE, NIGERIA

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ABSTRACT

The study deals with the determination of geothermal potential of Yankari Game reserve which involves; estimate of the Curie point depth, heat flow and geothermal gradient from spectral analysis of aeromagnetic data covering an area located approximately at longitude 9.7567 ^{o}N and Latitude 10.5094 ^{o}E. Radially power spectrum was applied to the aeromagnetic data of the study area divided into 4 square blocks and each block analyzed using the spectral centroid method to obtain depth to the top, centroid and bottom of magnetic sources. The depth values were subsequently used to evaluate the Curie-point depth (CPD), geothermal gradient and near-surface heat flow in the study area. The values of the curie point depths (Z_b), range from 8.91 km to 10.11 km, with a mean value of 9.71 km, geothermal gradient, range from 57.37 ^{o}Ckm^{-1} to 65.10 ^{o}Ckm^{-1}, with mean value of 60.10 ^{o}Ckm^{-1} and heat flow (q), range from 143.43 mWm^{-2} to 162.75 mWm^{-2}, with a mean value of 150.24 mWm^{-2}. These results entails that the area under study has good geothermal potential for exploration.

Keywords: Aeromagnetic data, Curie point depth, Exploration, Geothermal, Spectral analysis

INTRODUCTION

Geothermal energy originates from the formation of the earth and decay of long-lived isotopes of uranium, thorium and potassium found within the Precambrian basement rocks (Downing and Gray, 1986). The uprising of magma to the surface during the rifting often results in different geodynamic activities such as the surface expressions of tectonic lineaments and manifestation of geothermal resources (Komolafe, 2010). These lineaments such as faults and fractures play major roles in the study of the evolution and dynamism of the rift zones. Investigations into the tectonic lineaments and surface thermal structures are very crucial to the understanding of the geothermal activities and processes associated with the region. Continuous accumulation of tectonic strain helps to maintain faults and fractures as conduits for fluids flow thereby sustaining the geothermal systems (Komolafe, 2010).

In geothermal energy exploration, the potential fields of gravity and magnetic have been used to delineate bedrock valleys concealed by sediments or volcanic materials and mapping of permeable fractures during the early stages of investigation of Olkaria and Meningai fields, Kenya (Mariita, 2013). These measurements can significantly reduce the number of wells needed to characterize a prospect while improving the confidence of interpretations. In the same vein, the delineation of geothermal heat source is best carried out using gravity and magnetic measurements, while reservoir characteristics are best imaged by use of electric or electromagnetic techniques (Mariita, 2013). In Nigeria, the much dependence on oil and gas as the main source of energy has virtually collapsed her economy. It therefore becomes pertinent to find an alternative source of energy. So, the exploitation of possible geothermal resource areas in Nigeria could be a vital alternative to an industrializing nation like Nigeria (Obande and Lawal, 2013). The Wikki warm spring of Bauchi State and the Ikogosi warm spring of Ekiti State, the two main known geothermal resource areas in Nigeria are associated with circulation of water to great depths through faults in the Basement Complex rocks of the area (Obande and Lawal, 2013). As oil reserves decline, geothermal energy is becoming an attractive alternative, particularly in parts of western United States of America, such as the Salton Sea area of south California, where geothermal exploration and development have begun (Griscom and Muffler, 1971). The geothermal fields of Olkaria and Menengai in Kenya have equally witnessed intensive exploration and exploitation of geothermal energy in recent times (Mariita, 2013). Geothermal energy comes from steam and hot water trapped within the crust (Downing and Gray, 1986). It is relatively non- polluting form of energy that is used as a source of heat and to generate electricity. Much of Earth's geologic activity such as earthquakes, volcanism, moving plates and the origin of mountains is caused by internal heat. In fact, the slow release of the heat from the Earth's interior is one major factor that makes it such a dynamic Earth (Rybach and Mulffler, 1981).

One of the vital tools for investigating the thermal structure of the crust through aeromagnetic data is spectral analysis. Thermal structure of the crust determines the modes of deformation, depths of brittle and ductile deformation zones, regional heat flow variations, seismicity, subsidence/uplift patterns and maturity of organic matter in sedimentary basins (Dolmaz *et al*., 2005). Adequate knowledge of the thermal structures of lithosphere is required for a wide variety of geodynamic investigations, including rock deformation, mineral phase boundaries and rates of chemical reactions, electrical conductivity, magnetic susceptibility, seismic velocity and mass density (Afuwai *et al*., 2020; Chapman and Furlong, 1987; Kure *et al*., 2017 and Kure *et al*., 2019).

Lithospheric thermal gradients are often estimated from near-surface heat flow measurements but high-quality heat flow measurements are not available globally and 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 may provide a proxy for temperature- at - depth. In the last few decades, spectral analysis based on statistical models has been used in various geological applications like the estimation of average depth to the top of magnetic basement and the estimation of crustal thickness. The spectral method has been used extensively in the interpretation of magnetic anomalies (Spector and Grant, 1970). It 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, 1977).

The assumption that a number of independent ensembles of rectangular prismatic blocks are responsible for generating anomalies in a magnetic map (Bhattacharyya and Leu, 1977). Curie point depth (CPD) as the deepest level in the earth crust containing materials which create discernible signatures in a magnetic anomaly map (Bhattacharyya and Leu, 1977). This definition can be restated as the depth at which the dominant mineral in the crust passes from a ferromagnetic state to a paramagnetic state under the effect of increasing temperature (Bhattacharyya and Leu, 1977). Similarly, the Curie point depth (CPD) can be defined as the depth at which the iron and titanium oxide minerals of the earth lose their ferromagnetic property (Nur *et al*., 1999). Thus, the basal depth of a magnetic source from aeromagnetic data is considered to be the Curie point depth. This study focuses on the interpretation of aeromagnetic data in Yankari Game reserve, Bauchi State Nigeria in order to determine the geothermal potential of the area under study using spectral analysis. The result of this study will be a useful tool for further Geothermal Exploration activities in the area under study.

Study Area

The study area is located at longitude 9.7567 N and latitude10.5094 E located within the northeast Nigeria. The study area is made up of the cretaceous Benue trough, Precambrian basement Complex, Sedimentary Basins (Gongola and Yola Basins), Jurassic younger Granites, and tertiary – recent sediments of the central and north-eastern Nigeria as shown in Figure 1.0 (Obande and Lawal, 2013). The study area is localized at Yankari Game reserve. The data for this study constitute the aeromagnetic sheets 128 (Kafin Madaki) northeastern Nigeria. To achieve the objectives of the study earlier stated above, aeromagnetic sheets 128 was acquired through purchase, assembled and analyzed. The aeromagnetic data was obtained as part of nationwide aeromagnetic survey sponsored by the Geological Survey Agency of Nigeria (GSAN).

The geomagnetic gradient was removed from the data using the Internationally Geomagnetic Reference Field (IGFR). The data were made available in the form of contoured maps on a scale of 1:100,000. The procedure involved in this study includes digitization of the aeromagnetic maps in order to extract the total field intensity values of the area.

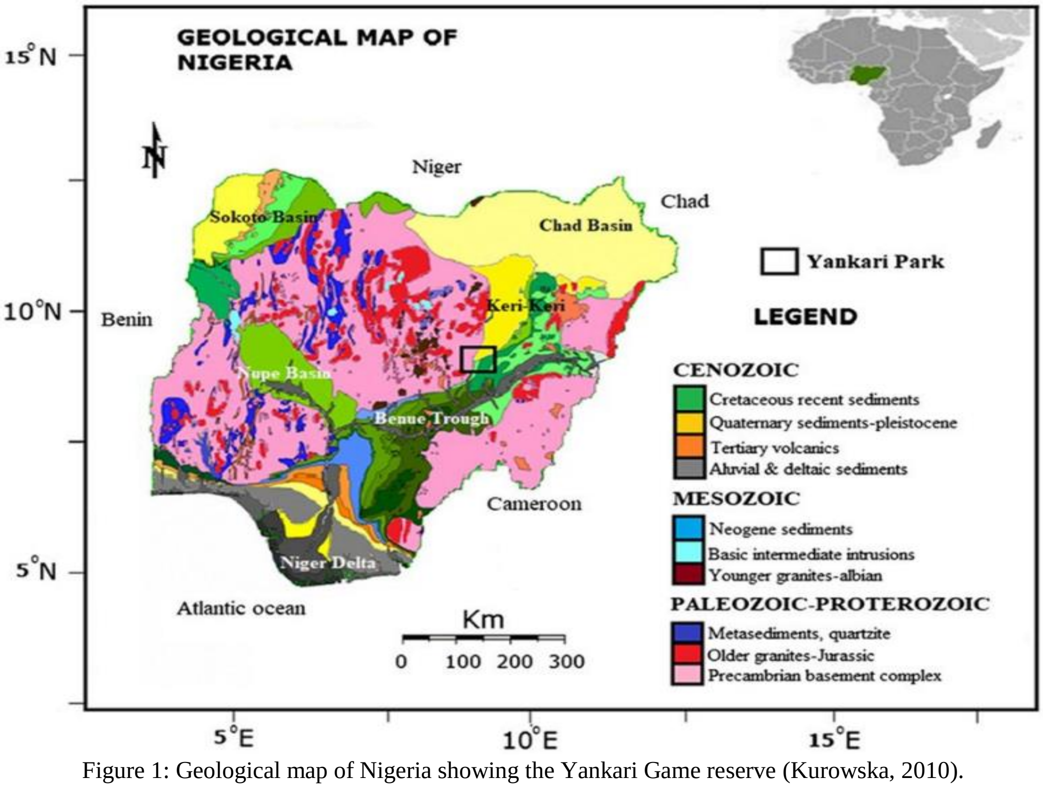

Figure 1: Geological map of Nigeria showing the Yankari Game reserve (Kurowska, 2010).

MATERIALS AND METHODOLOGY

Data Acquisition

The data for this study constitute the aeromagnetic sheets 128 (Kafin madaki) northeastern Nigeria. To achieve the objectives of the study earlier stated above aeromagnetic sheets 128 was acquired through purchase, assembled and analyzed. The aeromagnetic data was obtained as part of nationwide aeromagnetic survey sponsored by the Geological Survey Agency of Nigeria (GSAN). The geomagnetic gradient was removed from the data using the internationally geomagnetic reference field (IGFR). The data were made available in the form of contoured maps on a scale of 1:100, 000. The procedure involved in this study includes digitization of the aeromagnetic maps in order to extract the total field intensity values of the area. The regional anomaly was removed from the observed data by fitting a plane polynomial surface to the data. The residual data were subjected to computer processing techniques of filtering by spectral analysis in order to obtain quantitative parameter, which describe the depths to the magnetic sources (Curie point depth). Consequently, surface maps of depths to magnetic sources/layers were produced and analyzed. The Curie point depth information was then used to calculate the vertical geothermal gradient and heat flow of the study area respectively. Finally, the Curie point depth information was used to estimate the depth to the heat source (geothermal energy). Total magnetic field intensity maps of the area comprising of the sheets were plotted using Oasis Montaj software (version 8.4). The composite colour map effectively displayed both long wavelength and short wavelength features.

Methods

Digitization of Aeromagnetic Maps

The Aeromagnetic map obtain was digitized and during the digitization the following procedures were required:

i. Study of the aeromagnetic map itself to know the trend and the interval of the contours.
ii. Measurements of the aeromagnetic map both in horizontal and vertical paths (usually each aeromagnetic map is 55 km by 55 km).
iii. Drawing grids on the maps: the flight lines were used as grid lines of 2km interval.
iv. Picking the intersection points: the intersections of the flight lines were picked with respect to their latitudes and longitudes.

Separation Digitized Aeromagnetic Data

The contoured digitized data which is referred to as total magnetic field intensity (TMI) map of the study area, contains both the regional and residual anomaly. To interpret the local field, the regional field was removed from the data. In this case, a linear trend surface was fitted on to the digitized aeromagnetic data by a multiple repression technique for the purpose of removing the regional magnetic gradient. The linear surface so fitted was removed from the digitized data to obtain the residual aeromagnetic map that would then be interpreted.

Estimation of Depth to Basement

In order to determine the number of magnetic horizons in the study area and their average depths, power spectrum of the magnetic data was computed and interpreted. The amplitude of the logarithm of radially average power spectrum was plotted against the radial frequency. Best fit least squares lines were then virtually fitted to the spectrum. The slopes of the linear segment of the spectrum correspond to separate depths. Accurately, aeromagnetic data can be represented by an analytical function using Fourier series. In order to estimate depth to basement across the study area, the spectra analysis (Fourier transform) method was used. The method used in this study involves Fourier transformation of digitized aeromagnetic data to compute the amplitude spectrum due to its user friendly and relatively low cost. The gradients of the low frequency linear segment were evaluated and the depths to the magnetic sources were determined using

$$Z = -ML/2\lambda \qquad (1)$$

Data Interpretation

The interpretation of magnetic anomaly maps was both qualitatively and quantitatively interpreted. The qualitative interpretation of the aeromagnetic map was done by visual inspection of the total magnetic intensity map (TMI) and the residual anomaly map. The qualitative interpretation was done by visual inspection of the total magnetic field intensity map, noting the following: The trend of contours, the positive and the negative values of the contours and the minimum and maximum values of the contours and their aerial extent. Thus, there are three features that are important in qualitative interpretation namely: Sharp changes in contours gradients defines structural trends, the alignment of lateral shift (which offset the main anomaly) suggests faulting and the alignment of closed anomalies suggests presence of magnetic bodies.

A complete quantitative interpretation of potential field data estimates was carried out in the study area. The purpose of quantitative interpretation is to obtain information about the depth to magnetic sources, its shape and size and probably about its susceptibility, with the aim of estimating the sedimentary thickness variations, map the configuration of the Curie temperature isotherm and the associated geothermal gradient, reveal the origin of hot spring close to the study area and to reveal the petroleum potential of the study area. So, in order to achieve the above stated objectives across the study area using the Fourier transform method, several profiles were taken on the residual aeromagnetic map of the study area. The method was chosen because of its advantage of filtering all the noise away from the data. Moreover, during the application of this method, information is not lost in the process unlike other methods.

Consequently, graphs of the natural logarithms of the amplitude against frequencies obtained for the various profiles were plotted. Linear segment from the low frequency portion of the spectral, representing contributions from the deep-seated causative bodies were drawn from each graph. The gradients of the linear segment were evaluated and the depths to magnetic sources were determined along the selected profiles. A plot of the logarithm of the amplitude versus frequency usually shows straight line segments which decrease in slope with increasing frequency and the slopes of the segment give estimates of the depth to the magnetic sources (Bhattacharyya and Leu, 1977).

The magnetic field observation made at or above the surface of the earth and the magnetization at the top of the magnetic parts of the crust are characterized by relatively short spatial wavelengths, while magnetic field from the magnetization at the Curie-point depth are characterized by longer wavelengths and lower amplitude magnetic anomalies. This difference in frequency characteristics between the magnetic effects from the top and bottom of the magnetized layer in the crust was used to separate magnetic effects at the two depths to determine the Curie depth. The average radial energy spectra were estimated and displayed in a logarithm of energy versus frequency. Therefore, the slopes acquired from equation (2) were replaced into equations (3) and (4) to estimate centroid depth and depth to the top boundary Z_0 and Z_t respectively, for each of the four spectral cells. While these depth values were further replaced into equation (5) to generate Curie point depth. These Curie point depth values were put into equation (6) to generate the geothermal gradient of the area. Ultimately, the heat flow was acquired using equation (7).

$$\text{Slope } (m_1, m_2) = \text{LOG Energy/ Frequency} \qquad (2)$$

$$Z_0 = -m_1/2\pi \qquad (3)$$

$$Z_t = -m_2/2\pi \qquad (4)$$

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

$$dT/dZ = \Theta c/Z_b \qquad (6)$$

$q = k[\theta^o/Z_b]$ (7)

Where Z_0 = Deep depth, Z_t = Shallow depth, Z_b = Curie depth, dT/dZ = Geothermal Gradient, θ_c = Curie temperature, q = Heat flow Rate, k = Coefficient of Thermal Conductivity

It was assumed that the surface temperature was 27 ^{o}C while Curie temperature was 580 ^{o}C (Geodynamics, 1997). It was ensured that the effect of aliasing was avoided or reduced. The effect of aliasing arises from the ambiguity in the frequency represented by the sampled data.

RESULTS AND DISCUSSION

Results

Table 1: Data Presentation

Block	Centroid Depth(Z_0) in Km	Depth to the Top(Z_t) in Km	Curie Depth Z_b=($2Z_0$-Z_t) In Km	Geothermal Gradient dT/dZ ^{o}CKm^{-1}	Heat flow (q)mWm^{-2}
1	5.12	0.53	9.71	59.73	149.33
2	5.30	0.53	10.11	58.18	145.45
3	5.30	0.50	10.11	57.37	143.43
4	4.78	0.64	8.91	65.10	162.75
Mean			9.71	60.10	150.24

Observation from the above Table 1 shows that the calculated Curie point depths in the area range between 8.91 to 10.11 km with an average depth of about 9.71 km. The deep Curie-point depth could be as a result of thick sediment, while the shallow Curie-point depth in the region could be on account of the intrusion of igneous rocks or magmatic materials. The geothermal gradient of the area range between 57.37 ^{o}C km^{-1} to 65.10 ^{o}Ckm^{-1}, with an average of 60.10 ^{o}Ckm^{-1}. Table 1 shows that the heat flow in the region varies between 143.43 to 162.75 mWm^{-2}, with an average heat flow of 150.24 mWm^{-2}. Critical observations from values in Table 1.0 reveal that the heat flow and geothermal gradient rise as the Curie depth drop. This fluctuation happened with the results obtained by other researchers who estimated an average Curie point depth in Wikki Warm Spring, situated in parts of Benue basin, which join up the Chad Basin in the north to be 10.72 km, with an average thermal gradient of 54.11°C/km and average heat flow values of 135.28 mWm^{-2}.

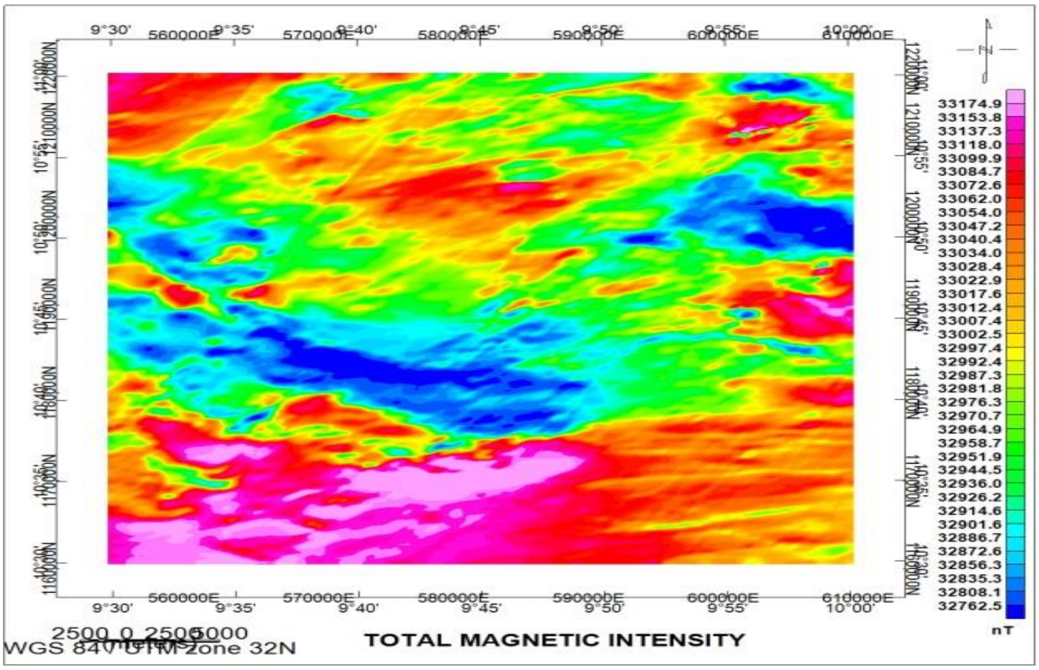

Figure 2: Showing the Total Magnetic Intensity Map of the Study Area

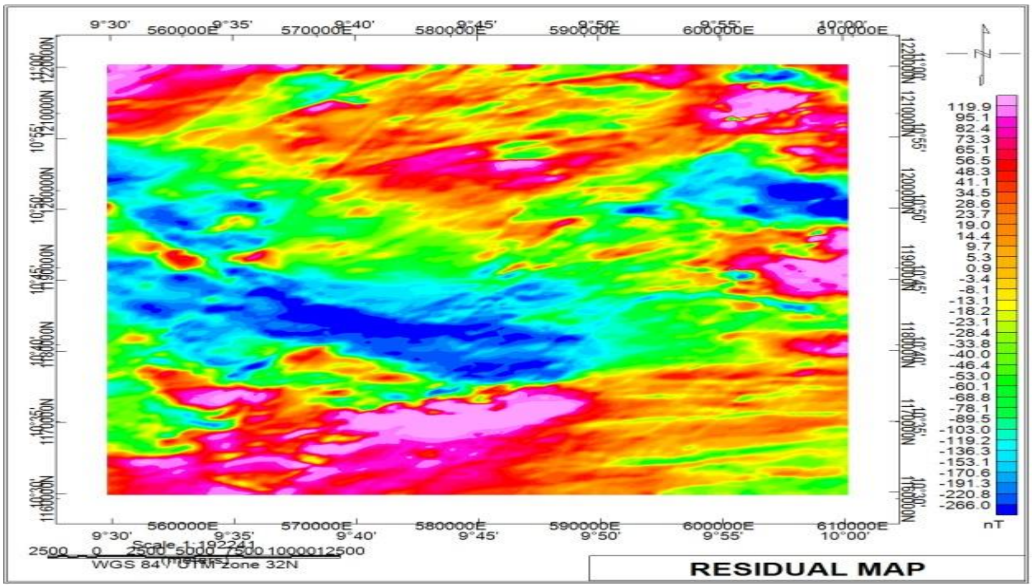

Figure 3: Showing the Residual Map of the Study Area

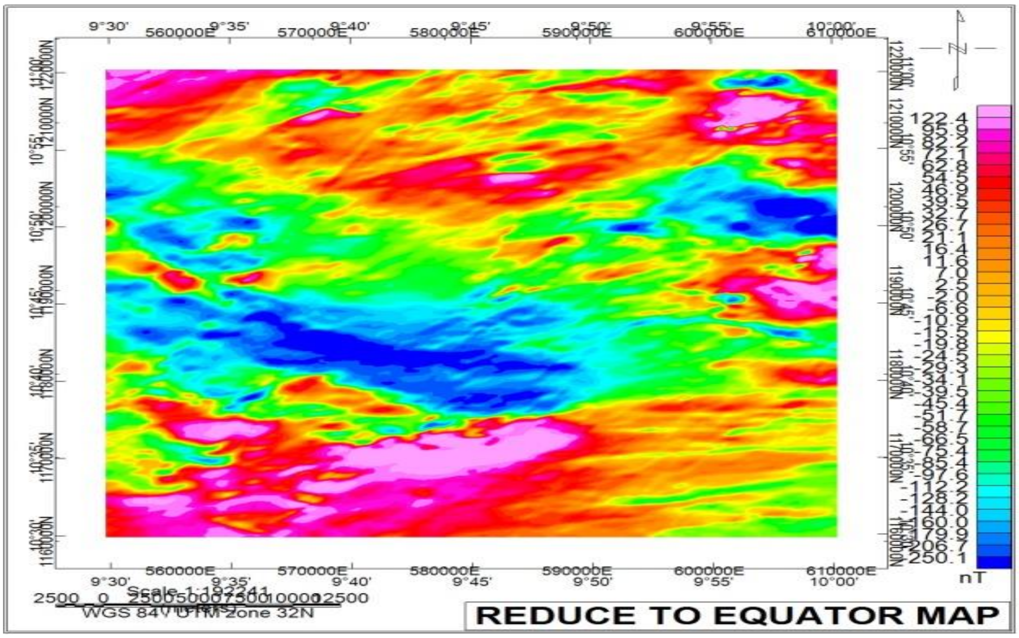

Figure 4: Showing the Reduce to Equator Map of the Study Area

The magnetic susceptibility contrast across a fracture zone due to oxidation of magnetite to hematite and or infilling of fracture planes by dyke-like bodies whose magnetic susceptibilities are different from those of their host rocks (Chinwuko *et al*., 2012). Thus, the geologic features may appear as thin elliptical closures or nosing on an aeromagnetic map. The thematic map of the study area suggests the presence of magnetic bodies.

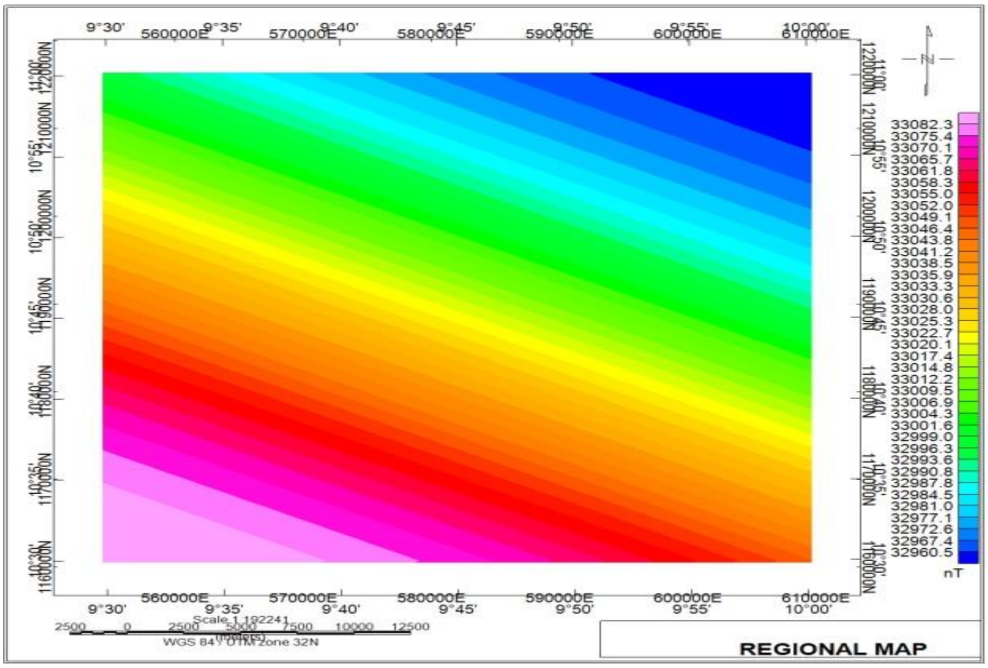

Figure 5: Showing the Regional Map of the Study Area

Again, visual inspection of the aeromagnetic map over the study area indicates that the deep purple colour in the southwest and few part of the eastern part of the map which shows thicker sediments as shown in Figure 2. This shows that the depth to the basement is higher in the southwest and eastern part compared to other areas of the map which suggest shallow sedimentary thickness. In addition, the residual anomaly map shows positive magnetic anomaly and larger sedimentary thickness indicating deeper depths at the southwest and eastern parts of the study area, while the other parts of the map show negative magnetic anomaly with smaller sediment thickness which indicates shallow depths as indicated in Figure 3 and 4.

Therefore, the aeromagnetic map shows two major areas of differing magnetic pattern as seen above (Figure 5). The first is the area of magnetic high is in southwestern part of the arear. Another area of high magnetism is the Eastern part of the area under study. These areas are associated with the intrusive masses or volcanic domes and the geothermal area. The second area is an area of relatively smooth which is the rest of the areas under study. The magnetic anomalies represent variations in the amount and susceptibility of magnetic minerals (mainly magnetite) and the intensity of their remnant magnetization (Griscom and Muffler, 1971).

Discussion

Observation from the result of the spectral analysis of the study area shows that the calculated Curie point depths in the area ranges between 8.91 to 10.11 km, with an average depth of about 9.71km while the Centroid Depth Ranges between 4.78 to 5.30 and the Depth to the Top ranges between 0.50 - 0.64. The deep Curie-point depth could be as a result of thick sediment, while the shallow Curie-point depth in the region could be on account of the intrusion of igneous rocks or magmatic materials. The geothermal gradient of the area range between 57.37 ^{o}C km^{-1} to 65.10 ^{o}Ckm^{-1}, with an average of 60.10 ^{o}Ckm^{-1}. The result shows that the heat flow in the region varies between 143.43 to 162.75 mWm^{-2}, with an average heat flow of 150.24 mWm^{-2}.

Critical observations from the results reveal that the heat flow and geothermal gradient rise as the Curie depth drops. The results from this work also show that the southwestern part of the area under study provides a great source of geothermal energy as temperatures greater than 100 ^{o}C can be reached at depths less than 2 km. The average heat flow in thermally "normal" continental regions is around 60 mWm^{-2} and values in excess of about 80 - 100 mWm^{-2} indicate anomalous geothermal conditions have been assigned to all heat flow values which are all well above 100mW/m^{2} (Jessop *et al*., 1976).

The knowledge of the depth to the basement provides the thickness of the sedimentary fill which in turn is a key indicator in determining whether the deeper parts of the basin have been buried to sufficient depth to reach maturation window. So, for any area to be viable for hydrocarbon formation, the thickness of sediment must be up to 2.30 km as well as other conditions necessary for hydrocarbon formation (Wright *et al*., 1925). Based on the sedimentary thickness of 4.78 - 5.30 km, the possibility of hydrocarbon generation is feasible. It is hereby noted that one of the economic significances of this study is the consideration of hydrocarbon potential and it can be seen from the result that sedimentary thickness obtained in this analysis is sufficient to allow for accumulation of hydrocarbon. Gracefully, NNPC Limited have their Oil wells in KOLMANI few kilometers away from the area under study.

CONCLUSION

A study of interpretation of aeromagnetic data over Yankari Game reserve Bauchi State, Nigeria in order to determine the geothermal energy potential of the area has been carried out using spectral analysis. It has been discovered that the depth to the top of magnetic sources varies from 0.50 to 5.30 km for the area. The study revealed that the region is characterized by shallow Curie depths and high heat flow. The Curie point depth estimated the average depth of magnetic sources and is concluded to reflect thermal structures. The study area is underlain by a Curie point isotherm as shallow as 8.91 km in south west and some part of the east a deep Curie point isotherm as 10.11 km in the rest of the area under study. The result was also subjected to geothermal gradient computation and heat flow, where an estimated values range from 57.37 to 65.10 ºC/km and 143.43 to 162.75 mWm^{-2} respectively.

The results from this work show that the Southwest and eastern part of the area provides a great source of geothermal energy as temperatures greater than 100 ºC can be reached at depths less than 2 km. The average heat flow in thermally "normal" continental regions is around 60 mWm^{-2}. Values in excess of about 80 - 100 mWm^{-2} indicate anomalous geothermal conditions (Jessop *et al*., 1976). For this study anomalous geothermal condition have been assigned to all determined heat flow values which are all well above 100 mWm^{-2}. The southwestern part of the study area is an area with great geothermal energy potential for geothermal exploitation. The study proves to us that magnetic method of data analysis can adequately be utilized for this purpose.

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