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REGIONAL ESTIMATION OF CURIE POINT DEPTH, GEOTHERMAL GRADIENT AND HEAT FLOW INFERRED FROM HIGH RESOLUTION AEROMAGNETIC DATA OVER SHELLENG AND ENVIRONS, NORTH-EASTERN NIGERIA

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ABSTRACT

A regional estimation of Curie-point depths (CPDs), geothermal gradient and heat flow from high resolution aeromagnetic (HRAM) data over Shelleng and environs, North-Eastern Nigeria was carried out using Oasis Montaj (7.5version), Microsoft excel, Matlab (2016 version) and Surfer8 software and spectral centroid analysis method. The HRAM data were divided into 64 overlapping blocks, and each block was analysed to obtain depths to the top, centroid, and bottom of the magnetic sources. The depth values were then used to assess the CPD, geothermal gradient and subsurface crustal heat flow in the study area. The result shows that the CPD varies between 4.95 and 7.69 km with an average of 6.69 km, the geothermal gradient varies between 47.23 and 86.57 °C km^{-1} *with an average of 58.73 °C km*$^{-1}$*, and the crustal heat flow varies between 21.13 and 216.43 mWm*$^{-2}$ *with an average of 166.72 mWm*$^{-2}$*. This study showed that geodynamic processes are mainly controlled by the thermal structure of the Earth's crust and therefore important for appraisal of the geo-processes, rheology, and understanding of the heat flow variations in the area, North-eastern Nigeria.*

***KEYWORD**: Aeromagnetic data, Curie point depth, Geothermal Gradient, Heat flow, Thermal structure and Spectral centroid.*

Introduction

This present research study is concerned with regional estimation of Curie point depth, geothermal gradient and heat flow inferred from High Resolution aeromagnetic data over Shelleng and environs, North-Eastern Nigeria, which has not been given adequate attention in the recent past by geologists and geophysicists. This may be due to lack of immediate geologic and economic values even though it is fast becoming an important study area for geoscientists. There are increased efforts to explore for new and more energy locations, being part of Cameroon Volcanic Line in Nigeria. However, geophysical study in the area is minimal, with no records of crustal thermal studies, Curie point depths, heat flow, oil and gas prospecting. The knowledge of Curie point depths, geothermal and heat flow assessment would significantly compliment the geophysical information of the area to bridge the gap of lacking crustal studies information.

The study area is located between latitude 8° 30' and 10° 30' N and longitude 11 00' and 13 00' E, North -Eastern Nigeria and it covers an area of approximately 48,224 km^2. The area is characterized by rugged terrain. It is one of the crystalline pre-Cambrian basement blocks in Nigeria. The study area was subjected to periods of regional metamorphism, tectonism and magmatism which led to the development of fractures and faults as well as the emplacement of intrusive and dyke like structures (Ofoegbu, et al, 1992; Kasidi and Nur, 2013).

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; Bhattacharyya and Leu, 1975, 1977; Byerly and Stolt, 1977; Blakely and Hassan zadeh, 1981; Okubo et al., 1985, 2003; Blakely, 1988, 1995; Maus et al., 1997; Tanaka et al., 1999; Chiozzi et al., 2005; Eppelbaum and Pilchin, 2006; Ross et al., 2006; Ravat et al., 2007; Trifonova et al., 2009; Gabriel et al., 2011, 2012; Bansal et al., 2011, 2013, 2016; Nabi, 2012; Hsieh et al., 2014; Nwankwo and Shehu, 2015; Nwankwo and Sunday, 2017 etc.). Studies showed that 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 (Stacey, 1977). 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 (Langel and Hinze, 1998; Nwankwo and Sunday, 2017). Curie point depth is defined as the depth at which CPT is reached within the subsurface, can be considered as an index of depth to the bottom of magnetic sources (DBMS) and can consequently be calculated from geomagnetic anomalies (Bansal et al., 2011, 2013; Hsieh etal., 2014). However, in some circumstances DBMS can be caused by contrasts in lithology instead of CPT and may not necessarily coincide with CPT in detail (Bansal et al., 2011; Trifonova et al., 2009). For instance, Trifonova et al., (2009) opined that even if the spectral method provides a good estimate of DBMS there is no assurance that it represents the CPD. They reasoned that a variety of geologic reasons exist for truncated magnetic sources that are unrelated to crustal temperatures; for example, a sequence of relatively non-magnetic sediments below young volcanic material may limit the depth of magnetic sources regardless of the CPT, and another reason is the variety of magnetic minerals like titanomagnetite ($Fe_{3-x}Ti_xO_4$), is the most important iron oxide in crustal magnetic sources; it has a CPT that is strongly influenced by the amount of titanium and ranges from 150 to 580 °C. In some geologic environments, alloys of iron with CPTs in excess of 620 °C may be significant contributors to magnetic anomalies. In spite of these limitations, many studies (Tanaka et al., 1999; Trifonova et al., 2009; Bansal et al., 2011; Hsieh et al., 2014; etc.) have reasonably used DBMS as an estimate of CPD and therefore serve as a proxy for temperature at depth. Again, Trifonova et al. (2009) pointed out that several studies have identified low-titanium titanomagnetite as the dominant magnetic phase, and CPTs at these depths are estimated to be between 575 and 600 °C. This confirms the estimated value of 580 °C by Stacey (1977) as the case in this study. Another important justification is that DBMS/CPD estimations can similarly be used to complement geothermal data in regions where deep boreholes are unavailable (Chapman and Furlong, 1992; Ross et al., 2006; Bansal et al., 2011, 2013).

Shelleng and Environs is one of the least studied in North-Eastern Nigeria. Up to date, the area under study has no information on seismicity, no exploratory wells penetrated its sequences, and deep crustal data are limited. The present work employs spectral analysis method to estimate the Curie point depths, geothermal gradient and heat flow of the region and is expected to contribute immensely to a better understanding of the geothermal structures and geodynamic processes in the entire north-east, Nigeria.

Location and Geology of the Study Area

Shelleng and environs is located within the Northeast Basement Complex of Nigeria. The geology of the study area is made up of the Precambrian Basement complex rocks, which are considered to be undifferentiated basement consisting mainly of migmatites-gneisses complex, Older Granite rocks, Cretaceous sedimentary rocks and Tertiary to recent volcanic rocks (Fig.1).

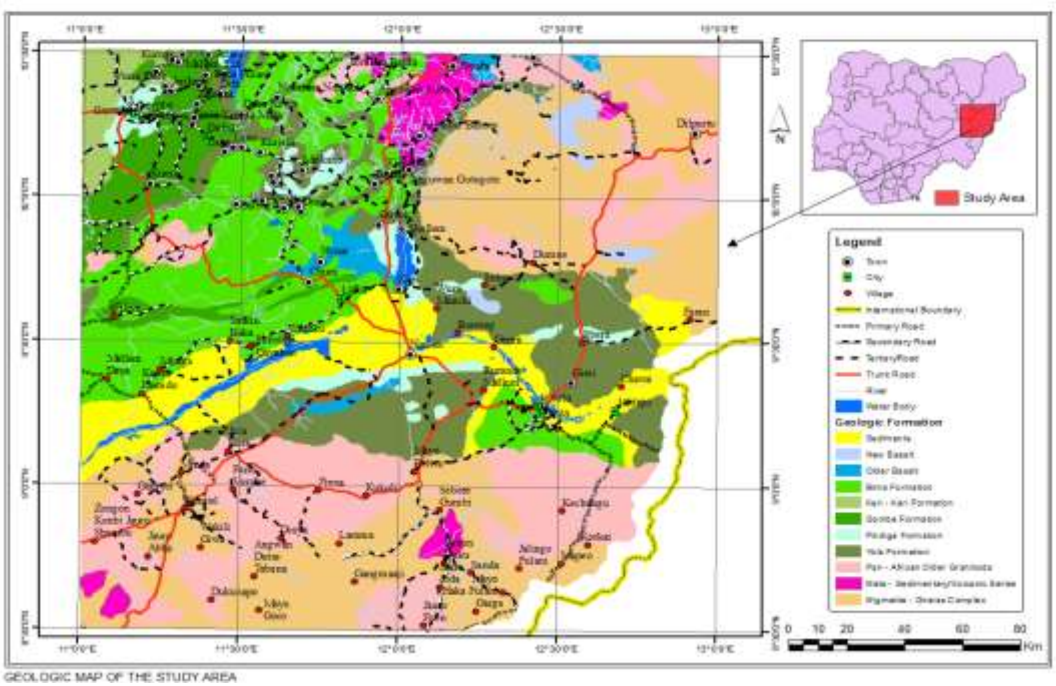


Fig 1 Geologic Map of the Study Area

The oldest rocks of the area, the gneisses which are believed to be of birrimian age (Oyawoye, 1970) are overlain by recent alluvium, resulting from the weathering and erosion of hills and decomposed rock material. They cover a large part of the crystalline basement rocks. The migmatite gneisses exhibit great variation in the percentage of light and dark mineral components that resulted from the protolithic they were derived under pressure and temperature conditions which they were formed. The older granites of Nigeria intrude the basement complex and are seen within great part of the studied area. They outcropped at the northern part. They are banded, foliated with felsic and ferromagnesian minerals forming the light and dark bands respectively. The mineral differentiation imparts the foliation to the rocks. The older granites which are younger are intrusive to the gneissic and magmatic rocks (Adebayo, 2010).

Data Acquisition and Analysis:

The high resolution aeromagnetic data of parts of North- Eastern Nigeria used for this study were obtained from the Nigerian Geological Survey Agency (NGSA) using a 3 x Scintrex CS2 caesium vapour magnetometer. Fugro Airborne Surveys carried out the airborne geophysical work in 2009. The survey was flown at 80m elevation along flight lines spaced 500m apart and nominal tie line spacing of 2 km. The flight line direction was 135° while the tie line direction was 225°. The data was generally plotted using Universal Transverse Mercator (UTM) projector method. WGS1984 Spheroid and WGS 1984 datum were also used. Grid mesh size was 125 metres. The geomagnetic gradient was removed from the data using International Geomagnetic Reference Field (IGRF).

The materials used for this study include sixteen digitized half degree aeromagnetic sheets namely:Gombe (sheet152), Wuyo (sheet153), Shani (sheet 154), Garkida (sheet 155), Kaltingo (sheet 173), Guyuk (sheet 174), Shelleng (sheet 175), zummo (sheet 176), Lau (sheet 194), Dong (sheet 195), Numan (sheet 196), Gerei (sheet 197), Jalingo (sheet 215), Monkin (sheet 216), Jada (sheet 217) and Mapeo (sheet 218) on a scale of 1:100000 superimposed on residual total magnetic intensity map of the study area shown in fig 2. Software applications used include: Oasis Montaj (7.5 version), Microsoft excel, Matlab (2016 version) and Surfer8 etc.

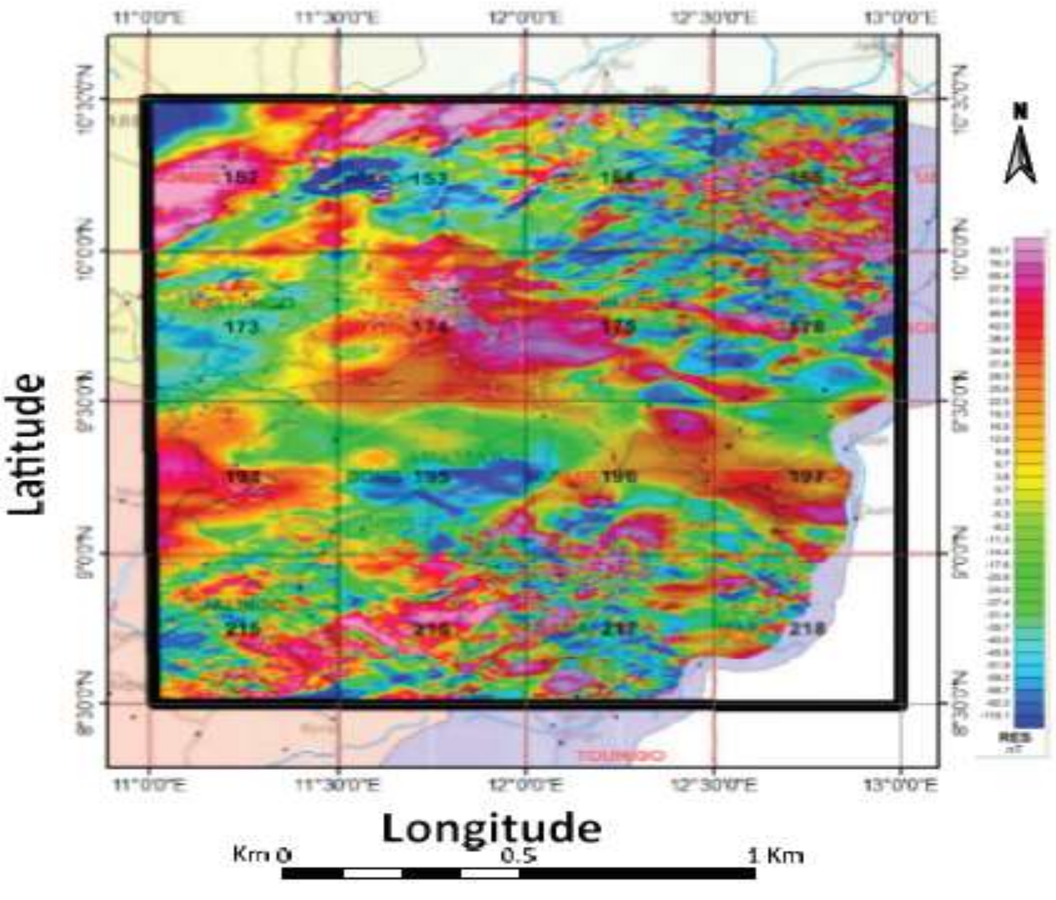


Fig.2 **Residual magnetic intensity map of the Study area with superimposed federal survey half-degree sheets and showing major towns flown over.**

To carry out Spectral analysis, the study area was divided into eight overlapping blocks. Each block covers a square area of approximately 55 by 55km, which represent a square grid of 32 by 32 data points except for the last empty block which fall out into republic of Cameroun. In doing this, it was ensured that no essential part of the anomaly was cut-off by the blocks, each block was continued upward to eliminate shallow source (short wavelength and enhance the deep seated magnetic sources).

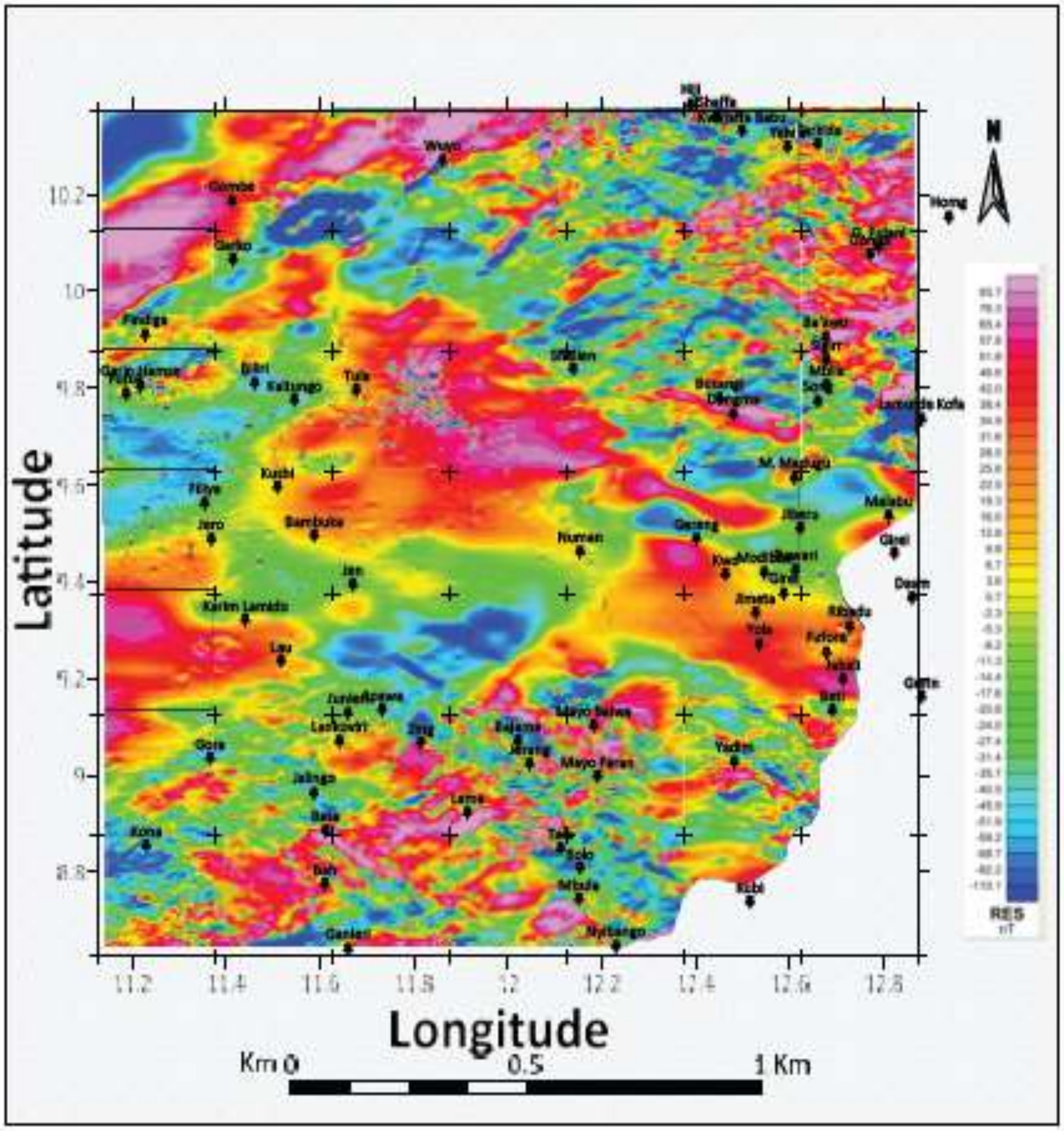


Fig.3 Residual Magnetic Intensity Map of the Study Area superimposed on the Topographic Map of the study area showing towns and villages.

Estimation of Curie-point depth

Curie point depth is estimated in two steps (Bhattacharyya and Leu, 1975, Okubo et al., 1985, Kasidi and Nur, 2012, Kamurayina and Nur, 2021): to perform the analysis the first step is to estimate the depth to the centroid (Z_o) of the magnetic source from the slope of the longest part of the wave length spectrum.

$$In[\frac{p(s)^{\frac{1}{2}}}{/s/}] = InA - 2\pi/s/Z_o \qquad (1)$$

where $p(s)$ is the radially average 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 wave length special segment (Okubo et al., 1985).

$$Inp[(s)^{\frac{1}{2}}] = InB - 2\pi/s/Z_t \qquad (2)$$

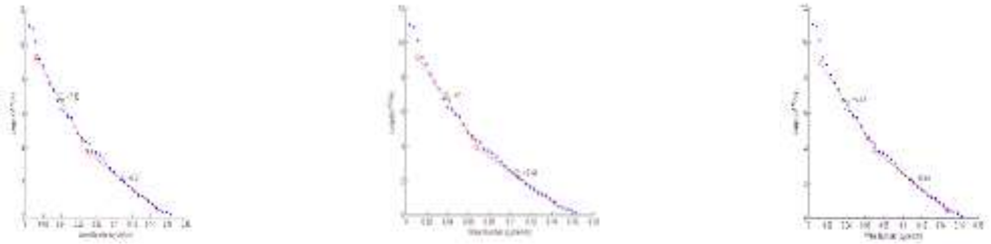
where B is the sum of the constants, the basal depth independent of $/s/$.

Then basal depth (Z_b) of the magnetic source is calculated from equation (3)

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

The basal depth (Z_b) of the magnetic source in the area is assumed to be the Curie point depth (Bhattacharyya and Leu, 1975, Kasidi and Nur, 2012 and Okubo et. al., 1985). Some few examples of graphs of the logarithms of the spectral energies verses wave numbers obtained for blocks 13 - 18 using the Oasis Montaj software, from which table 1 was extracted are shown in Figure 4 below.

BLOCK13 BLOCK 14 BLOCk 15



BLOCK 16 BLOCK 17 BLOCK 18

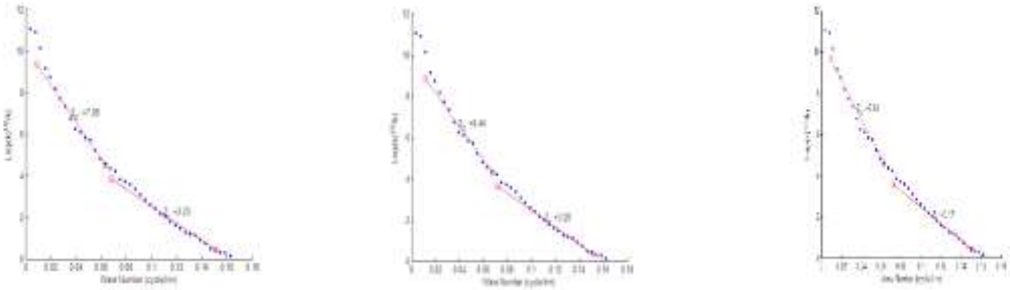


Fig. 4 Graphs of the logarithms of the spectral energies verses wave numbers of Blocks 13 to 18

Heat flow and geothermal gradient

Heat flow is the movement of heat (energy) from the interior of earth to the surface. According to Tanaka et al. (1999), the basic relationship for conductive heat flow is the Fourier's law. The estimation of heat flow and thermal gradient is calculated using the Fourier's Law with the following formula:

$$q = \lambda[\frac{\partial T}{\partial Z}] \qquad (4)$$

In order to relate the Curie point depth (Z_b) to Curie point temperature variation, the vertical direction of temperature variation and the constant thermal gradient was assumed. The geothermal gradient $\left(\frac{\partial T}{\partial Z}\right)$ between the earth and the Curie point depth (Z_b) is defined by the equation:

$$\frac{\partial T}{\partial Z} = \frac{580℃}{Z_b} \qquad (5)$$

where 580^0C is the Curie temperature at which ferromagnetic minerals are converted to paramagnetic minerals. Furthermore, the geothermal gradient is related to heat flow (q) using the formula:

$$q = \lambda(\frac{\partial T}{\partial Z}) = \lambda(\frac{580℃}{Z_b}) \qquad (6)$$

where λ is the coefficient of thermal conductivity. A thermal conductivity of 2.5 $Wm^{-1}\,{}^0C^{-1}$ was used (Abdulsalam, et al., 2011, Nwanko, 2007, Popoola and Ojo, 2010, Tanaka, et al., 1999 and Stacey, 1977) as the average for igneous rocks, was used to compute the subsurface heat flow. Equation (6) shows that the Curie point is inversely proportional to the heat flow (Tanaka et. al., 1999 and Stamploids et. al., 2005).

Equations (5) and (6) were used in computing values of geothermal gradients and heat flow of the study area respectively. These values ate presented in table1 below.

Table 1: Calculated Curie point depths, geothermal gradient and heat flow of the study area with their corresponding Spectral Block N0S, longitudes and latitudes.

Spectral Block NO	*Longitude*	*Latitude*	*Depth to the top Z_t (km)*	*Depth to Centroid Z_o (km)*	*Depth to bottom Z_b (km)*	*Geothermal gradient ($^0C\ km^{-1}$)*	*Heat flow (mWm^{-2})*
1	11.125	10.375	3.11	7.52	11.93	48.62	121.50
2	11.375	10.375	3.03	6.49	9.95	58.29	145.73
3	11.625	10.375	3.03	6.49	9.95	58.29	145.73

4	11.875	10.375	3.41	6.80	10.19	56.92	142.30
5	12.125	10.375	3.65	6.73	9.81	59.12	147.80
6	12.375	10.375	3.37	7.38	11.39	50.92	127.30
7	12.625	10.375	3.28	6.44	9.60	60.43	150.75
8	12.875	10.375	3.17	7.51	11.85	48.95	122.38
9	11.125	10.125	3.08	6.63	10.18	56.97	142.25
10	11.375	10.125	3.08	5.63	11.26	51.51	128.78
11	11.625	10.125	3.12	6.49	9.86	58.82	147.05
12	11.875	10.125	3.37	5.50	7.63	76.02	190.05
13	12.125	10.125	3.44	7.00	7.63	76.02	190.05
14	12.375	10.125	3.65	6.73	9.81	59.12	147.80
15	12.625	10.125	3.37	7.38	11.39	50.92	127.30
16	12.875	10.125	3.23	7.09	10.95	52.96	132.40
17	11.125	9.875	3.28	6.44	9.60	60.42	150.50
18	11.375	9.875	3.17	7.57	11.97	48.45	121.13
19	11.625	9.875	3.15	6.89	10.63	54.56	136.40
20	11.875	9.875	3.67	7.42	11.17	51.92	129.80
21	12.125	9.875	3.22	5.83	8.44	68.72	174.80
22	12.375	9.875	2.87	6.36	9.85	58.88	147.20
23	12.625	9.875	3.40	7.24	11.08	52.34	130.85
24	12.875	9.875	3.37	7.07	10.77	53.85	134.63
25	11.125	9.625	3.46	6.99	10.52	55.13	137.83
26	11.375	9.625	3.61	7.34	11.07	52.39	130.98
27	11.625	9.625	3.23	7.36	11.49	50.48	126.20
28	11.875	9.625	3.36	5.29	7.22	80.33	200.83
29	12.125	9.625	3.46	7.18	10.90	53.21	133.03
30	12.375	9.625	3.26	6.54	9.82	59.06	147.65
31	12.625	9.625	3.61	6.33	9.05	64.09	160.23
32	12.875	9.625	3.33	7.60	11.87	48.86	122.15
33	11.125	9.375	3.60	6.89	10.18	56.97	142.43
34	11.375	9.375	3.37	7.00	10.63	54.56	135.40
35	11.625	9.375	3.38	7.06	10.74	54.00	135.00
36	11.875	9.375	3.09	6.56	10.22	56.75	141.88
37	12.125	9.375	3.09	6.73	10.37	55.93	139.83
38	12.375	9.375	3.42	6.69	9.96	58.23	145.58
39	12.625	9.375	3.26	6.63	10.00	58.00	145.00
40	12.875	9.375	3.09	4.93	6.77	86.57	216.43
41	11.125	9.125	3.22	7.33	11.44	50.70	126.75
42	11.375	9.125	2.84	5.54	8.24	70.39	175.98
43	11.625	9.125	3.56	7.09	10.58	54.82	137.05

44	11.875	9.125	3.49	7.21	10.93	53.06	132.65
45	12.125	9.125	3.11	5.96	8.81	65.83	164.58
46	12.375	9.125	3.49	6.73	9.97	58.17	145.43
47	12.625	9.125	3.33	6.73	10.13	57.25	143.13
48	12.875	9.125	3.47	5.86	8.25	70.30	175.75
49	11.125	8.875	3.25	5.48	7.71	75.23	188.08
50	11.375	8.875	3.18	7.45	11.72	49.49	123.73
51	11.625	8.875	3.07	4.95	6.83	84.92	212.30
52	11.875	8.875	2.96	6.73	10.50	55.24	138.10
53	12.125	8.875	3.42	7.66	11.90	48.74	121.85
54	12.375	8.875	3.33	6.93	10.53	55.08	137.70
55	12.625	8.875	3.23	6.98	10.73	54.05	135.13
56	12.875	8.875	3.02	5.36	7.70	75.32	188.30
57	11.125	8.625	3.23	6.98	10.73	54.05	188.30
58	11.375	8.625	3.33	6.12	8.91	65.10	162.75
59	11.625	8.625	3.24	7.76	12.28	47.23	118.08
60	11.875	8.625	3.26	6.19	9.12	63.60	159.00
61	12.125	8.625	3.56	7.08	10.60	54.72	136.80
62	12.375	8.625	3.38	6.33	9.28	62.50	156.25
63	12.625	8.625	3.17	6.73	10.29	56.37	140.93
64	12.875	8.625	-	-	-	-	-
Average			3.29	6.69	9.88	58.73	166.72

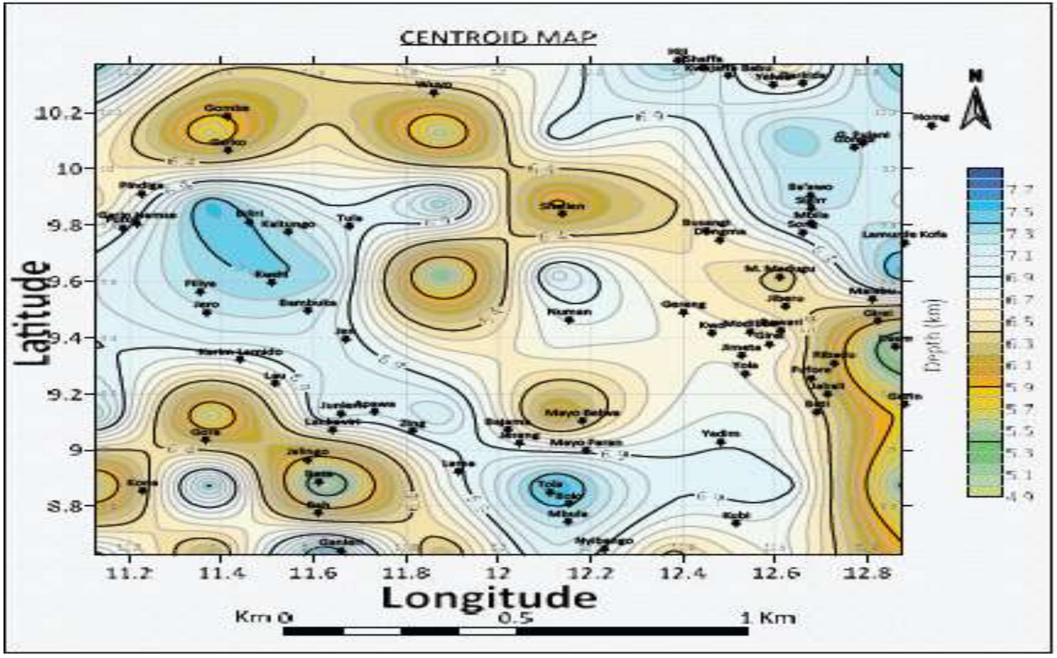


Fig.5 Map showing depth Centroid (Z_O) of the study area

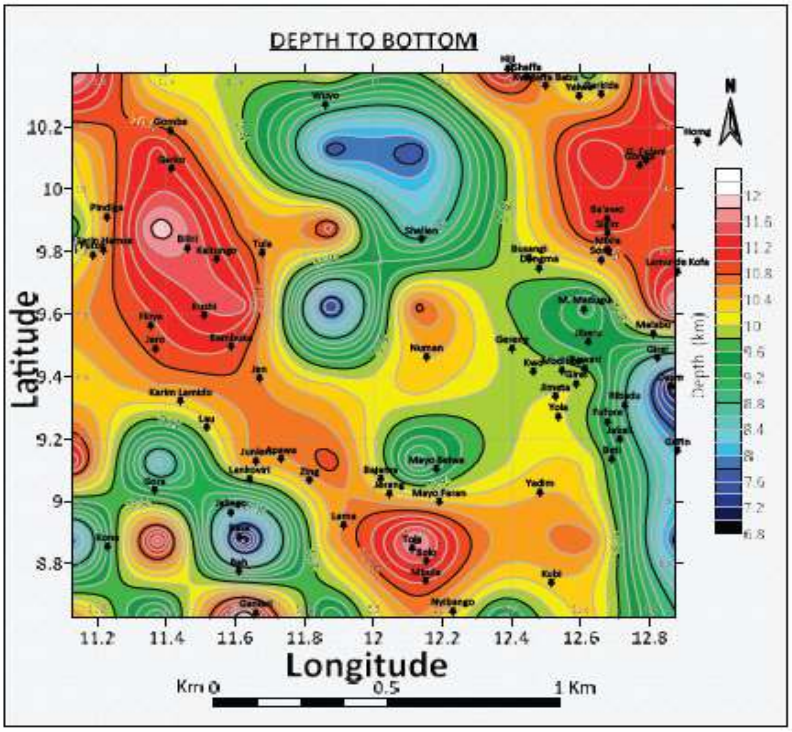


Fig.6 curie Point Depth Map (Z_b) of the study area

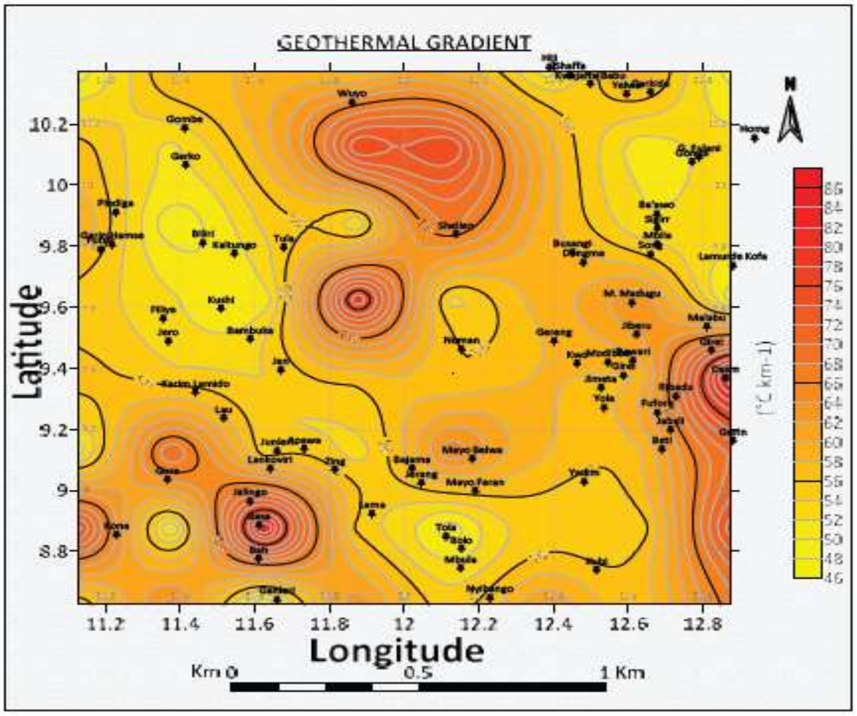


Fig.7 Geothermal gradient Map of the study area

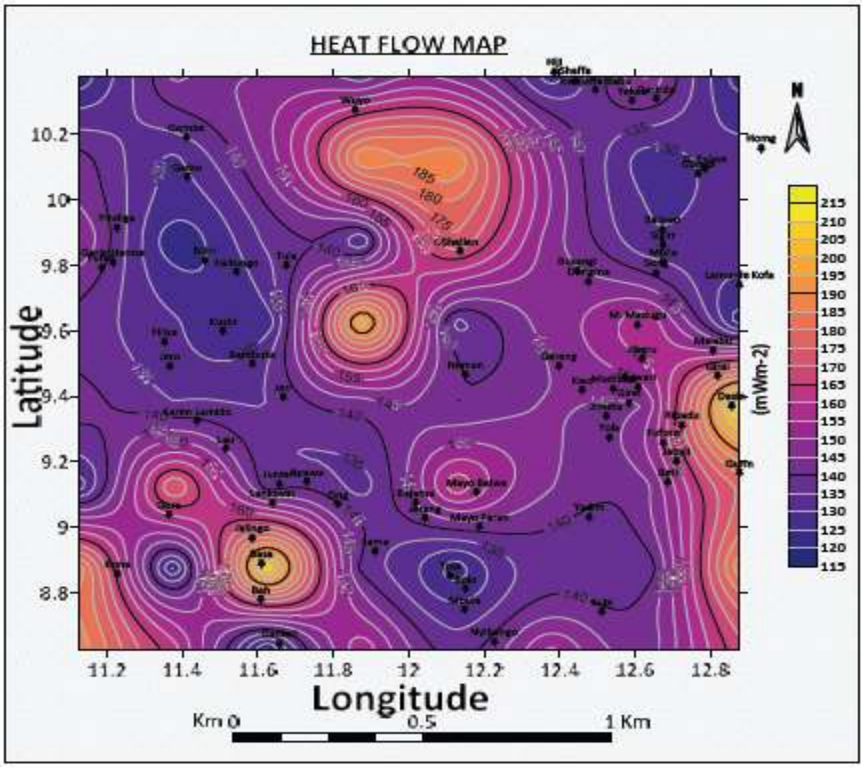


Fig.8 heat flow Map of the study area

Results and Discussion:

Figure 3 showed the residual magnetic data (RMD) map of the study area superimposed on the Topographic Map of the study area showing towns and villages after values of the regional field have been removed. This map was obtained using Oasis montaj (7.5version) Computer software. Magnetic values from the RMD map ranges from -110.10 to 93.70 nT. The magnetic high of magnitude 93.7 nT is observed in North-Western (NW), North-Eastern (NE), Central parts with a spatial occurrences at the Southern Part of the study area which include, areas southwest and north east of Gombe, Wuyo, Guyuk, Gombi Fulani, Dongma, Ba’awo,northeast and southeast of Tula, Gereng, Jabali, Mayobelwa, Zing, Lama, Mbula, and Ganleri. This could be as a result of presence of basaltic rocks belonging to Eastern arm of Cameroon Volcanic Line (CVL). Intermediate magnetic values occurin areas aroud Gombe, Garkida, Yola, Bambuka, Lau, Sigirr, Fufore, Numan, Yadim and M. Madugu while magnetic low values are observed at Kwajaffa Babu, Pindiga, Garin Hamse, Biliri, Kaltingo, Shelleng, Girei, Song, Apawa. Bolo, Kona, northwest of Filya and Jaling.

Figure 4 showed some few examples of graphs of the logarithms of the spectral energies verses wave numbers of Blocks from which the results in table 1 for Z_0 and Z_t were obtained.

Graphs of the logarithms of the spectral energies versus wave numbers, from which Curie point depths were estimated (Table 1), showed that the depth to the Centroid (Z_o) ranges from 4.95 to 7.16 km with an average value of 6.69 Km. The depths to the top boundaries (Z_t) of magnetic sources ranges from 2.84 to 3.67 km and an average value of 3.29 Km below sea level (b.s.l).The corresponding calculated curie point depths (Z_b) ranges from 8.25 to 12.28 km and an average value of 9.88 Km (b.s.l). These results are shown in figures (5) and (6) respectively.

CPD varies greatly with different geological settings (Tanaka et al., 1999; Salk et al., 2005). 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.

Using a Curie point temperature of 580^{o}C and the estimated curie depths, geothermal gradient and heat flow variations in the study area were calculated as given in Table 1. Table 1 show that the geothermal gradients in the area vary between 47.23 and 86.57 °C km^{-1} with an average of 58.73 °C km^{-1}, while the crustal heat flow varies between 121.13 and 216.43mWm^{-2} with an average of 166.72mWm^{-2}. These results are depicted in figures (7) and (8) respectively. The lowest value for the geothermal gradient of 47.23 °C km^{-1} was found in the south-western portion of the study area. The north-westward trend of gradient increase was found to result in a maximum value of 86.57 °C km^{-1} in the north-western part. The minimum heat flow value required for considerable generation of geothermal energy is approximately 60mWm^{-2}, whereas values ranging from 80 to 100mWm^{-2} and above indicate anomalous geothermal conditions (Jessop et al., 1976). Crustal heat flow in the area under study also exhibits NE–SW trending, while the calculated amounts increase from the central portion towards the north-west, with maximum value of 216.43mWm^{-2} observed in the north central portion. This portion signifies an anomalous crustal thermal state and, therefore, is recommended for further investigations.

Generally, the units that comprise of high heat flow values correspond to Volcanic and metamorphic regions since the two rock units have high heat conductivities (Nwanko et al., 2011). This makes the study area to have geothermal potentials.

CONCLUSION

The newly acquired high resolution aeromagnetic data over Shelleng and environs, north eastern Nigeria have been analyzed to estimate the Curie-point depths, geothermal gradients, and near-surface crustal heat flow. The result shows that the CPD varies between 4.95 to 7.16 km with an average of 6.69 km, the geothermal gradient varies between 47.23 and 86.57 °C km^{-1} with an average of 58.73 °C km^{-1} and the crustal heat flow varies between 121.13 and 216.43mWm^{-2} with an average of 166.72mWm^{-2}. Regions are observed in the area of study with shallow Curie-point depths (below 15 km) and corresponding high heat flows (above 80mWm^{-2}), thus suggesting anomalous geothermal conditions (Jessop et al., 1976). Hence, further detailed studies are recommended in such regions. Finally, oftentimes, direct crustal temperature measurements may not be too feasible for regional studies; hence, the derived geothermal gradients suffice for the entire area. Moreover, geodynamic processes are mainly controlled by the thermal structure of the Earth's crust; therefore this study is anticipated to contribute significantly to the quantitative appraisal of the geo-processes, rheology, and understanding of the heat flow variations over Shelleng and Environs in North-eastern Nigeria.

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