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ESTIMATION OF CURIE POINT DEPTHS AND SUCCEEDING GEOTHERMAL PARAMETERS FROM HIGH-RESOLUTION AEROMAGNETIC DATA OF THE YOUNGER GRANITE COMPLEXES OF JOS AND ENVIRONS NORTHCENTRAL NIGERIA

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ABSTRACT
A regional estimation of Curie point depths and succeeding geothermal gradients and subsurface crustal heat flow has been carried out from the spectral centroid analysis of High-Resolution Aeromagnetic Data of Jos and environs in north central Nigeria. The High-Resolution Aeromagnetic Data were divided into nine 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 evaluate the Curie point depth, subsurface crustal heat flow of the area and geothermal gradient. The estimated Curie point depth value varies from 9.70 to 17.79 km with an average value of 13.84 km. The value of heat flow ranges from 82 to 149 mWm^{-2} with an average value of 109 mWm^{-2} whiles the value of geothermal gradient ranges from 32.60 to 59.79 $°Ckm^{-1}$with an average value of 43.52 $°Ckm^{-1}$. Negative relationship was observed between the Curie point depth and heat flow within the study area. The Curie point depths have a small relationship with topography due to isostatic compensation and rifting. The Digital Elevation Model map of the study area show elevation values that ranges between 218.908 to 1404.595 m. This study is important for appraisal of the geo-processes, geology, and understanding of the heat flow variations in the Younger Granite Complexes of the study area.

Keywords: Curie Point Depth, Digital Elevation Model, High-Resolution Aeromagnetic Data, Jos Plateau, Maijuju Town, Younger Granite Complexes.

INTRODUCTION
This study aims at quantitative estimation of regional Curie point depth and succeeding geothermal structures that is geothermal gradients and subsurface crustal heat flow anomalies, in the Younger Granite Complexes of Jos and environs north central Nigeria using the spectral centroid analysis of the acquired high-resolution airborne magnetic (HRAM) data. The high-resolution airborne magnetic surveys were carried out by Fugro Airborne Survey Limited for the Nigerian Geological Survey Agency (NGSA) between 2003 and 2009. Acquisition, processing, and compilation of the high-resolution airborne magnetic data were mutually financed by the Federal Government of Nigeria and the World Bank as part of the Sustainable Management for Mineral Resources Project (SMMRP) in Nigeria. Numerous studies have shown that regional magnetic data can be used widely to ascertain the thermal structure of the Earth's crust in various geologic environments (Spector and Grant, 1970; Bhattacharyya and Leu, 1975, 1977; Byerly & Stolt, 1977; Blakely & Hassanzadeh, 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). For example, major magnetic minerals in the Earth's crust pass from ferromagnetic to paramagnetic state at a temperature, commonly called Curie-point temperature. Magnetite (Fe_3O_4) is the most common magnetic material in igneous rocks and has an approximate Curie-point temperature value of 580 ^0C (Stacey, 1977). At temperature above Curie-point temperature, the thermal agitation causes the spontaneous alignment of the various domains in the mineral to be obliterated (or randomized) to the extent that the ferromagnetic minerals become completely paramagnetic (Langel and Hinze, 1998). Consequently, Curie-point depth which is defined as the depth at which Curie-point temperature is reached within the subsurface, can be measured as an indicator of depth to the bottom of magnetic sources and can therefore be calculated from geomagnetic anomalies (Bansal *et al*., 2011, 2013; Hsieh *et al.*, 2014). Nevertheless, in some condition's depth to the bottom of magnetic sources can be caused by contrasts in lithology and may not necessarily coincide with Curie-point temperature (Bansal *et al*., 2011; Trifonova *et al*., 2009). For instance, Trifonova *et al*. (2009) opined that even if the spectral method gives a good estimate of depth to the bottom of magnetic sources there is no assurance that it represents the Curie-point depth. They explained that a variety of geologic reasons exist for truncated magnetic sources that are not related 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 Curie-point temperature, and another reason is the variety of magnetic minerals like titanomagnetite ($Fe_{3-x}Ti_xO_4$). Titanomagnetite is the most important iron oxide in crustal magnetic sources; it has a Curie-point temperature that is strongly influenced by the amount of titanium and ranges from 150 to 580 ^0C. In some geologic environments, alloys of iron with Curie-point temperatures in excess of 620 ^0C 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) have realistically used depth to the bottom of magnetic sources as an estimate of Curie-point depth 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 Curie-point temperatures at these depths are estimated to be between 575 and 600 ^{0}C. This confirms the estimated value of 580 ^{0}C by Stacey (1977) as the case in this study. Another important justification is that the bottom of magnetic sources/Curie-point depth estimations can similarly be used to complement geothermal data in regions where deep boreholes are unavailable (Chapman & Furlong, 1992; Ross *et al*., 2006; Bansal *et al.,* 2011, 2013). The Younger Granite Complexes of Jos area in Nigeria have not been studied in detail to date. This has led to absence of heat flow data in the area. The area has no information on seismicity, no deep exploratory wells have penetrated its sequences and deep crustal data are limited. Therefore, the present work is expected to contribute immensely to a better understanding of the geothermal structures and geodynamic processes in the Younger Granite Complexes of Jos and its environs in the north central part of Nigeria.

Location and Geology of the Study Area

The study area is part of the Younger Granite complex, north central Nigeria which lies between Latitudes 9°00'N to 10°30'N and Longitudes 8°30'E to 10°00'E and it covers an area of approximately 27,225 km^2 (Fig. 1). The study area is enclosed within the nine (9) aeromagnetic maps acquired from the Geological Survey of Nigeria. Major roads found in this area provides access from Jos to Bauchi, Wase, Kerang, Ganawuri as well as other local communities in the study area such as Maijuju, Kofai, Bokkos, Miango, Foron, Barkin Ladi and Tafawa Balewa to mention but a few. There are other minor roads, which provide access to smaller settlements, farms, rivers and streams. The bedrock geology is predominantly Basement Complex consisting of biotite gneisses, Older granites, Younger Granite, Older Basalts, Newer Basalts and batholiths (Turner, 1989) (Fig. 1). However, rocky granitic residuals form inselbergs of varying sizes and shapes, and constitute the main local relief (Dada *et al.,* 1993).

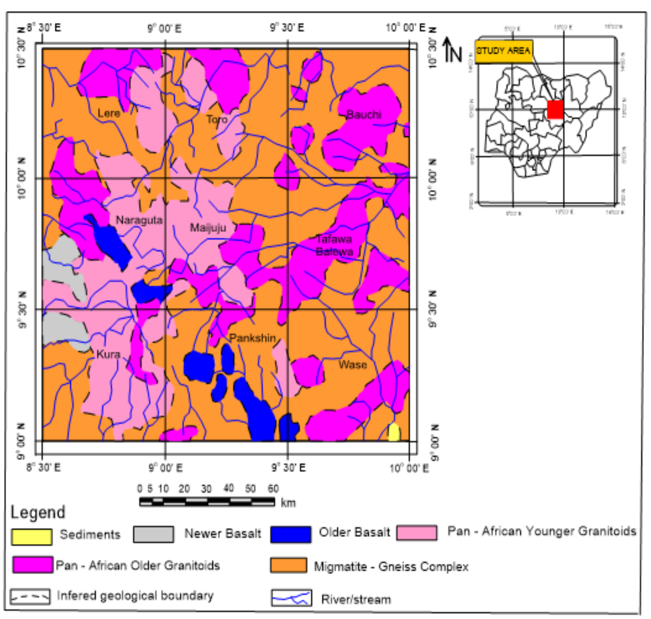

Fig. 1: Geologic Map of the study area (extracted from Geological map of Nigeria, 2009)

MATERIALS AND METHODS

Materials

Nine half degree high resolutions aeromagnetic data provided both in grid and data-based format including DGRF-2005 removed, each on a scale of 1: 100,000 were purchased from the Nigerian Geological Survey Agency in Abuja. The data sheets comprise Lere (sheet 147), Toro (sheet 148), Bauchi (sheet 149), Naraguta (sheet 168), Maijuju (sheet 169), Tafawa Balewa (sheet 170), Kura (sheet 189), Pankshin (sheet 190) and Wase (sheet 191). The data was acquired using 3X Scintrex CS3 Cesium Vapour Magnetometer. The following flight parameters were utilised during the survey; flight line spacing was 500 meters, terrain clearance was 80 meters, flight direction was in the NW-SE, tie line spacing was 2 kilometres and tie line direction was in the NE-SW direction. Software used for data analysis is the Oasis Montaj version 8.4.

Methods

Curie Point Depth Estimation

The methods for estimating the Curie depth have been described by several Authors, Bhattacharrya and Leu, 1975; Okubo *et al*., 1985; Onwuemesi, 1997; Tanaka, *et al*., 1999; Stampolidis *et al*, 2005 and Kasidi and Nur, 2012b, the method used for this work examine the patterns of the anomalies (Spector & Grant, 1970). The crustal field map in Fig. 4 was upward continued to 15 km to procure the map of Fig. 5. The 15 km depth represent a distinct break in density, with depths ≥15 km signifying the main field in Fig. 3, and depths ≤15 km represent the crustal field associated with the Earth's crust in Fig. 4 (Cain, 1989). The map in Fig. 5 was divided into nine square grids and each window grid was 55 x 55 km in size. The estimation of the Curie point depth was based on spectral analysis of the residual data. Bhattacharyya & Leu (1975) presented that depth to bottom (Z_b) of a magnetic source body could be estimated as follows; firstly, is the estimation of depth to the centroid (Z_o) of the magnetic source from the slope of the longest wavelength part of the spectrum yielding,

$$\ln\left[\frac{P(S)^{\frac{1}{2}}}{lsl}\right] = \ln A - \frac{\frac{2\pi l}{s}}{Z_O} \qquad 1$$

Where p(s) is the radially averaged power spectrum of the anomaly, *lsl* is the wave number, and A is a constant.

The second step is the estimation of depth to the top boundary (Z_t) of that distribution from the slope of the second longest wavelength spectral segment (Okubo *et al.,* 1985) thus,

$$\ln\left[\frac{P(S)^{1/2}}{lsl}\right] = \ln B - \frac{\frac{2\pi l}{s}}{Z_t} \qquad 2$$

Where B, is the sum of constants independent of *lsl*

Then the basal depth (Z_b) of the magnetic source was calculated from the equation below

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

The obtained basal depth (Z_b) of magnetic sources is assumed to be the Curie point depth (Bhattacharyya & Leu, 1975; Okubo *et al.,* 1985).

Estimation of Heat Flow and Geothermal Gradient

The model used is based on Fourier's law in which the direction of the temperature variation is vertical and the temperature gradient is assumed constant. Fourier's law then takes the form;

$$q = \lambda \left(\frac{dT}{dZ}\right) \qquad 4$$

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Where q is the heat flow and λ is the coefficient of thermal conductivity,
According to Tanaka *et al* (1999) the Curie temperature Θ_c can then be defined as

$$\frac{dT}{dZ} = \frac{580^{\circ}C}{Z_b} \qquad 5$$

Where 580 ^{0}C is the Curie temperature at which ferromagnetic minerals are converted to paramagnetic minerals. Furthermore, the geothermal gradient was related to heat flow (q) using the formula: From equation (4) and equation (5) a relationship was determined between the Curie point depth (Z_b) and the heat flow (q) as follows

$$q = \lambda\left(\frac{dT}{dZ}\right) = \lambda\left(\frac{580^{\circ}C}{Z_b}\right) \qquad 6$$

The overall result obtained from the analysis is summarized in Table 1, were used to plot the curie depth, heat flow and geothermal gradient maps. Thermal conductivity (λ) of 2.5 mWm^{-2} Curie temperature of 580 ^{0}C are used as standard in this research.

RESULTS

The total magnetic intensity (TMI) map over Jos and environs shows TMI values ranging from 32880.135 nT to 33168.248 nT with an average value of 33065.10 nT. Fig. 2 shows a colour range of total magnetic intensity values, with pink colour as high and blue colour as low.
The highest TMI values were depicted by pink and red colours, with the intermediate values represented by orange, yellow and green colours whereas the lowest values were shown by blue and cyan colours (Fig. 2).
.
The main field map of the study area which is removed from the total magnetic intensity map (TMI), shows a NW–SE trending lines that have increasing values from the SW portion (blue colour) to the NE portion (pink colour) have values ranging from 33446.4 nT to 33792.500 nT with an average value of 33470.6 nT (Fig. 3).

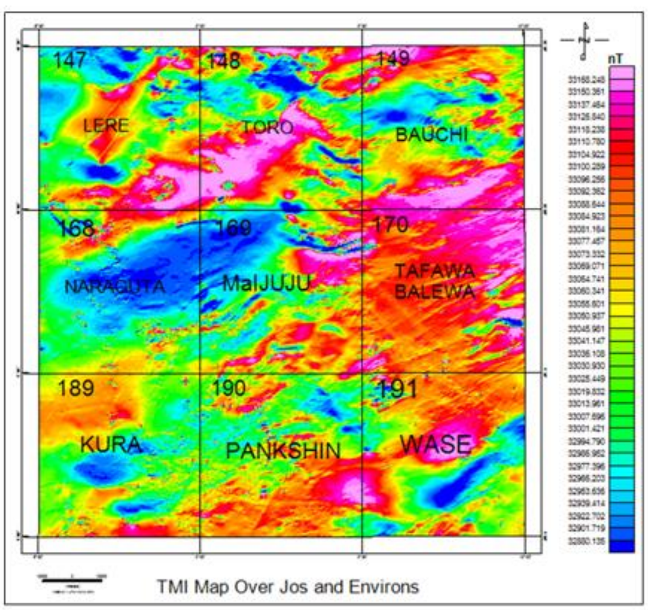

Fig. 2: Total magnetic intensity map of Jos and environs, north-central Nigeria

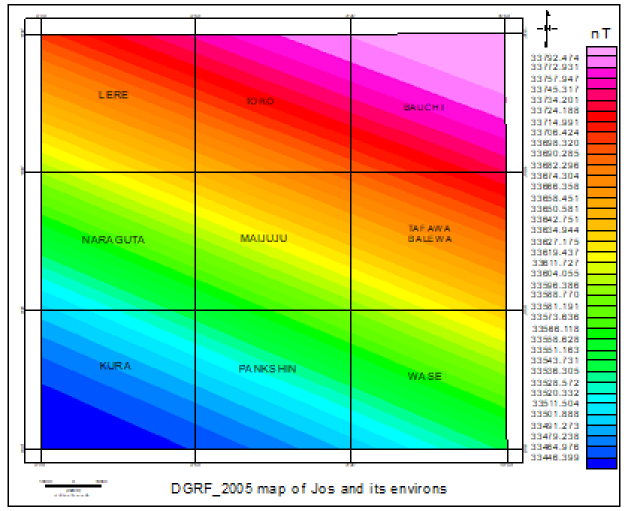

Fig. 3: Main field map of Jos and environs, north-central Nigeria

The crustal magnetic field map over Jos and environs show values ranging from -809.200 nT to -381.500 nT with an average value of -405.500 nT. The crustal magnetic field map shows high magnetic susceptibility in areas of high magnetic values pink colour (-429.342 to -381.500) and red colour (-500.552 to -429.342) are found mainly on Kura, Pankshin and Wase sheets while less magnetic susceptibility areas are depicted as low magnetic values blue colour (-809.200 to -729.883) and cyan colour (-729.883 to -662.358) found within Bauchi, Toro, Lere, Naraguta and Maijuju sheets. The intermediate colours are orange (-544.616 to -500.552), yellow (-69.000 to -544.616) and green (-662.358 to -569.000) found in the entire area (Fig. 4).

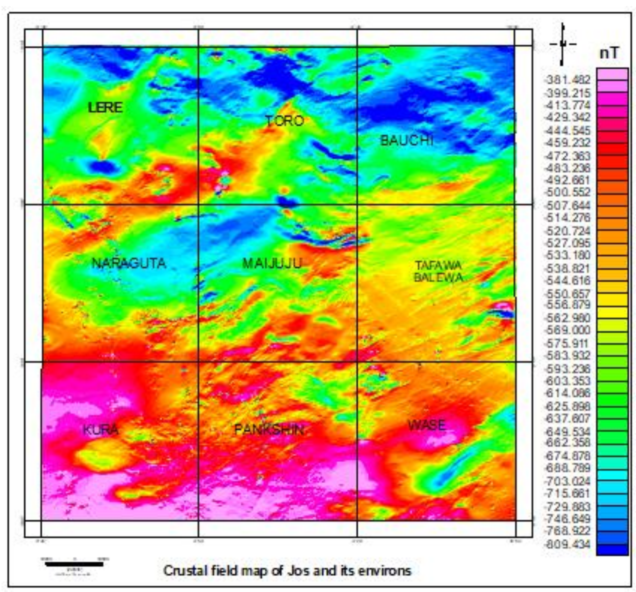

Fig. 4: Crustal field map of Jos and environs, north-central Nigeria

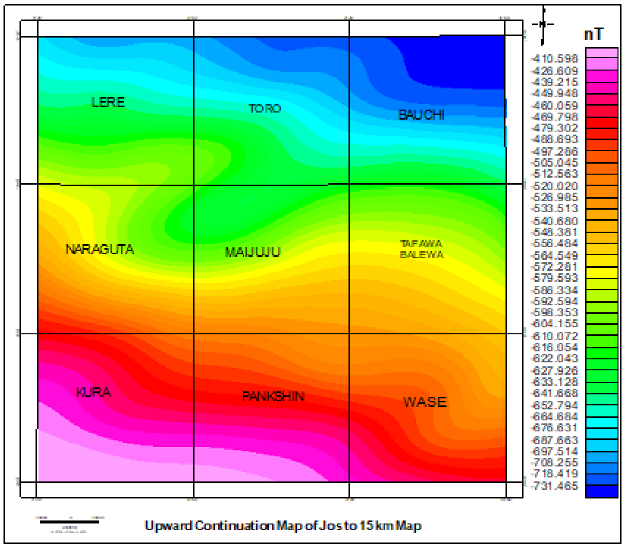

Fig. 5: Crustal field map of Jos and environs, north-central Nigeria, upward continued to 15 km

The Curie point depth over Jos and environs shows values ranging from 9.70 to 17.79 km with an average value of 13.84 km (Fig. 6). Previous studies have shown that two major regional fault lines of Romanche and Chain are likely to have traversed the study area (Fig. 7) (Ajakaiye *et al*., 1986).

The value of heat flow ranges from 82 to 149 mWm^{-2} with an average value of 109 mWm^{-2} (Table 1). The value of geothermal gradient within the study area ranges from 32.60 to 59.79 °Ckm^{-1} with an average value of 43.52 °Ckm^{-1} (Table 1). The maps of Curie point depth, heat flow and the geothermal gradient are shown in Figs. 6, 8 and 10 respectively. Their trends are mostly in the NE–SW and NW- SE directions. For the relationship between heat flow and curie depths, from the result obtained in Table 1, the inferred Curie point depth was plotted against heat flow, the graph showed that, the heat flow in the study area decreases with increasing Curie point depth (Fig. 9).

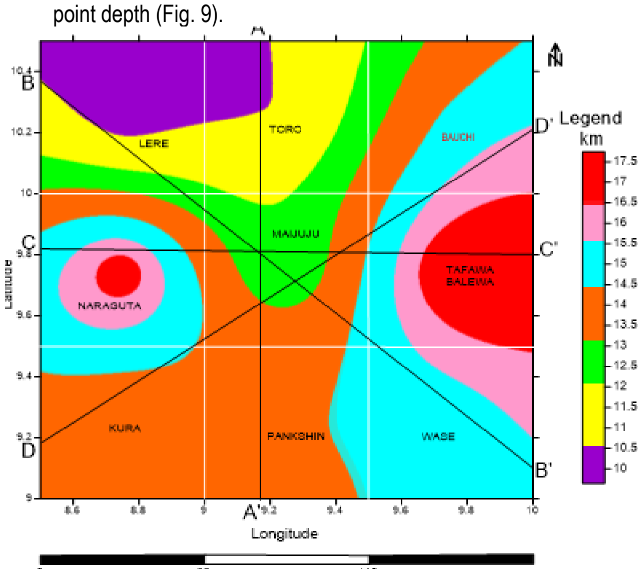

Fig. 6: Curie isotherm map showing the profiles A-A' to D-D' used for constructing 2-D Curie point depths

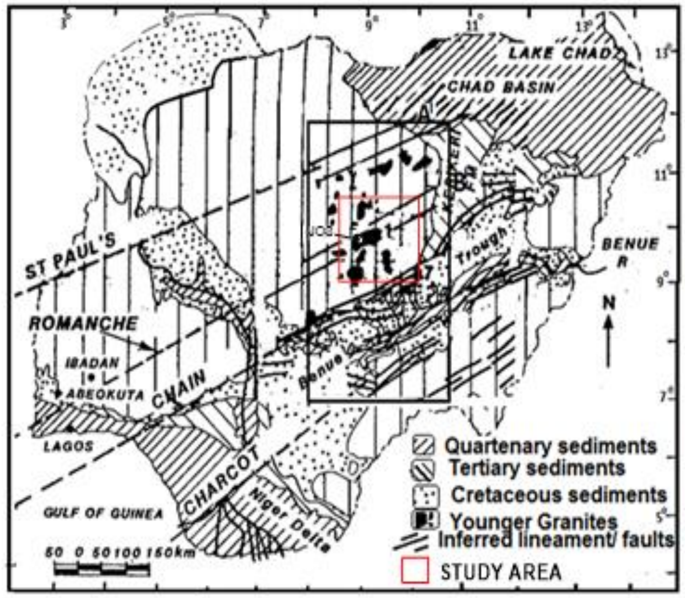

Fig. 7: Geological map of Nigeria showing the locations of inferred lineaments and faults and the aligned Younger Granite Complexes (modified from Ajakaiye *et al*., 1986)

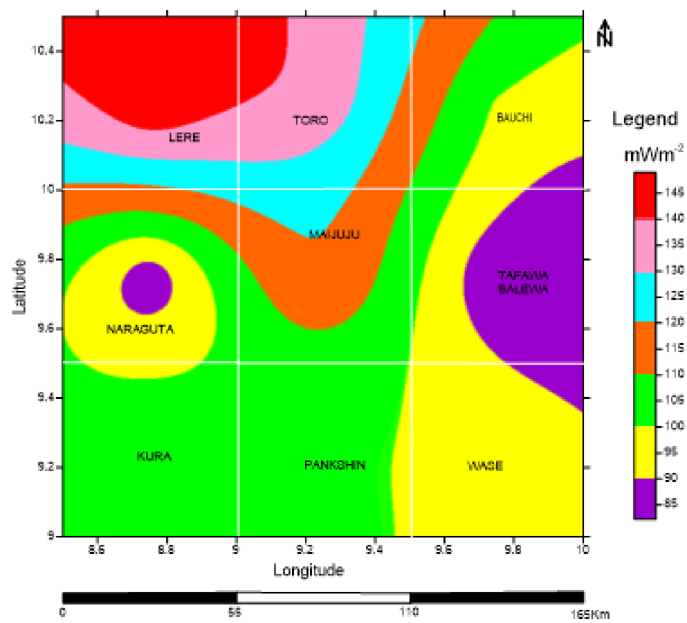

Fig. 8: Heat flow Map of Jos and environs, north-central Nigeria

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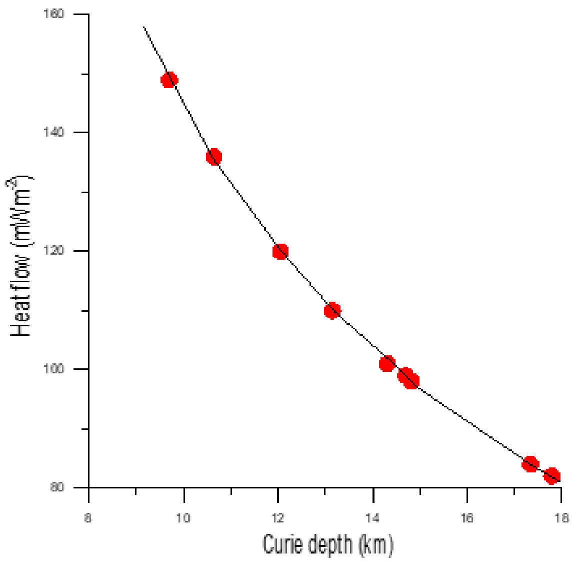

Fig. 9: Heat flow versus Curie point depth of Jos and environs, north-central Nigeria

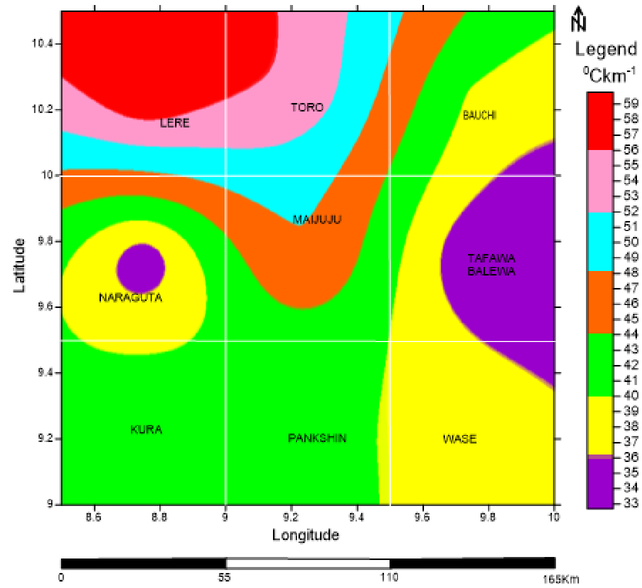

Fig. 10: Geothermal Gradient Map of Jos and environs, north-central Nigeria.

Table 1: Calculated Heat Flow and Geothermal Gradient from Curie Depth

Blocks	Longitude (^{0} E) x_1	x_2	Latitude (^{0} N) Y_1	Y_2	Centroid depth Z_0 (km)	Depth to the top Z_t (km)	Depth to bottom Z_b (km)	Geothermal Gradient (^{0}Ckm^{-1})	Heat flow (mWm^{-2})
Lere	8° 30'	9° 00'	10° 00'	10° 30'	5.69	1.68	9.70	59.79	149
Toro	9° 00'	9° 30'	10° 00'	10° 30'	5.83	1.01	10.65	54.46	136
Bauchi	9° 30'	10° 00'	10° 00'	10° 30'	8.06	1.42	14.70	39.46	99
Naraguta	8° 30'	9° 00'	9° 30'	10° 00'	9.04	0.737	17.34	33.44	84
Maijuju	9° 00'	9° 30'	9° 30'	10° 00'	6.65	1.25	12.05	48.13	120
Tafawa Balewa	9° 30'	10° 00'	9° 30'	10° 00'	9.85	1.91	17.79	32.60	82
Kura	8° 30'	9° 00'	9° 00'	9° 30'	7.72	2.29	13.15	44.11	110
Pankshin	9° 00'	9° 30'	9° 00'	9° 30'	7.56	0.806	14.31	40.52	101
Wase	9° 30'	10° 00'	9° 00'	9° 30'	7.91	0.999	14.82	39.13	98
Average					7.59	1.34	13.84	43.52	109

The Digital Elevation Model (DEM) map of the study area show elevation values that ranges between 218.908 and 1404.595 m (Fig. 11). Four cross Profiles lines (A– A', B– B', C– C' and D– D') (Figs. 7 and 12) were drawn across the maps to show the topography variations. The relationship between topography and Curie point depth are shown in Figs. 12 to 15. The highest elevation is depicted by pink colour and the area with the lowest elevation is represented by blue colour (Fig. 11). The topography of the study area has been divided into three segments namely:

1: Highest elevation represented by pink, magenta and red colours, the area is characterized by a rugged topography with elevation values ranges from 1028.807 to 1404.595 meters above sea level.

2: Intermediate elevation is denoted by orange, yellow and green colours with elevation values ranges from 594.696 to 1028.807 meters above sea level.

3: The area with the lowest elevation is designated by green, cyan and blue colours with elevation values ranges from 218.908 to 594.696 meters above sea level.

Figs 12 to 15 show the relationship between Curie point depth and topography of the study area. The correlation coefficient between topography and Curie point depth (Figs. 6 and 11) for the four cross profiles lines (A– A', B– B', C– C' and D– D') are shown in Table 2. The result shows a positive value of 0.871 for Profiles line (A– A') and a negative value of - 0.573, -0.546 and -0.574 for Profiles lines (B– B', C– C' and D– D') respectively.

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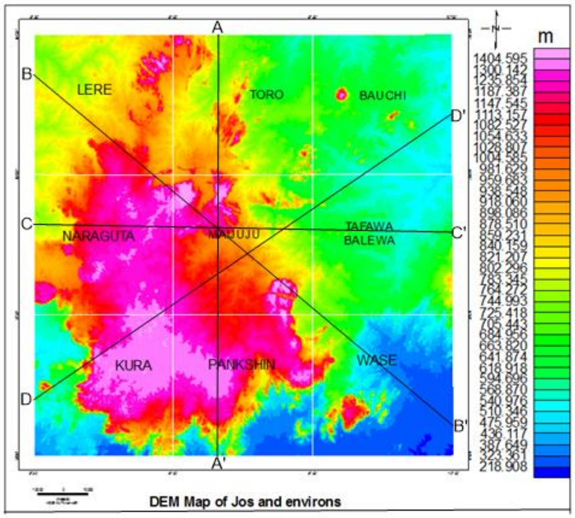

Fig. 11: Digital Elevation Model (DEM) showing the profiles A-A' to D-D' used for constructing 2-D topographic elevation of Jos and environs, north-central Nigeria.

Table 2: Correlation Coefficient between topography and Curie point depth of the study area

S/NO	Profile Line	Correlation Coefficient
1	A – A'	0.871
2	B – B'	- 0.573
3	C – C'	- 0.546
4	D – D'	- 0.574

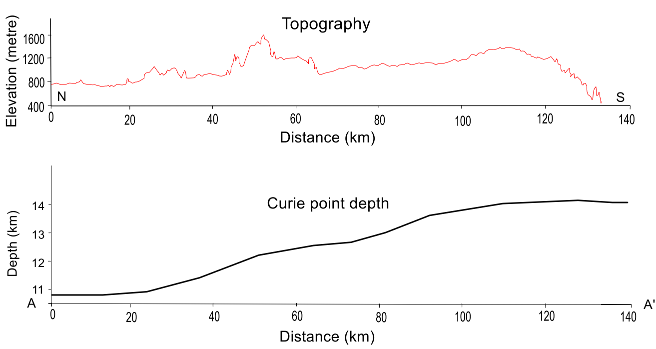

Fig. 12: 2-D Curie depth model of Profile A – A' of Jos and environs, north-central Nigeria

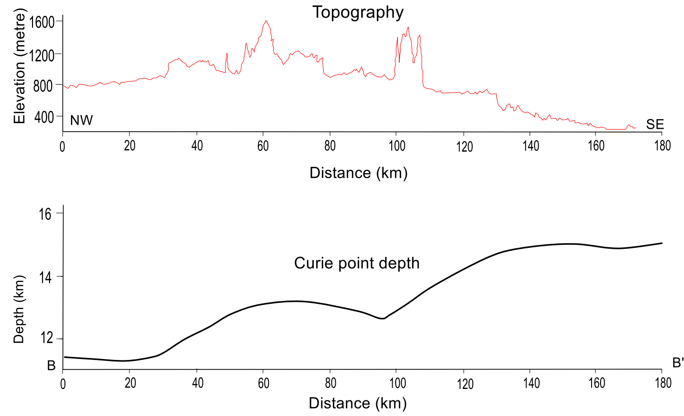

Fig. 13:2-D Curie depth model of Profile B– B' of Jos and environs, north-central Nigeria

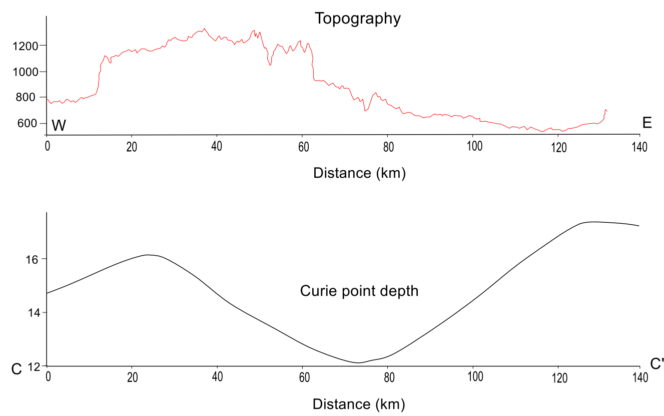

Fig. 14: 2-D Curie depth model of Profile C – C' of Jos and environs, north-central Nigeria

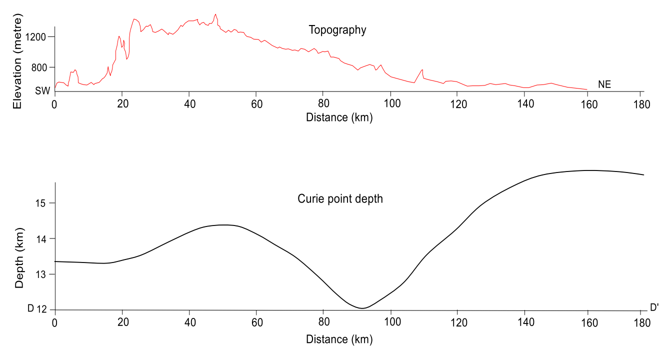

Fig. 15: 2-D Curie depth model of Profile D – D' of Jos and environs, north-central Nigeria

DISCUSSION

The Total Magnetic Intensity map shows combination of regional, residual and noise signals. The short-wavelength components are attributed to shallow magnetic sources associated with intrusive bodies such as dykes and plutons. The high magnitude of strong amplitude magnetic anomaly could be due to the presence of outcrops of gneiss–migmatite complex or the rocks existing at shallow depths in the study area. Low magnetic anomaly is characterized by regions of relatively low magnetite content which could be associated with Younger Granite in the study area. The

Earth's surface TMI value field strength is about 60,000 nT at the poles and 30,000 nT at the equator (Olsen *et al*., 2000b). This value is similar to the value of (32880.135 nT - 33168.248 nT) computed from the study area, implying that the study area is around the magnetic equatorial region. According to Kasidi (2014) TMI values ranging from 32,500 to 32,900 nT are indicative of the presence of remarkable magnetic features which could be a result of migmatite associated with the migmatite-gneiss complex in the study area. The crustal magnetic field map of the study area shows values ranging from -809.2 nT to -381.5 nT. Areas with high magnetic values (pink colour) have shallow to near surface magnetized bodies. The high magnetic anomalies in most part of the study area shows that the migmatite-gneiss complexes are probably exposed on the surface or may have been buried at relatively shallow depths. While areas with low magnetic values (blue colour) are underlain by deep seated magnetized bodies and due to magnetic basement subsidence resulting from the epeirogenic uplift within the study area. The values shown by the crustal field map of the study area are all negatives indicating that the study area is located in the southern hemisphere of the magnetic equatorial region.
The Curie point depths that are shallower than 15 km according to Tanaka *et al* (1999) suggests that the entire area is volcanic and geothermal field since Curie point depth is greatly dependent on geologic conditions. This is particularly related to Lere portion of the study area which is made up of volcanic rocks with the shallowest Curie point depth. Tanaka *et al* (1999) pointed out that, when the Curie point depths are shallower than about 10 km it signified volcanic and geothermal areas, 15 to 25 km are island arcs and ridges, deeper than 20 km are plateaus and deeper than 30 km are trenches. It is reasonable to expect a thin magnetic crust in a rift zone due to the extensional crustal thinning which result in elevated heat flow. Thus, the relatively low Curie point depth values over the Lere, Toro, Kura and Maijuju Sheets of the study area may be similarly consistent with probable positions of Romanche and chain paleofracture zones that passed through the study area. Aeromagnetic data have been widely used to determine the depth to Curie isotherms (Okubo *et al*., 1985; Tsokas *et al.,* 1998; Tanaka *et al.,* 1999; Stampolidis & Tsokas, 2002) and the obtained Curie depths have been seen to correlate well with heat flow measurements.

The heat flow values of the present study ranges from 82 to 149 mWm^{-2}. The results of the heat flow in the study area are supported by geologic evidence of high heat flow as volcanoes and is connected with the two major regional fault lines of Romanche and Chain paleo fracture zones that pass through the study area; these are believed to be extensions of the onshore lineaments in West Africa, which are part of the major weakness in the crust that predates the opening of the Atlantic Ocean, and were reactivated in the early stages of continental rifting(Ajakaiye *et al*., 1986). Thus, the relatively high heat values (101 – 149 mWm^{-2}) over Lere, Toro, Kura, Maijuju and Pankshin Sheets of the study area may be similarly consistent with probable positions of these two paleofracture zones that pass through the study area. The geothermal heat flow can vary significantly over distances of only tens of kilometres due to local geologic settings (Majorowicz & Embry, 1998; Dahl-Jensen, *et al*., 2003a; N¨aslund, *et al.,* 2005). The minimum heat flow value required for considerable generation of geothermal energy is approximately 60 mWm^{-2} whereas values ranging from 80 to 100 mWm^{-2} and above indicate anomalous geothermal conditions (Jessop *et al*., 1976; Sharma, 2004). The heat flow values of the present study ranges from 82 to 149 mWm^{-2} these values are significantly anomalous crustal thermal state. The Crustal heat flow in the area increase from the eastern and western portion towards the northwest, with maximum values around 149 mWm^{-2} observed in the Lere sheet. The areas having high heat flow correspond to volcanic cones; this could be as a result of the age of the last magmatic activities which took place during Tertiary and Quarternary Period within the study area. These portions indicate an anomalous crustal thermal state and, therefore, are recommended for further investigations.
The result of the relationship between heat flow and Curie point depths in the study area is comparable with the work of Nwokocha (2016) who worked on parts of the Younger Granite of Nigeria. Certainly, it is an indication that, when heat flow increases, Curie point depth will decrease, and vice versa. This shows that all the areas with high heat flow are expected to have shallow Curie point depth.
The geothermal gradient values of the study area ranges from 32.60 to 59.79 $°Ckm^{-1}$. The geothermal gradient from the study area is higher than the geothermal gradient values of 21.07 to 24.28 $^{O}Ckm^{-1}$ which was obtained from Nwokocha (2016) in part of the Younger Granite Complex of Nigeria. Measurements have also shown that, a region with significant geothermal energy is characterised by an anomalous high temperature gradient and heat flow. It is expected that geothermically active areas will be associated with shallow Curie points. A place with significant heat flow has high geothermal energy potentials, characterised by anomalously high temperature, and thus, related with shallow Curie point depth. In this study, areas of high heat flow are considered to have geothermal energy potential which may be of economic importance to the community and Nigeria at large. In the Lere, Toro, Bauchi, Kura, Pankshin and Maijuju sheets of the study area, there were emplacement of intrusives/extrusive rocks along the lines of weaknesses and faulting as well as Tertiary to and perhaps younger, Newer Basalt Lava flows and volcanic cones.

The Digital Elevation Model (DEM) map of the study area show elevation values that ranges between 218.908 to 1404.595 m. Nwokocha (2016) reported that the ring complexes are mainly associated with surface exposure that rose between the range of 1182 and 1614 m above mean sea level, he identified the slope of the ring complex to represent a sudden change in topography from 924 to 578 meters above mean sea level. The area with the highest elevation is characterized by a rugged topography; these areas form a dendritic drainage pattern which signify various rivulets, gullies and drains that flow towards the lowest part of the study areas. The highest topographical relief areas are represented by the pink colour correlates to the Younger Granite on the geological map; the elliptic covers parts of the Jos Younger Granite Complexes. The rock types found in these areas are Newer Basalt, Older Basalt and Younger Granite rocks. These areas comprise Naraguta, Maijuju, Kura and Pankshin sheets. Therefore, the topographically high areas are characterized by Younger Granites and the low areas are characterized by older granites and migmatitic gneiss complexes of the pre-Cambrian age. Almost everywhere these Younger Granites rocks directly overlie the pre-Cambrian basement rocks, which means that the Younger Granites were emplaced in uplifted areas that were undergoing erosion. This explains the emplacement of the Younger Granite Ring Complexes been associated with epeirogenic uplift. The evolution of the Younger Granites followed the same pattern. They began with

volcanic phase that was associated with eruption of large volume of rhyolites via ring fractures, and then followed by formation of ring dykes of granite-porphyry upon subsidence of the rock's interior to the ring fracture.
The rock type found in the areas with intermediate elevation is the older granite rock. This area is mainly a slope and is characterized by a lot of gullies, rivers and streams; they comprise Toro, Bauchi, Tafawa Balewa and western part of Lere sheets. The slope of the ring dyke is identified where the red and orange colours are closely packed. The areas with the lowest elevation will be highly prone to weathering; the rock type around this area is composed of the pre-Cambrian basement rocks of older granites and migmatites-gneiss complex. High elevations within these low-lying areas corresponds to older granites: these areas include Naraguta, Maijuju, Kura and Pankshin sheets. The digital elevation model in the study area observed that most of the basement complex rocks trend in the NW – SE and NE – SW directions.
The Curie isotherm and digital elevation model (DEM) maps, have four profiles drawn on each in order to construct 2-D Curie point depth in the study area. The 2-D model can be described as follows:

1: The Curie point depths have a small relationship with topography, this relationship might be as a result of isostatic compensation and rifting around Lere, Toro, Naraguta, Maijuju, Kura and Pankshin sheets.

2: The curie surface is not uniform rather it is undulating and deepens from 9.70 km in Lere sheet to 17.79 km in Tafawa Balewa sheet.

Even though earlier studies by Stampolidis *et al.* (2005) showed that the Curie point depth is related to the geological setting of an area. This study clearly indicates that the Curie point depths have a minute relationship with the topography of the study area and does not depend on the topography.

Conclusion

The high-resolution aeromagnetic anomaly data over the Jos and environs north central Nigeria have been analysed to estimate the Curie-point depths, near-surface crustal heat flow and geothermal gradients. The result shows that the Curie point depth over Jos shows values varying between 9.70 to 17.79 km with an average value of 13.84 km, and the heat flow varies between 82 to 149 mWm^{-2} with an average value of 109 mWm^{-2}. The heat flow and Curie point depth show a negative relationship. The geothermal gradient values range from 32.60 to 59.79 °Ckm^{-1} with an average value of 43.52 °Ckm^{-1}. Regions observed in the area with shallow Curie-point depths (below 15 km) correspond to high heat flows (above 80 – 100 mWm^{-2}), thus suggesting anomalous geothermal conditions. Thus, further in-depth studies are recommended in such areas. The Digital Elevation Model (DEM) map of the study area show elevation values that ranges between 218.908 to 1404.595 m.

The result of correlations between the Curie isotherm map and digital elevation model (DEM) map drawn from four profiles revealed that Curie point depth vaguely dependent on surface topography. Finally, oftentimes, direct crustal temperature measurements may not be too feasible for regional studies; therefore, the resultant geothermal gradients suffice for the entire study 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 evaluation of the geoprocesses, geology, and understanding of the heat flux discrepancy in the Jos and environs in north central Nigeria.

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