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RESEARCH ARTICLE

Assessment of Geothermal Potentials In Some Parts of Upper Benue Trough Northeast Nigeria Using Aeromagnetic Data

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Abstract

The assessment of geothermal potentials over part of the upper Benue trough corresponding to Kaltungo, Guyok, Lau and Dong areas, North Eastern Nigeria using spectral depth analysis of aeromagnetic data has been carried out. The study area is bounded by latitudes 9°00'N and 10°00'N and longitudes 11°00'E and 12°00'E. This research work is necessitated by the need for renewable and alternative sources of energy for use in Nigeria. Regional/residual separation was carried out on the total magnetic field using polynomial fitting method of order one. The residual map was divided into nine overlapping blocks for the spectral analysis. The centroid depths and depth to top of basement were obtained from the plot of log of power spectrum against wavenumber. These two parameters were used to estimate the Curie point depth using $Z_b = 2Z_o - Z_t$, where $Z_b,\ Z_o$ and Z_t are Curie depth, centroid depth and depth to top of basement respectively. The results from the spectral analysis suggested that in the parts of the Upper Benue trough, the basement is deepest at the south western portion towards the Lau area and varies between 0.55 and 3.8 km, while the centroid depth varies from 7.26 to 18.00 km. From the same portion of the trough, the Curie-point depths vary between 12.43 and 33.91 km and the corresponding geothermal gradient and heat flow values varying from 17.10 to 46.66 °C/km with an average of 30.75 °C/km and 42.75 to 116.65 mW/m^2 with an average of 75.91 mW/m^2 respectively. The maximum heat flow is found around the south western portion of the study area (Lau). The entire study area with high heat flow values might probably be good sources for geothermal and thereby recommended for both geothermal exploration and exploitation.

Keywords: Aeromagnetic data, Curie point, Geothermal gradient, Heat flow

1. Introduction

The study involves the quantitative estimation of Curie-point depths (CPD), geothermal gradients and subsurface heat flow anomalies for the assessment of geothermal potentials in some parts of the upper Benue trough northeast Nigeria using spectral analysis of the recently acquired high resolution aeromagnetic data. The high resolution aeromagnetic data was obtained from the Nigerian Geological Survey Agency (NGSA) as part of the airborne magnetic survey data acquired between 2005 and 2009.

Several studies have shown that regional magnetic data can be used extensively to determine the thermal structure of the Earth's crust in various geologic environments (Spector and Grant, 1970; Nur *et al.*, 1999; Bhattacharyya and Leu, 1975, 1977; Tanaka *et al.*, 1999; Ravat *et al.*, 2007; Bansal *et al.*, 2011, 2016; Nwankwo *et al.*, 2011; Eletta and Udensi, 2012; Kasidi and Nur, 2012, 2013; Nwankwo and Sunday, 2017). For example, dominant magnetic minerals in the Earth's crust pass from ferromagnetic to paramagnetic state at temperature, commonly called Curie-point temperature (CPT). Magnetite (Fe_3O_4) is the most common magnetic material in igneous rocks and has an approximate CPT value of 580 °C (Nwankwo and Sunday, 2017). At temperature above CPT, the thermal agitation causes the spontaneous alignment of the various domains in the mineral to be destroyed (or randomized) to the extent that the ferromagnetic minerals become totally paramagnetic (Nwankwo and Sunday, 2017).

The Curie-point is the temperature at which the spontaneous magnetization vanishes and magnetic minerals show paramagnetic susceptibility. The Curie-point depth is known as the depth at which the dominant magnetic minerals in the crust pass from a ferromagnetic state to a paramagnetic state under the effect of increasing temperature (Nagata, 1961). For this purpose, the basal depth of a magnetic source from aeromagnetic data is considered to be the Curie-point depth. Curie point temperature varies from region to region depending on the geology and the mineralogical content of the rocks. The assessment of the variations in the Curie-point depth of an area can provide valuable information about the regional temperature distribution at depth and the potential of subsurface geothermal energy (Tselentis, 1991). The geothermal gradient is the rate at which the earth's temperature increases with depth. The temperature in sedimentary basins increases downward with depth while heat is transferred upward by a process known as heat flow.

Assessment of geothermal energy involves studies and research aimed at assessing the nature and energy production capacity of geothermal systems. It is based on the data available at any given time, or stages in the development of a system, such as surface exploration data, the results of the drilling of exploration and production wells, as well as production monitoring data. So far, geothermal issues have not been widely known in Nigeria, although investigation of subsurface temperature of rock mass was carried out in hundreds wells due to exploration for oil and gas within sedimentary basins. There were several projects being aimed at exploration of subsurface temperature distribution, carried out with the use of data from oil and gas boreholes as well as shallow water wells. The results of those studies as well as investigation of geothermal surface manifestations give an idea about geothermal conditions of Nigeria (Kurowska and Schoeneich, 2003).

The idea of using aeromagnetic data to estimate CPD is not new, and it has been widely applied to various parts of the world. Bhattacharyya and Leu, (1975) mapped Curie point isothermal surface for geothermal reconnaissance of the Yellowstone National Park in USA. In this area, CPD was estimated 4–8 km. Tselentis (1991) calculated CPD in Greece from aeromagnetic and heat flow data. Tselentis's objective was to understand the nature and extent of the regional geothermal system at a depth beneath the area of Greece by constructing the Curie isotherms. The results of his investigations revealed that the CPD varies considerably beneath Greece, reaching 20 km towards western Greece and about 10 km beneath the Aegean. In East and Southeast Asia, CPD was determined based on the spectral analysis of magnetic anomaly data by Tanaka et al. (1999). In this study, they used many heat flow data from the boreholes. The estimated CPD for this area using centroid method varied from 9 to 46 km. In addition, they predicted CPD from heat flow data. The CPD estimated from the heat flow data were very similar to the results of the CPD analysis of magnetic data.

Eletta and Udensi (2012) investigated the CPD from magnetic data in the Benue trough. Their area of investigation lay between 7°N and 9°30′N and between 9°30'E and 12°E. Their study area cuts our study area in half toward the southern region and lies within the sedimentary formation of the middle Benue Trough and partly in the basement complex region of north-central Nigeria. Their estimated CPDs varied between 2 and 8.4 km. Also, that the aeromagnetic anomalies suggest that a series of buried NE–SW lineaments of incipient rifts controlled the deposition of the individual complexes. Onuba *et al.* (2012) interpreted aeromagnetic data over parts of the upper Benue trough and southern Chad basin within latitudes of 10°30′N to 11°30′N and longitudes of 12°E to 13°E. They obtained depths to magnetic sources ranging from 0.5 to 2.5 km and concluded that the estimated depths were representative of the sedimentary thicknesses and intrusive bodies within the area. The present study utilizes spectral analysis to estimate the Curie-point depth and the heat flow to determine the geothermal history of the region. Alagbe and Sunmonu (2014) conducted evaluations on aeromagnetic data from the upper Benue trough within latitudes of 7°N to 8°N and longitudes of 11°E to 12°E. Their estimated depth to the magnetic sources ranged between 0.01 and 3.45 km. They attributed the shallow depths to near-surface intrusive rocks in their study area.

With a rapidly growing world-population, and ever-increasing environmental concerns, sustainable energy development has become an issue of crucial importance for mankind (Tiwari and Ghosal, 2005). Geothermal resources have the potential of contributing significantly to sustainable energy use in many parts of the world. In Nigeria, the quest for a sustainable power supply has been a great challenge to the government (past and present) for the smooth running of the economy and the sustenance of lives and property. This research aims to provide an insight into the geothermal energy potential of the study area as an alternative source of sustainable energy production of power (for electricity generation or direct use for heating residential houses, or both) by identifying and delineating the areas with favourable geothermal conditions and utilizations, through the estimation of the Curie-point depth, geothermal gradient and heat flow..

2. Location and Geology of the Study Area

The study area (Figure 1) which is part of the upper arm of the Benue trough lies between Latitude 9°N and 10°N and Longitude 11°E and 12°E with an estimated area of about 12,100 km^2. The area is accessible with a good network of roads and rural feeder roads.

The Benue trough is a major NE-SW trending rift basin of 50 – 150 km width and over 100 km length. It is geographically sub-divided into lower, middle and upper portion. The upper Benue trough (Figure 2) is Y shaped made up of three arms, namely: the E – W trending Yola arm, N – S trending Gongola arm or Gongola basin and the NE – SW trending main arm (Muri – Lau basin) (Shettima *et al.*, 2016). The outcrops of various lithologic units of the upper Benue trough are inliers of the prominent Bima sandstones (Onuba *et al.*, 2008) and deposited as extrusive lithographic units during the Albian transgressive phase (Ukaegbu and Akpabio, 2009). This transgressive episode led to the deposition of the various formations that made up the sedimentary basin which outcrops or occurs as shallow marine deposit of limestone, shale and mudstone. Ogungbesan and Akaegbobi (2011) however observed that the outcrop units of the formation consist of Sandstone, Shale and Basaltic rocks lying unconformably on the Basement rocks. These Aptian-Albian pyroclastics sediments were described as the earliest sedimentation of the entire Benue trough.

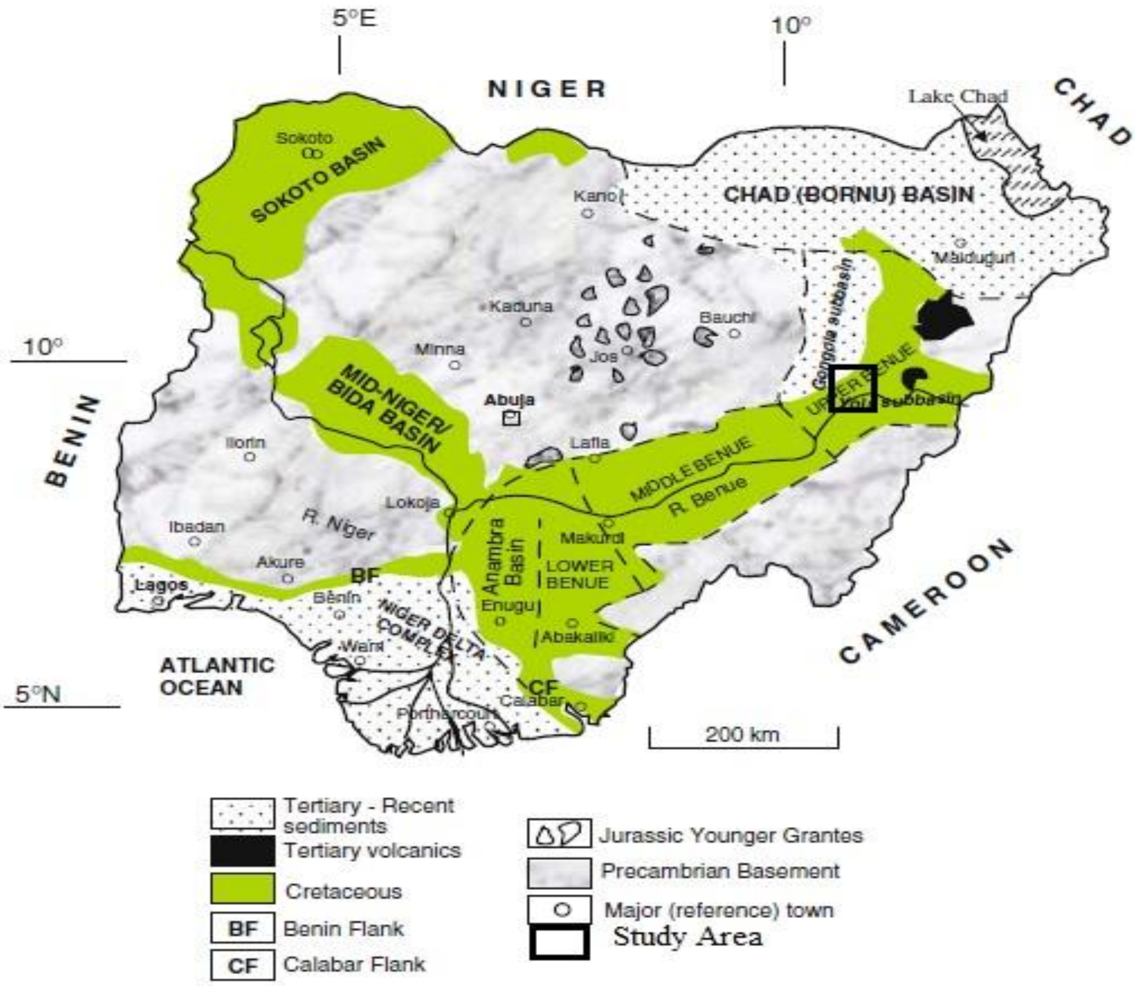


Fig.1. General Geology map of Nigeria showing the location of the study area. (modified from Obaje, 2009)

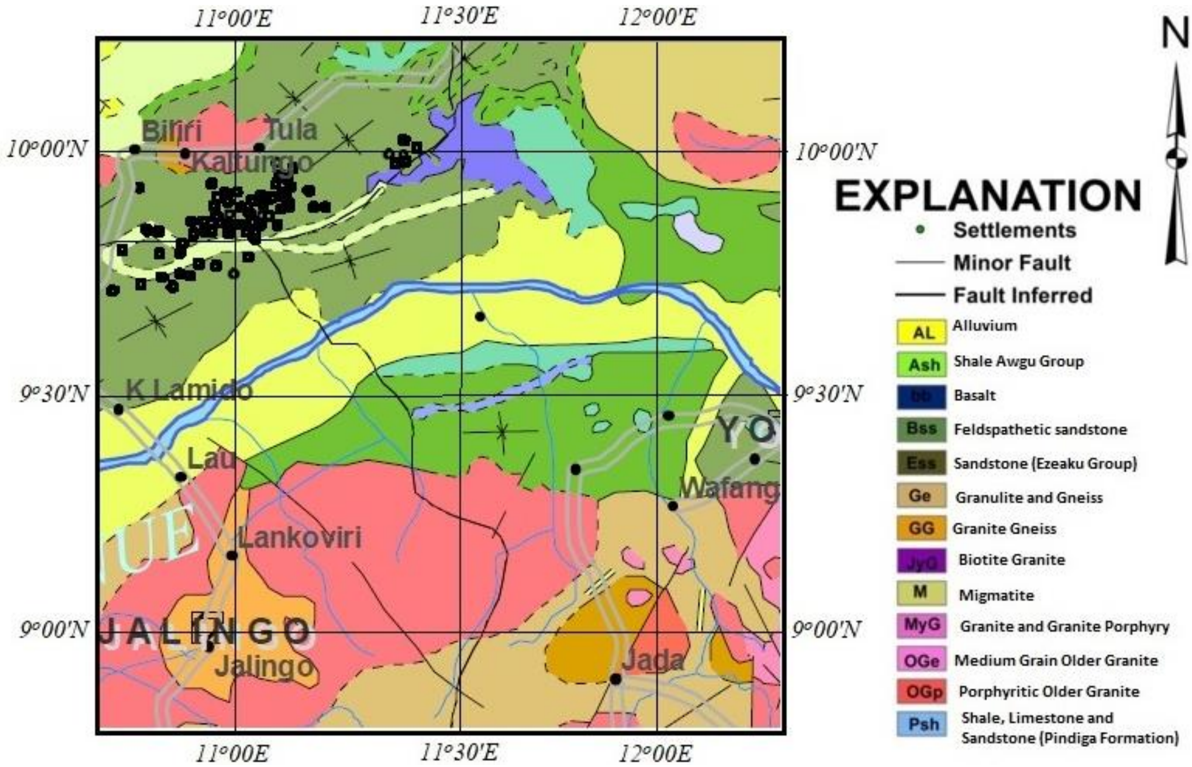


Fig. 2. Geological map of the study Area (Extracted from Geological map of Nigeria, NGSA)

3. Materials And Method

Four aeromagnetic maps (Sheets 173,174,194 and 195) covering Kaltungo, Guyok, Lau and Dong areas of part of the upper Benue trough were acquired from the Nigerian Geological Survey Agency (NGSA). These maps were obtained as part of the nationwide aeromagnetic survey of 2009 sponsored by the NGSA. The data were acquired along a series of NE – SW flight lines with a spacing of 200 m and an average flight elevation of about 80 m while tie lines occur at about 500 m interval. The geomagnetic gradient was removed from the data using the International Geomagnetic Reference Field (IGRF), 2005. The data were made available in the form of grids on a scale of 1:100,000. These data were processed and merged together into a common dataset. In this study, the total area to be covered is about 12,100 sq.km extending from Latitude 9°N – 10°N and from Longitude 11°E – 12°E.

The procedures involved in this study include the following; production of Total Magnetic Intensity (TMI) map using OASIS MONTAJ software, separation of the regional and residual anomalies, division of residual map into nine overlapping blocks, performing spectral analysis on each blocks, evaluating the depth to the magnetic source using spectral analysis, estimating the geothermal gradient and heat flow.

Theory of methods; Calculation of Curie-point depth, geothermal gradient and heat flow.

The centroid depth is calculated from the low wave number part of the scaled power spectrum as

$$Ln\,[\,P(k)^{1/2}\,/\,k] = A - |k|\,Z_0 \qquad (1)$$

Where *ln* is the natural logarithm, P (k) is the radially averaged power spectrum, k is the wave number (2π/km). A is a constant depending on the properties magnetization and its orientation and Z_0 is the centroid depth of the magnetic sources (Tanaker *et al.*, 199). For the high wave number part, the lower spectrum can be related to the top of the magnetic sources by a similar equation:

$$Ln\,[\,P(k)^{1/2}\,/\,k] = B - |k|\,Z_t \qquad (2)$$

Where B is a constant: Z_1 is the depth to the top of the magnetic sources. The depth of the bottom of magnetization Z_b is :

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

Summarily, the depth to the base of the magnetic source (the Curie point depth) is calculated in four steps (Tanaka *et al.*, 1999):

i. Calculate the radially averaged power spectrum of the magnetic data in each window
ii. Estimate the depth to the top of the magnetic source(Z_t) using the high wave number portion of the magnetic anomaly power spectra
iii. Estimate the depth to the centroid of the magnetic source (Z_o) using a lower wave number portion of the magnetic anomaly power spectra
iv. Calculate the depth to the base of the magnetic source (Z_b) using $Z_b = 2Z_o - Z_t$. The value of the Z_b is the Curie point depth/DBMS.

Therefore, the geothermal gradient in relation to the heat flow q. (Tanaka *et al.*, 1999):

$$q = k\frac{\theta°C}{d} \qquad (4)$$

The surface temperature is θ°C and $\frac{dT}{dZ}$ will remain constant provided there are no heat sources or heat sinks between the earth's surface and the Curie point depth. The Curie temperature depends on magnetic mineralogy. For example, although the Curie temperature of magnetite (Fe_3O_4) is at approximately 580°C, an increase of Titanium (Ti) contents of titanomagnetite ($Fe_{2-x}Ti_xO_3$) will cause a reduction of the Curie temperature. A curie temperature of 580°C and thermal conductivity of 2.5 W m^{-1} °C^{-1} which is the average thermal conductivity for igneous rocks will be used in the study as standard (Nwankwo *et al.*, 2011; Tanaka *et al.*, 1999), we then calculate the value for K the geothermal gradient in the study area using the empirical relation between Curie point, Curie temperature and geothermal gradient.

Heat flow estimates on the crust may therefore be made using the depth and thickness information. The Curie point temperature at which rocks lose their ferromagnetic properties provides a link between thermal models and models based on the analysis of magnetic sources. The magnetic susceptibility and strength of the material that make up the crust are controlled by the temperature. At temperature higher than the Curie point, magnetic ordering is loose and both induced and remanent magnetization disappear, while for temperatures greater than 580°*C* those materials will begin to experience ductile deformation. The basic relation for conductive heat transport Is Fourier's law. In one dimensional case under assumption that the direction of the temperature variation is vertical and the temperature gradient $\frac{dT}{dZ}$ is constant; Fourier's law takes the form:

$$q = -k\frac{dT}{dZ} \qquad (5)$$

Where *q* is heat flow and *k* is thermal conductivity. The Curie temperature $\theta°C$ can also be defined as:

$$\theta°C = \left(\frac{dT}{dZ}\right)d \qquad (6)$$

Where *d* is the Curie point depth (as obtained from the spectral magnetic anomaly).

4. Results and Discussion

The total magnetic intensity map (TMI) of the study area (Fig. 3) shows that the magnetic intensity of the study area is divided into regions of high and low magnetic signatures respectively. The high magnetic signature is depicted by the pink colouration on the map and the low magnetic signature is by the blue colouration on the map. The high magnetic signature region is well pronounced in the north eastern and south western part of the TMI map of the study area, showing that the high magnetic signature trends northeast – southwest in the study area The variation in magnetic signatures could be as a result of degree of strike, variation in depth, difference in magnetic susceptibility and lithology. The low magnetic signature is also pronounced in the south eastern part of the study area. Also, low magnetic signature could be found in south-western and north western part of the study area, although the low magnetic signature is less pronounced in these parts of the study area.

The residual magnetic intensity map (Fig. 4) of the study area shows that the magnetic intensity values ranges from -52.8 nT to 50.3 nT respectively. The high magnetic anomaly signatures are majorly observed in the north-eastern, south-eastern north western part of the study area. Although, scattered traces are also observed in the south west and the central parts of the study area. The low magnetic anomaly signatures can be observed in the south-east and trending towards the south-west and northwards, while scattered traces are observed elsewhere in the northern, eastern, southern and western parts of the study area. The high magnetic anomalies might be as a result of basement intrusion into the sediments while low magnetic anomalies are associated with the sedimentary region.

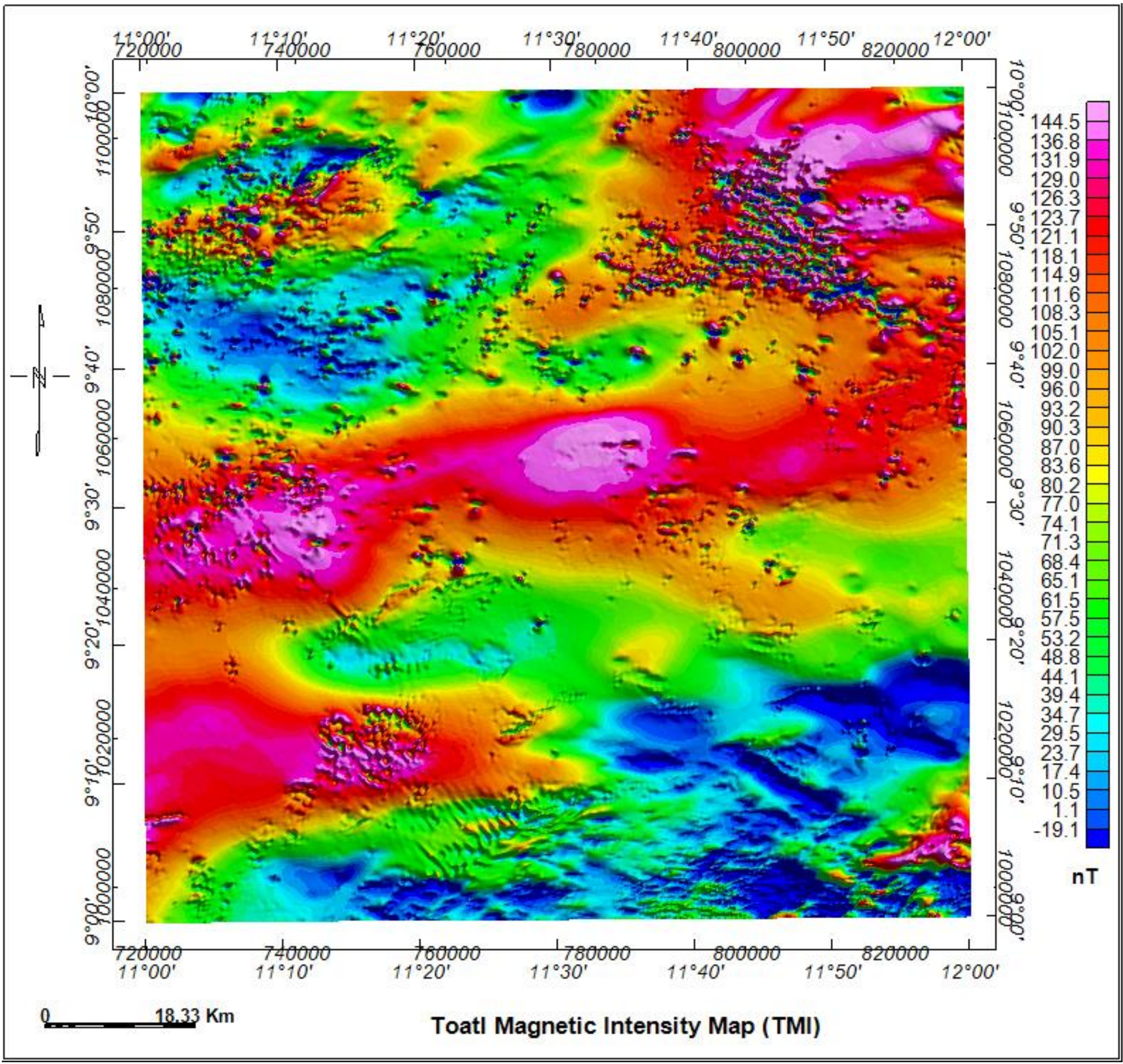


Fig. 3. Total Magnetic Intensity (TMI) map of the study area (IGRF of 33000 nT must be added to get the exact value at any point).

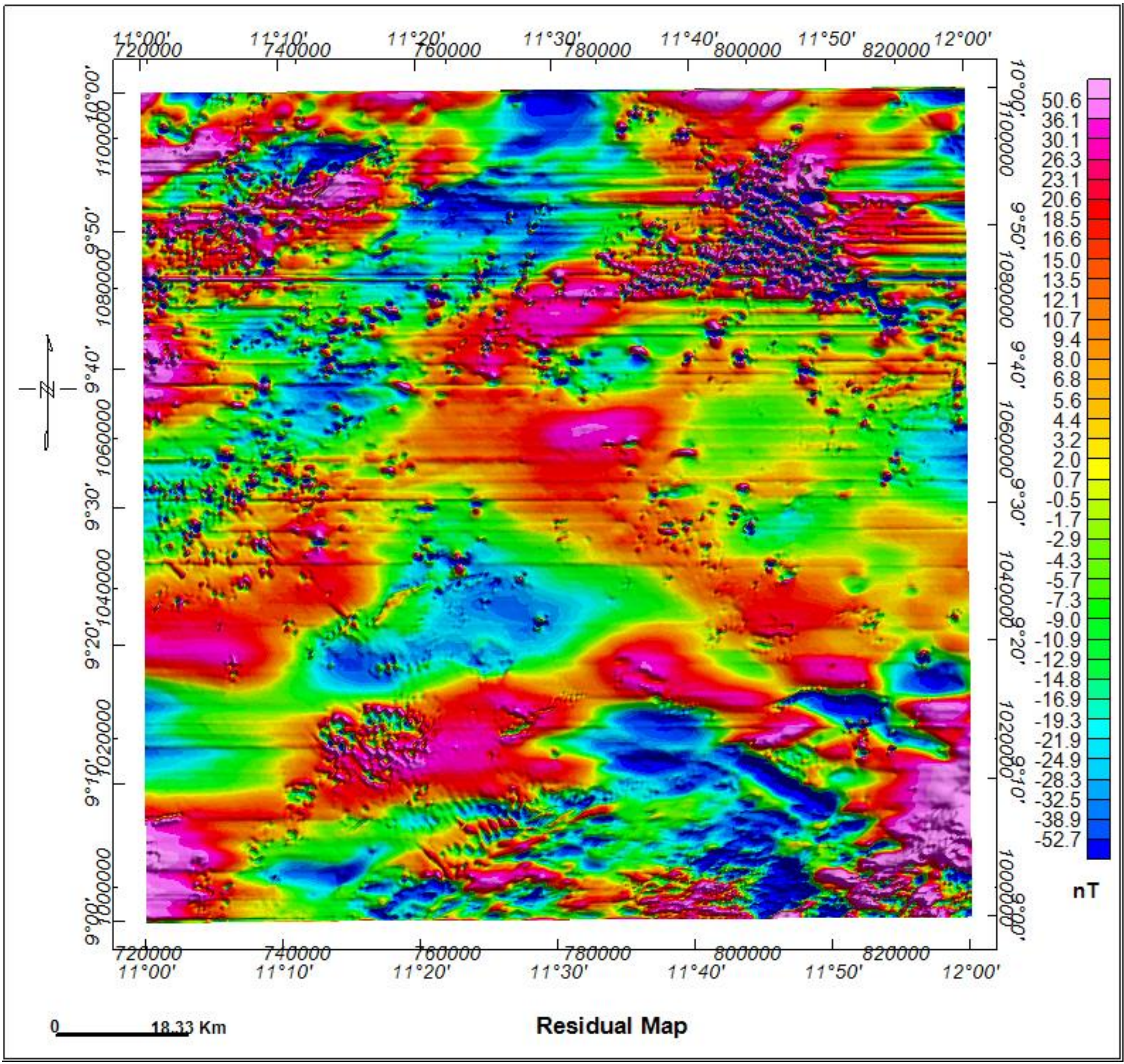


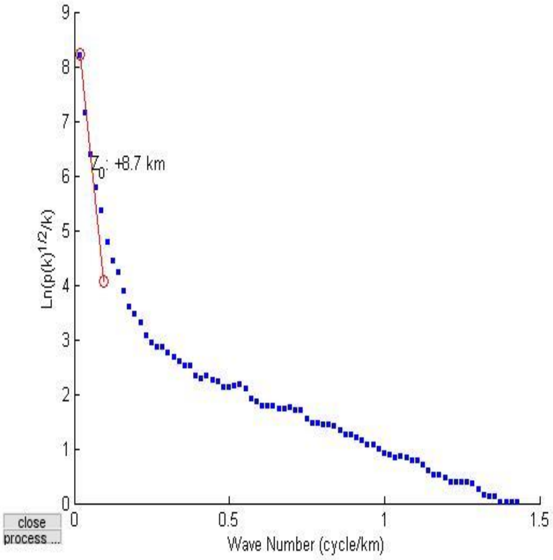
Fig. 4. Residual map of the study area (Magnetic unit in nT)

The residual map (Fig.4) of the study area was divided into nine spectral blocks (Spct A - I) of overlapping sections. The divisions of the residual map into spectral sections were done manually and the spectral energies were plotted within it. The Spectral data obtained were later exported to Microsoft excel worksheets one after the other. The spectral blocks energy files were used as input files into a spectral program plot (SPP) developed with MATLAB. The whole nine spectral energies were plotted using a MATLAB with the developed program.

Graphs of logarithms of the spectral energies against frequencies estimated for various blocks were obtained and the results tabulated (Table 1). The graphs (Fig. 5) of the logarithm of the spectral energy against frequency for block A, where the first graph of the figure shows the slope of the lower-wave-number part of the wave-number-scaled spectra, which leads to the estimation of centroid depth (Z_o), while the second graph shows the slope of the high-wave-number portion of the spectra, which leads to the estimation of the depth to the top of magnetic sources (Z_t).

Equation 3 was then applied to estimate the Curie point depths (Zb). Using equation 6, a curie-point temperature of 580 °C and the derived curie-point depth, the geothermal gradients in the study area were calculated. Also, equation 4, the geothermal gradients and thermal conductivity of 2.5 Wm^{-1} $°C^{-1}$ (Nwankwo *et al*., 2009) was subsequently used to estimate the corresponding heat flow anomalies in the study area.

The estimated results (Table 1) shows that the estimated CPD varies from 12.43 to 33.91 km with an average of 18.83 km. The Curie point depth contour map usually varies greatly with different geological settings (Tanaka et al., 1999). Tanaka et al.,1999, after a compilation of CPD results from several researchers across the globe, inferred that volcanic, tectonic and associated geodynamic environments have CPD shallower than 10 km, while CPDs ranging between 15 and 25 km are as a result of island arcs and ridges, and deeper than 25 km in plateaus and trenches.



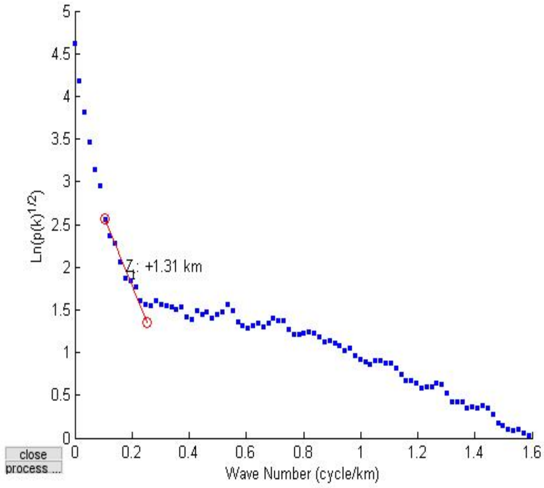


Fig. 5. Zo and Zt plots of energy against frequency for block A

Table 1. Estimated Curie point depth and succeeding geothermal parameters from spectral analysis in the study area

Blocks	*Longitude (°E)*	*Latitude (°N)*	*Centroid depth Z_o (km)*	*Depth to the top Z_t (km)*	*Curie depth Z_b (km)*	*Geothermal gradient (°C/km)*	*Heat flow (mW/m²)*
A	11.25	9.75	8.70	1.31	16.09	36.05	90.13
B	11.75	9.75	7.26	0.55	13.97	41.52	103.80
C	11.25	9.25	7.72	3.01	12.43	46.66	116.65
D	11.75	9.25	8.86	0.97	16.75	34.63	86.58
E	11.50	9.75	14.70	1.30	28.10	20.64	51.60
F	11.50	9.25	13.00	3.69	22.31	26.00	65.00
G	11.25	9.50	12.20	3.80	20.60	28.25	70.63
H	11.75	9.50	14.30	2.72	25.88	22.41	58.03
I	11.50	9.50	18.00	2.09	33.91	17.10	42.75
Average			11.64	3.46	18.83	30.75	75.91

Table 1 similarly shows that the geothermal gradient varies between 17.10 and 46.66 °C /km with an average of 30.75 °C /km. The corresponding heat flow values vary from 42.75 to 116.65 mW/m² with an average of 75.91 mW/m². The heat flow in the study area also exhibits a NE-SW trending with the derived amounts increasing from the central portion towards the northeast and southwest. The heat flow contour map (Fig. 6) is closely related to the geothermal gradient, meaning that most areas of high heat flow correspond to high geothermal gradient. Among the four areas making up the study area, the maximum heat flows are found around Guyok and Dong areas. All current literatures state that curie-point depths and heat flows greatly depend on geological conditions. In geothermal exploration, heat flow is the primary observable parameter. Generally, high heat flow values correspond to volcanic and metamorphic region since the two units have high heat conductivities (Nwankwo *et al.,* 2011). Additionally, heat flow is significantly affected by tectonically active regions (Tanaka *et al.,* 1999). Geothermal energy does also occur in areas where basement rocks that have relatively normal heat flow are covered by thick blanket of thermally insulated sediments (Ofor and Udensi, 2014). It can be inferred that the average high heat in the study area may be a direct consequence of the rift associated with the upper Benue trough. It may also be associated with areas where thick blanket of thermally insulated sediments cover basement rocks since there is no evidence of volcanic activities in the study area.

In thermally normal continental regions the average heat flow is about 60 mW/m², values between 80 and 100 mW/m² are good geothermal source, while values greater than 100 mW/m² is an indication of anomalous geothermal conditions (Nwankwo and Sunday, 2017). In view of this, the average heat flow of 75.91 mW/m² estimated in the study area corresponding to Kaltungo, Guyok, Lau and Dong areas makes the study area to be of favourable geothermal potentials.

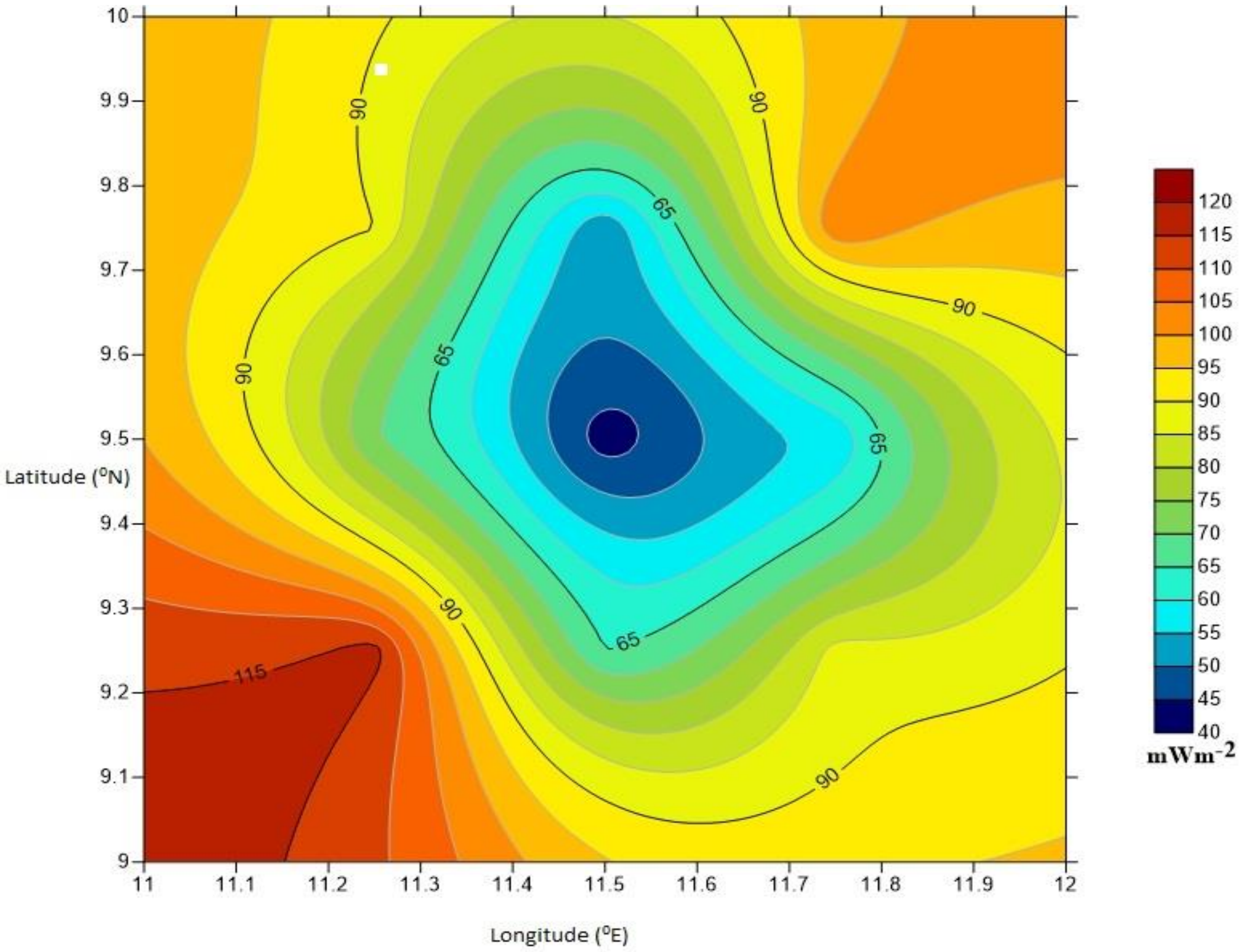


Fig. 6. Heat flow contour map of the study area (Contour interval of 5 mW/m^2)

5. Conclusion

The results of the estimated Curie-point depth for the study area reveals that, the Curie point depth varies inversely with heat flow; this shows that heat flow in the study area decreases with increase in Curie depth. The inferred Curie point depth obtained ranges from 12.43 to 33.91 km with an average of 18.83 km. The results compared favourably well with what was obtained by Nur *et al.* (1999). It also confirms that, Curie depths are indirect indicator of the thermal structure of the area. The calculated geothermal gradient in the study area based on the CPD varies between 22.41 to 46.66 $^{o}Ckm^{-1}$ with an average of 30.75 $^{o}Ckm^{-1}$. The corresponding heat flow values estimated from the geothermal gradient in the study area varies between 42.75 and 116.65 mWm^{-2} with an average of 75.91 mWm^{-2}.

The average heat flow value of 75.91 mWm^{-2} obtained in the study area agrees favourably with the range of values obtained by Nwankwo and Sunday (2017). The result is so good that it can be utilised for exploration of geothermal energy as an alternative source of power in these parts of the upper Benue trough.

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