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Estimating sedimentary pile thickness, structural lineaments and heat flow in parts of North Central Nigeria from aeromagnetic data

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Abstract

Evaluation, analysis and interpretation of aeromagnetic data acquired over parts of North Central Nigeria were carried out in order to characterise structural features and lineaments, sedimentary pile thickness, geothermal gradient and heat flow in the study area. Fourier domain digital filtering and reduction to pole (RTP) operations were done to enhance the data, while spectral analysis and source parameter imaging (SPI) were used to analyse the data. Results from the 2-D spectral analysis of the enhanced magnetic data suggest that the depth range to the top of magnetic sources Z_t is 0.33—0.73 km (average depth of 0.55 km); depth range to magnetic centroid Z_o is 2.51—5.83 km (average depth of 3.94 km); Curie point depth range is 4.41—10.96 km (average depth of 7.32 km); and average sedimentary rock cover thickness is 3.94 km. This compares with the results from SPI which gave depth ranges to various magnetic sources as 0.27—3.01 km. Structural lineament analysis indicates the major trend of the structural lineament is in the NE—SW, NW—SE and NNE-SSW. Average geothermal gradient of 82.87°Ckm^{-1} and heat flow of 207.19 mWm^{-2} were estimated, with a general increase in heat flow from the southern parts towards the northern parts of the study area. These relatively high geothermal gradient and heat flow may be associated with the mineralogical, thermal and tectonic history of the area, suggesting the study area has the potential of geothermal energy.

Keywords: Aeromagnetic; Heat flow; Sedimentary thickness; Geothermal energy; North Central Nigeria

1. Introduction

Aeromagnetic survey is a type of geophysical survey carried out using a magnetometer on-board or towed behind an aircraft. The principle is similar to a magnetic survey carried out with a hand-held magnetometer, but allows much larger areas of the Earth's surface to be covered quickly (Olasehinde, 2009). Aeromagnetic surveys and data can be applied for several solutions such as determination of depth to the basement below sedimentary basins, structural mapping, mineral exploration and geothermal energy potential amongst others. The study area is located in North Central Nigeria and is bounded by latitudes $8^0 30'$N and $9^0 30'$N, and longitudes $8^0 30'$E and $9^0 30'$E, and has an area extent of about 12,100 km^2 (Fig. 1). It traverses parts of Nasarawa and Plateau States and covers major towns like Yashi, Mangu, Pankshin, Akwanga, FadanAyu, Assaiko, Kwalla, Kwong, etc. The study area is very significant with respect to the geologic and tectonic history of Nigeria and holds good prospects for mineralization, hydrocarbon accumulation and geothermal energy. Evidence of potential sources of subsurface geothermal energy as manifested by hot springs (such as the Ikogosi, Ngeli, Wikki and Kerang hot springs) and intrusives have been documented extensively in the northern and central parts of the Benue Trough and the surrounding basement rocks. Works have been done by researchers (Akanbi and Udensi, 2006; Anudu et al., 2014; Ofor and Udensi, 2014; Oghuma et al., 2015; Onuba et al., 2012; Selemo and Akaolisa, 2010; Umeanoh, 2015) around the study area, however most are concentrated on the southern and northern parts, and perhaps were limited to the

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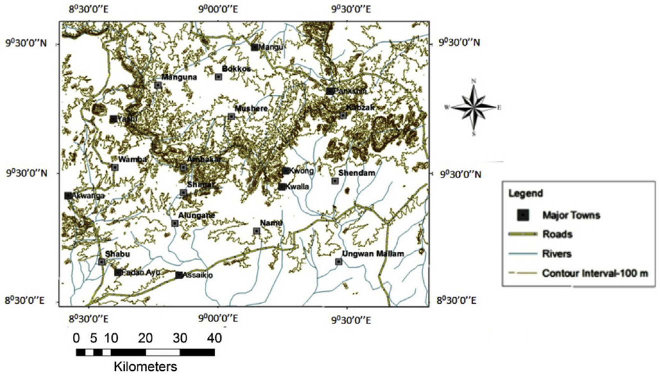

Fig. 1. Location map of the study area with major roads and settlement showed.

estimation of depth to magnetic sources and location of intrusives without much efforts on determining heat flow (potential geothermal energy) and other geologic characteristics in the area. This study, therefore, is intended to evaluate aeromagnetic anomalies in the study area in order to determine, analyse and understand the structures and lineaments, sedimentary thickness, heat flow and other characteristics as a tool for geothermal energy and economic mineral reconnaissance investigations.

2. Geologic setting of the study area

The study area is underlain by the Precambrian Basement Complex rocks, Younger Granites and Cretaceous Middle Benue Trough's sedimentary rocks (Fig. 2). The Nigerian Basement Complex forms a part of the Pan–African mobile belt and lies between the West African and Congo Cratons and south of the Tuareg Shield. It is intruded by the Mesozoic calc-alkaline ring complexes (Younger Granites) of the Jos Plateau and is unconformably overlain by Cretaceous and younger sediments. The basement rocks are believed to be the results of at least four major orogenic cycles of deformation, metamorphism and remobilization corresponding to the Liberian (2700 Ma), the Eburnean (2000 Ma), the Kibaran (1100 Ma), and the Pan–African cycles (600 Ma) (Oghuma, 2017). The first three cycles were characterized by intense deformation and isoclinal folding accompanied by regional metamorphism, which was further followed by extensive migmatization. The Pan–African deformation was accompanied by regional metamorphism, migmatization and extensive granitization and gneissification which produced syntectonic granites and homogeneous gneisses (Abaa, 1983). Late tectonic emplacement of granites and granodiorites, and associated contact metamorphism accompanied the end stages of this last deformation. The end of the orogeny was marked by faulting and fracturing (Gandu et al., 1986; Olayinka, 1992). The Basement Complex rocks in the area are grouped into two sections, namely Migmatite–Gneiss Complex and the Older Granites (or Pan–African granitoids). The migmatite–gneiss complex is Neo- Proterozoic to Meso-Archean (542–3200 Ma) in age and composed of migmatites and gneisses. It is the most extensive rock type in the area. The Older Granites (or Pan–African granitoids), which intruded and deformed the Migmatite–Gneiss Complex are Pan–African (600–200 Ma) in age and consist mainly of granites, diorites and dolerites. The Younger Granites are Jurassic (145–210 Ma) in age and

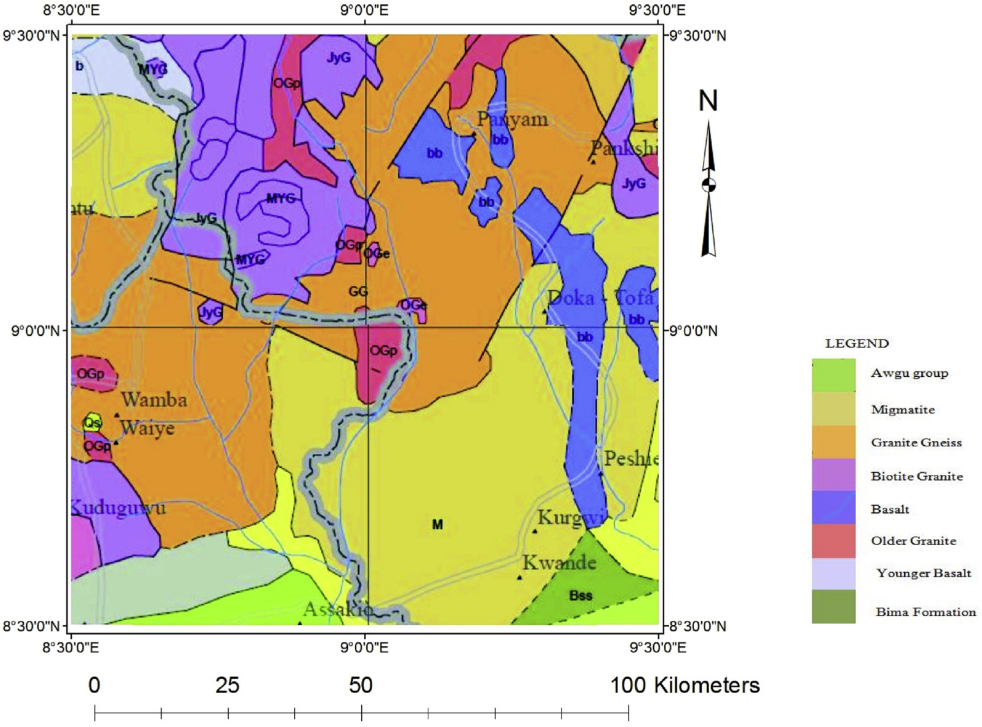

Fig. 2. Geologic map of the study area (Adapted from NGSA 2009).

are high-level anorogenic granites consisting mainly of microgranites and biotite-granites. The southern part of the study area forms part of the Middle Benue Trough and is underlain by Cretaceous sedimentary rocks, namely the Awgu Shale and Lafia Formation. The Awgu Shale is composed mainly of bluish-grey to black shale, whereas the Lafia Formation comprises mainly sandstone and claystone. According to Obaje et al. (1994), Paleogene basalt flows and dolerite sills have been encountered within the Lafia Formation.

3. Data description and methodology

Digital aeromagnetic survey maps of total magnetic intensity (TMI) (Kurra sheet 189, Pankshin sheet 190, Wamba sheet 210 and Kwalla sheet 211) obtained from the Nigerian Geological Survey Agency (NGSA) were used in this study. The aeromagnetic data were obtained as part of a nationwide aeromagnetic survey sponsored by NGSA and acquired by Fugro Airborne Surveys using Fugro's GENESISEM system. The data were acquired along a series of NW—SE flight lines with a spacing of 1 km and an average flight elevation of about 150 m, while tie lines are at about 2 km interval. The geomagnetic reference was removed from the data using the International Geomagnetic Reference Field (IGRF - 12). The data were made available in the form of a contoured map on a scale of 1:100,000. The total area covered is about 12,100 km^2.

A systematic methodology was used in analysing and interpreting the data. Firstly, data enhancement by filtering in the Fourier domain and reduction to pole (RTP) were carried out to enhance deep and/or shallow features as well as allow for more constrained interpretation. RTP operation can transform a magnetic anomaly caused by an arbitrary source into the anomaly that the same source would produce if it were located at the magnetic pole and magnetized by induction only. RTP also helps in the interpretation of magnetic data by removing the influence of magnetic latitudes and skewness on the anomalies. It is used in low magnetic latitudes to aggregate the peaks of magnetic anomalies to the centre of their sources so that the equivalent of the anomaly appears as if the source was observed at the magnetic north pole. This makes the magnetic anomalies easier to be visualized and interpreted at low latitudes while still retaining the geomagnetic information (Blakely, 1995). RTP is expressed by $(\Phi) = 1/[sinx + icosI.cos\ (D\text{-}y)]^{2}$, where I is the geomagnetic inclination; x is the inclination for amplitude correction which is always greater than one; D is the geomagnetic declination; y is the wave number direction; and $i = \sqrt{-1}$, the implicit assumption being that the magnitude of the magnetization remains the same while the direction is changed to being vertical. The RTP operation was carried out using Oasis Montaj™ software, with a geomagnetic inclination of $4^0\ 22'$, geomagnetic declination of $-0^0\ 16'$ and inclination for amplitude correction of 40.

After data enhancement, regional—residual separation was performed by polynomial fitting using multiple regression analysis. The surface linear equation used for the separation is as given by Davis (1973):

$$P(x, y) = a + bx + cy \tag{1}$$

Where a, b and c are constants; x and y are distances in x and y directions, P (x, y) is the magnetic value at x and y coordinates.

After regional-residual separation, the analytical signal method operation was performed on the residual map using the Oasis Montaj™ software. The analytic signal method is very useful for delineating magnetic source location. The analytic signal image simplifies the interpretation by placing the anomaly peaks directly above the source. The magnitude of the analytic signal of the total magnetic field produces maxima over magnetic contacts regardless of the direction of magnetization and is always positive. These magnetic contacts could result from differences in magnetic susceptibility between an intrusive rock and country rock, between geologic contacts, and across a fracture zone due to the oxidation of the magnetite or infilling of the fracture zone by magma which forms intrusive bodies whose magnetic susceptibility is different from that of the host rock. This method is very useful at low magnetic latitudes and it is independent of the inclination of the magnetic field (Ibeneme, 2018).

Spectral analysis was done to estimate depth to the magnetic source(s). This was achieved by subdividing the residual magnetic anomaly map of the study area into sixteen (16) square blocks and Discrete Fourier Transform applied to compute the energy spectrum which was then plotted on a logarithmic scale against frequency. The slopes of segments of the plots were used to obtain estimates of the average depths to the top of the magnetic source Z_t and centroid of magnetic source Z_o; while the Curie depth Z_b was estimated using the following relations:

$$Z_b = 2Z_0 - Z_t \tag{2}$$

Source parameter imaging (SPI), which is another method used in determining the depth to magnetic source was also applied to the residual magnetic anomaly map to constrain interpretations from spectral analysis. SPI was performed using the Oasis Montaj™ software. SPI utilizes the relationship between source depth and the local wave-number (k) of the observed field, which can be calculated for any point within a grid of data via horizontal and vertical gradients.

In the absence of heat flow data in the study area, an empirical relation which uses a one-dimensional heat conductive transport model to estimate heat flow and the geothermal gradient was used in this research. Curie point temperature of 580 °C and thermal conductivity of 2.5 Wm^{-1}°C^{-1} as average for igneous rocks were used as standard (Nwankwo et al., 2011). Heat flow and thermal gradient were estimated in accordance with the Fourier law expressed as:

$$q = \lambda \frac{dT}{dZ} \tag{3}$$

Where q is the heat flow and λ is the coefficient of thermal conductivity, assuming that the direction of the temperature variation is vertical, and the temperature gradient $\frac{dT}{dZ}$ is constant. According to Tanaka et al. (1999), the Curie temperature (θ) is obtained from the Curie point depth (Z_b) and the thermal gradient $\frac{dT}{dZ}$ using the following equation:

$$\theta = [\frac{dT}{dZ}]Z_b \tag{4}$$

assuming there are no heat sources or heat sinks between the earth surface and the Curie point depth, the surface temperature is 0 °C and $\frac{dT}{dZ}$ is constant. The Curie temperature depends on the mineralogy of the magnetic material.

4. Results presentation

4.1. Total magnetic intensity versus residual magnetic field maps

The TMI maps obtained after filtering and data enhancement (RTP) are presented as Figs. 3 and 4. The RTP transformation enhanced and better placed the anomaly peaks over the source with magnetic highs observed within the peripheries of the Younger Granite in the northern part, and parts of the southern region of the study area; and magnetic lows in the central part of the study area (Fig. 4). The TMI values range from 8260 nT to 8685 nT and its maps show variation in colour shadings indicative of high and low intensity of magnetization, with a regional gradient of increasing magnetic field intensity towards the central parts of the study area. It can be seen from the TMI maps that areas around Mangu, Kabzak, Ambakar, Kwalla, SE and SW of Wamba are characterised by high magnetic field intensity, while areas around Shabu, FadanAyu, Assaiko, UngwanMallam, Alungane, Namu, Yashi, Manguna, Bokkos, NE and NW of Pankshin are characterized by low magnetic field intensity. This is suggestive of a shallower depth to magnetic sources at the central parts compared to greater depths to magnetic sources at the northern and southern parts of the study area.

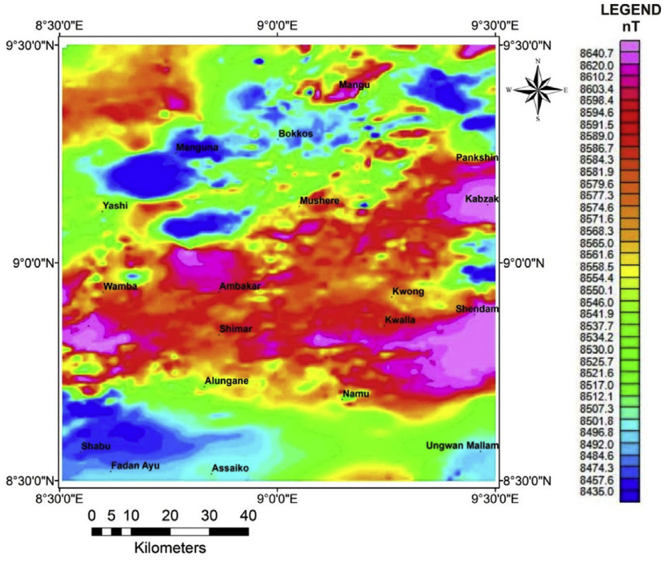

Fig. 3. Colour shaded map of the TMI (legend in nT).

The TMI values comprise two contributory parts − the regional field and the residual field. The regional field is relatively very high when compared to the residual field and hence can mask/distort vital information of interest which is usually embedded in the residual field. Qualitative and quantitative interpretation of aeromagnetic data requires the separation of the residual field from the regional field. The map of the residual magnetic field after regional-residual separation is presented as Fig. 5. It can be seen from the map that the residual magnetic field values range from −65 nT to 140 nT. The values of the residual magnetic field are predominantly positive suggesting the presence of magnetic source/bodies with significant magnetic susceptibility in the study area. The areas with negative residual field intensity are characterised by low magnetization while areas with positive residual field intensity are characterised by relatively high magnetization. Just like the TMI map, the residual field map also showed a regional gradient of increase in magnetic intensity towards the central parts of the study area. Analytical signal method operation performed on the residual map shows that the magnitude of analytic signal within the study area depends on the magnetic susceptibility contrast between Younger Granite intrusions and the Older Basement rocks (Older Granites, Migmatites and Gneisses). Basic igneous rocks have a higher magnetic susceptibility than acidic igneous rocks. Hence the peaks in the magnitude of analytic signal could result from magnetic susceptibility contrast between the rocks of the Younger Granite Complex intrusives and that of the Older Basement (Fig. 6).

4.2. Spectral analysis and source parameter imaging

The residual anomaly data was used to carry out spectral analysis after the regional-residual separation using the Oasis Montaj™ and Microsoft Excel™. Sixteen (16) overlapping square blocks were carefully selected in such a way that important parts of the anomaly were not distorted. Spectral analysis by Fourier Transform was carried out and plots of the logarithm of the spectral energy against frequency obtained (Fig. 7). The spectral plots showed two linear segments as illustrated by representative best-fit line, with each segment representing magnetic signature from shallower and deeper sources. Inferences from the analysis of the gradients of the two linear segments of the plots gave the average depth distribution to the top of magnetic sources Z_t and magnetic centroid Z_0. The second segment of the spectral plot corresponding to the higher frequency (shorter wavelength) was used to estimate Z_t, and it gave depth values ranging from 0.33 to 0.73 km, with an average depth of 0.55 km (Table 1). The first segment of the spectral plot corresponding to the lower frequency (longer wavelength) was used to compute Z_o and values ranging from 2.51 to 5.83 km with an average depth of 3.94 km obtained (Table 1).

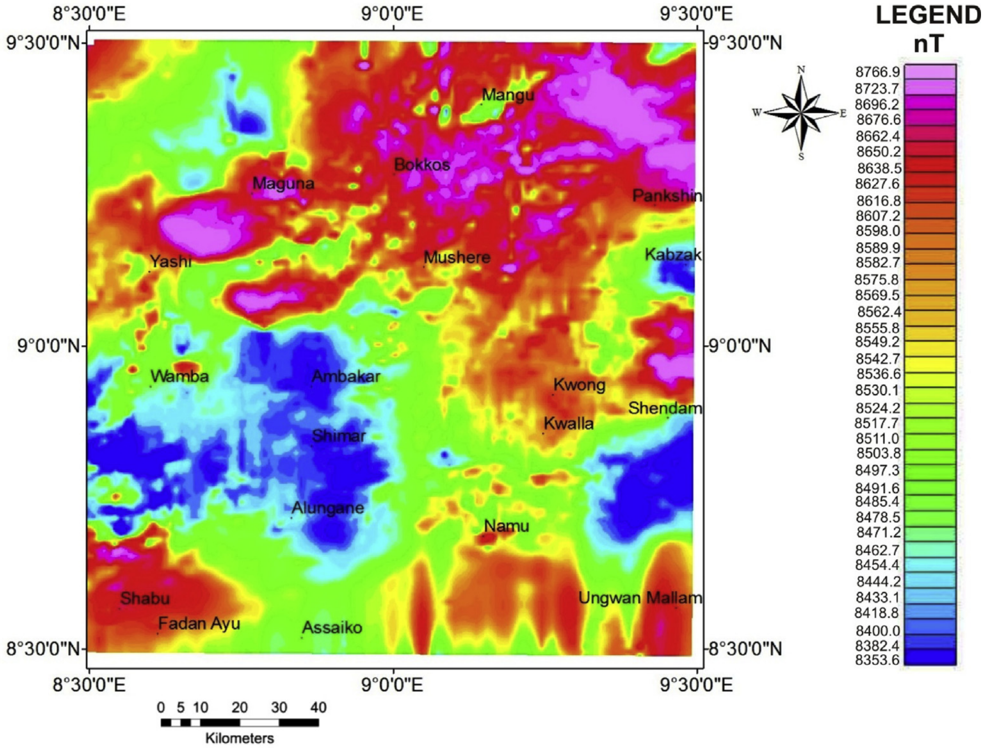

Fig. 4. Colour shaded TMI map of the study area after RTP operation.

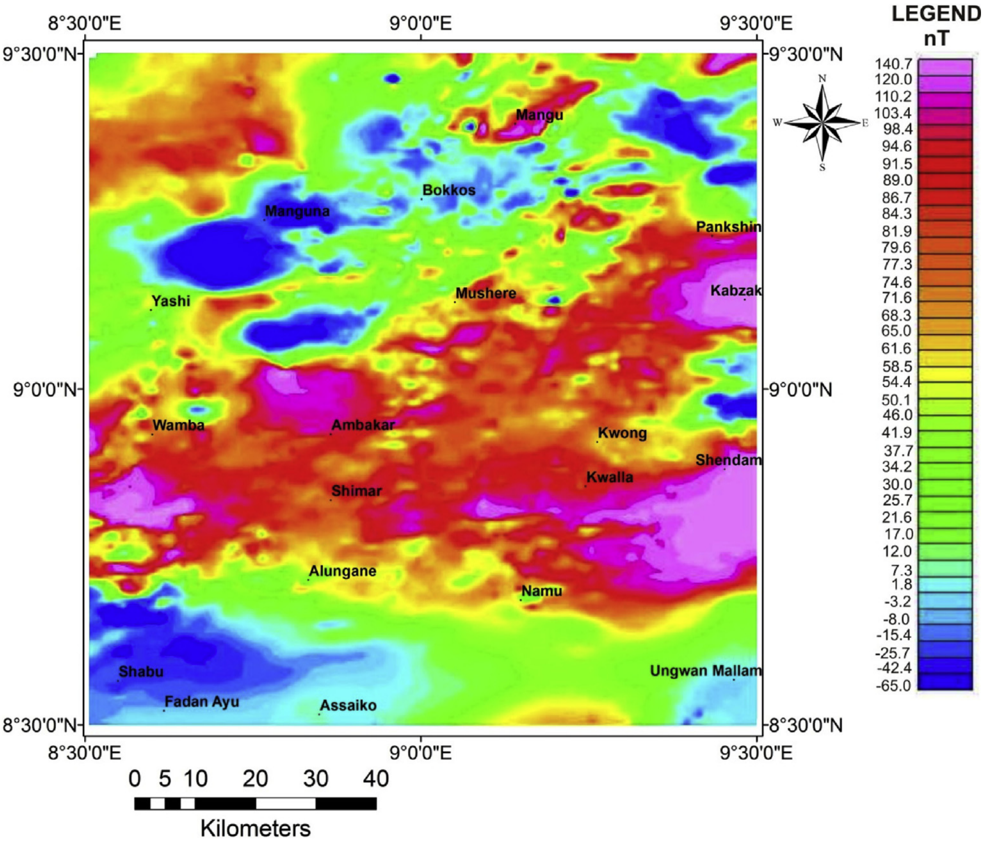

Fig. 5. Colour shaded map of residual magnetic anomaly.

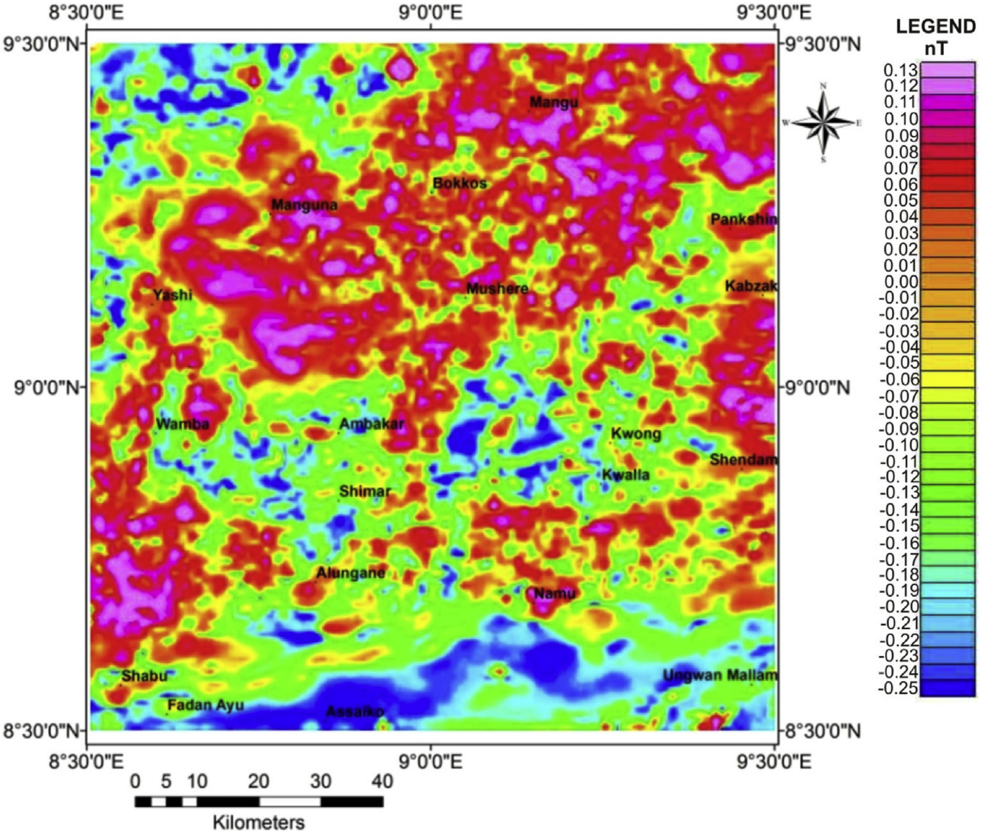

Fig. 6. Residual anomaly map after analytical signal method operation.

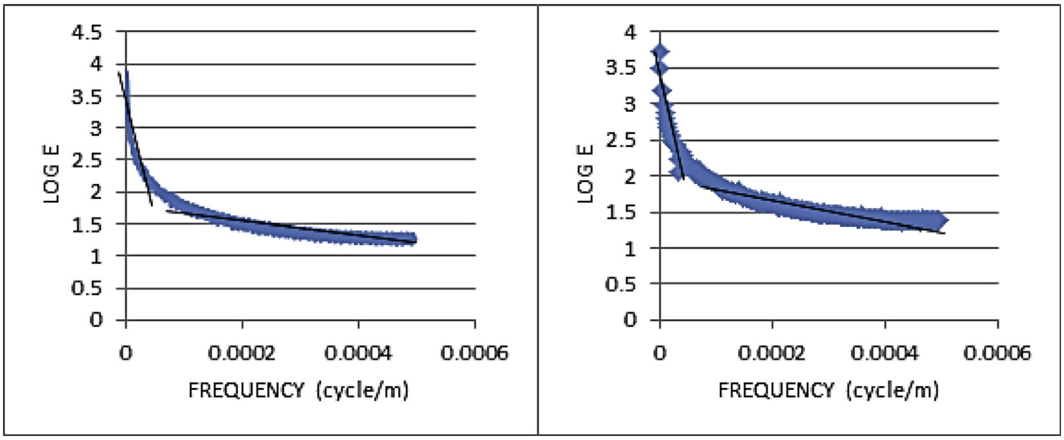

Fig. 7. Representative power spectrum plots of magnetic data from the study area.

Source parameter imaging was also performed on the filtered and enhanced residual aeromagnetic data, and from the image obtained (Fig. 8), depth to magnetic sources was estimated to range from 0.267 to 3.01 km. From the image, it can also be seen that the southern part of the study area is characterised by greater depth to the magnetic source which is in agreement with the fact that the area is part of the Lower Benue Trough (Sedimentary Basins). Some areas of the NW and NE parts of the study area also presented relatively greater depth to the magnetic source suggesting relatively thick sedimentary pile cover within the collapsed central parts of ring complexes. Other areas are characterised by relatively shallower depths to magnetic sources.

4.3. Heat flow and thermal gradient

Using a Curie point temperature of 580 °C and thermal conductivity of 2.5 $\mathrm{Wm^{-1}{}^{\circ}C^{-1}}$ as average values for rocks in the study area (Nwankwo et al., 2011), the geothermal gradient and the heat flow in the study area were calculated

Table 1
Summary of depths to the centroid, top of the magnetic source and curie depth; and geothermal gradient and heat flow estimated from spectral analysis.

Blocks	Depth (km)			Geothermal gradient (°Ckm^{-1})	Heat flow (mWm^{-2})
	Depth to the centroid (Z_o)	Depth to top of the magnetic source (Z_t)	Curie depth (Z_b)		
1	5.834	0.700	10.968	52.881	132.202
2	4.774	0.604	8.944	64.847	162.119
3	3.580	0.434	6.726	86.232	215.581
4	4.340	0.578	8.102	71.587	178.968
5	5.304	0.331	10.277	56.436	141.092
6	3.616	0.477	6.755	85.862	214.655
7	3.889	0.350	7.428	78.082	195.207
8	4.110	0.729	7.491	77.426	193.565
9	3.607	0.732	6.482	89.487	223.696
10	3.500	0.668	6.332	91.598	228.996
11	3.845	0.462	7.228	80.244	200.609
12	3.906	0.415	7.397	78.410	196.025
13	3.296	0.636	5.956	97.381	243.452
14	3.182	0.548	5.816	99.724	249.312
15	3.713	0.549	6.877	84.339	210.848
16	2.512	0.612	4.412	131.459	328.649

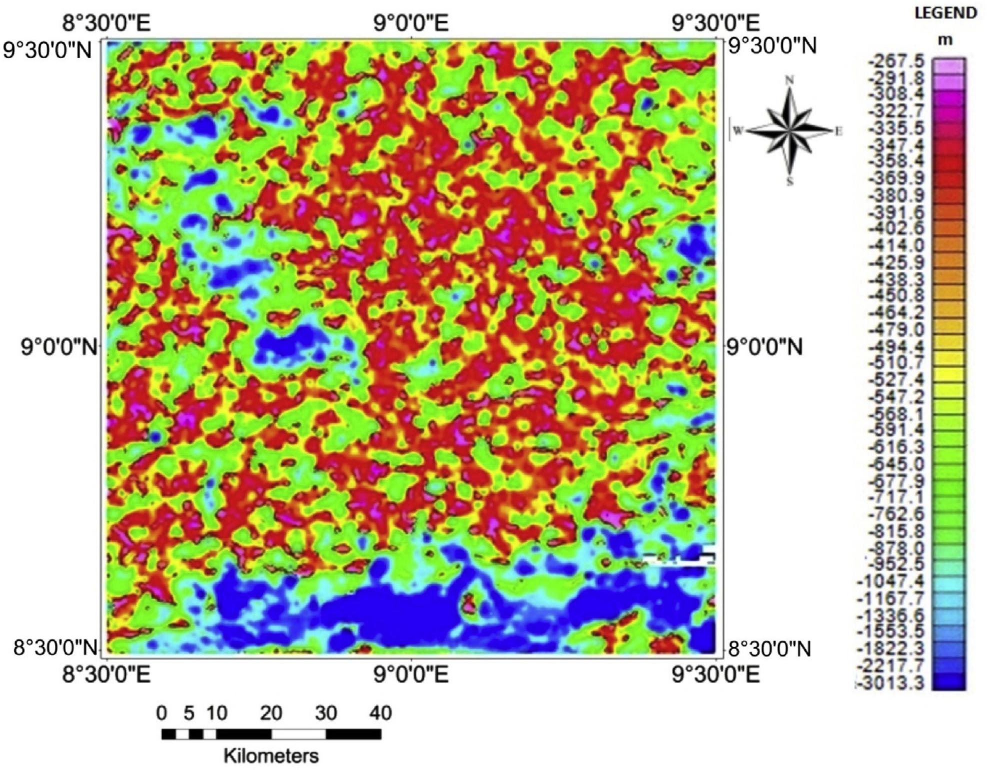

Fig. 8. Source parameter imaging of the study area showing the spatial distribution of depth to various magnetic sources.

using Eqs. (3) and (4). The geothermal gradient in the study area ranges from 52.88°Ckm^{-1} to 131.46°Ckm^{-1} with an average of 82.87°Ckm^{-1}, while the heat flow ranges from 132.20 mWm^{-2} to 328.65 mWm^{-2} with an average of 207.19 mWm^{-2}. It can be seen from the heat flow map that heat flow increases towards the north-eastern part with areas around Kabzak, Pankshin, Kwong, Kwalla, Shendam, Mushere and Manguna characterised by high heat flow; while it decreases towards the south-western parts with areas around Shabu, FadanAyu and Assaiko characterised by relatively low heat flow (Fig. 9). An inverse relationship was established between the estimated heat flow distribution and curie depth such that areas with high heat flow are characterised by shallow curie depth, and vice versa (Fig. 10).

5. Discussion

The study area covers parts of the North Central Block of the Nigerian Basement Complex to the north, and the Benue Trough sedimentary basin to the south. It can be seen from the

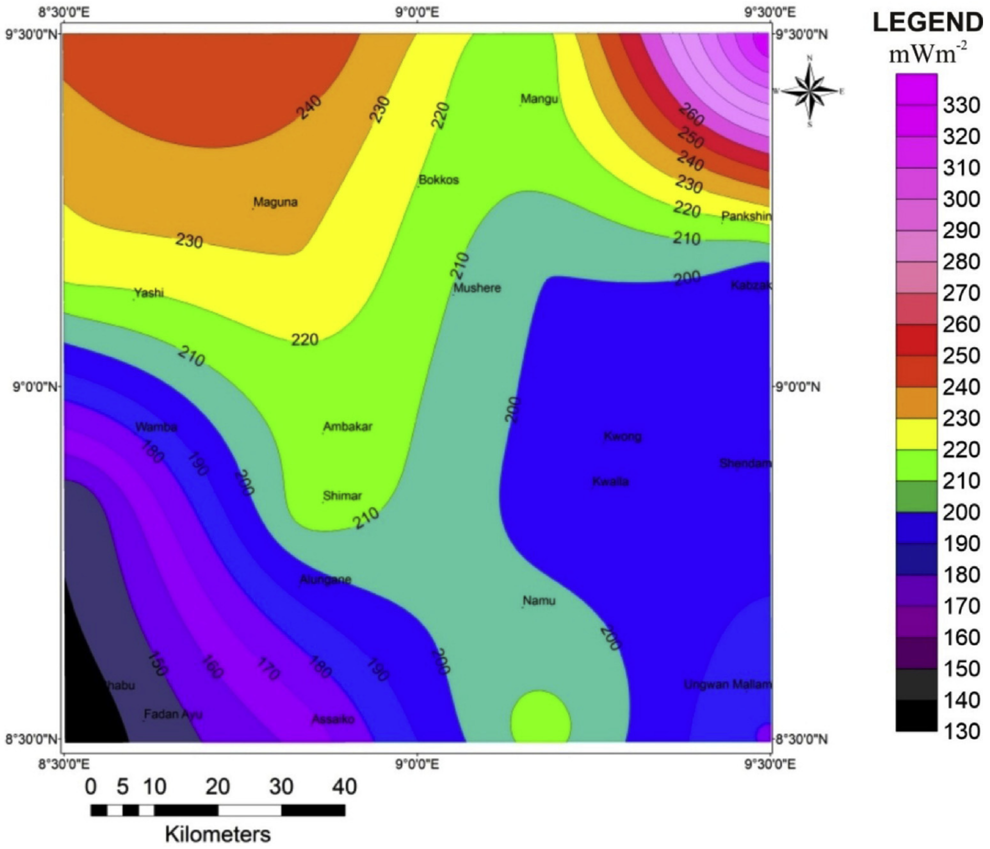

Fig. 9. Heat flow Map of the Study Area.

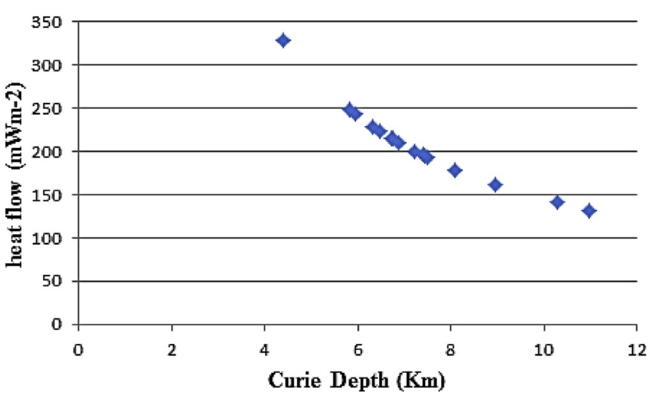

Fig. 10. A plot of heat flow versus Curie point depth in the study area.

residual magnetic field intensity map (Fig. 5) that the southern parts of the study area which correspond to parts of the Benue Trough Basin are characterised by relatively low magnetic field intensity when compared to the central and northern parts which are characterised by relatively high magnetic field intensity and corresponding to parts of the basement block. Sedimentary rocks and poorly consolidated sediments have much lower magnetizations compared to crystalline rocks (Oghuma et al., 2015, 2017; Reynolds, 1990). Some localized regions of relatively low magnetic intensity can also be seen towards the northern extremes of the study area, and these can

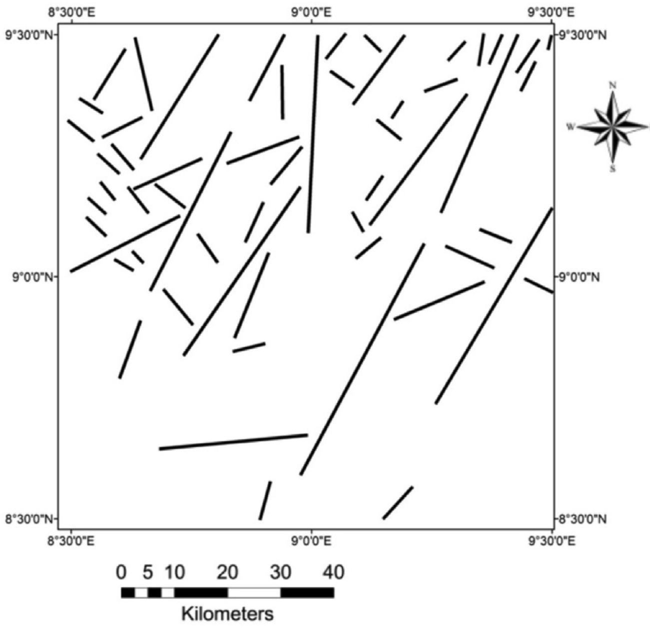

Fig. 11. Structural lineament map of the study area inferred from the aeromagnetic data and local geology.

be interpreted to represent localised areas of appreciable sedimentary rock cover over collapsed central parts of intrusive ring complexes.

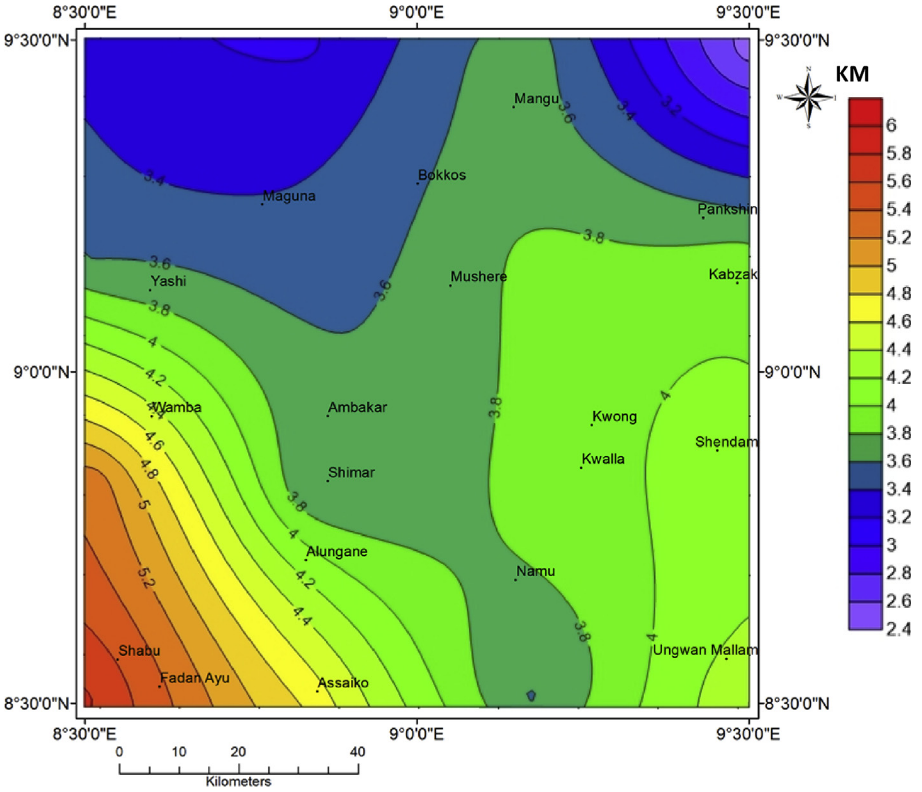

Fig. 12. Depth to basement map (and sedimentary pile thickness) of the study area in km.

The dominant trend of the magnetic anomaly as expressed by the contours is in the NE–SW direction, with secondary trends in the NW–SE orientation. Structural lineament map obtained by the integration of the qualitative analysis of magnetic anomaly trends, analytic signal and local geology of the area showed that the major structural lineament bearings are in the NE–SW, NW–SE and NNE-SSW, with minor NNW-SSE and E–W orientations (Fig. 11). These orientations are in conformity with the structural trends produced by the Pan–African events (Obiadi et al., 2015; Oghuma et al., 2015), and hence most probably developed during the Pan African Orogeny. Structures/structural lineament patterns are zones for minerals emplacement, and their trends are useful guide for mineral exploration and exploitation.

Spectral analysis gave depths range of 0.33–0.73 km to top of magnetic sources Z_t, with an average depth of 0.55 km; and depth range of 2.51–5.83 km to the magnetic centroid $Z_{0,}$ with an average depth of 3.94 km (Table 1). This compares with the depth range of 0.27–3.01 km to various magnetic sources obtained from source parameter imaging SPI. Z_t is inferred to be depth to near-surface intrusives. These intrusives which are mainly granite and acidic rocks (Fig. 2) are known to be associated with, and host metallic minerals of economic values. Metallic ores of Tin, Tungsten, copper, etc., have been mined and processed from these near-surface intrusives in the North Central Block of the Nigerian Basement Complex and Benue Trough (Obaje, 2009). The intrusives are emplaced as ring dykes, dykes, sills and batholiths of various sizes. The shape (circular and elliptical) and distribution of the magnetic anomalies presented in the residual anomaly map (Fig. 5) suggest and infer the presence of these near-surface intrusives at various locations within the study area. Akanbi and Udensi (2006) have described intrusions on aeromagnetic maps from the North Central Block of the Nigerian Basement Complex as elliptical or circular in outline. Magnetic centroid can be interpreted to emanate from the magnetic minerals/rocks in the basement rock, hence the Z_0 can, therefore, represent the average sedimentary pile thickness in the study area. Depth to magnetic centroid Z_0 map (Fig. 12) reveals the sedimentary pile thickness as thickest in the SW parts and decreases towards the NE of the study area.

An average geothermal gradient of 82.87 Ckm^{-1} and heat flow of 207.19 mWm^{-2} were estimated in the study area. Heat flow increases towards the NE parts and decreases towards the SW parts. This trend may be associated with the rock distribution which is characterised by sedimentary rocks to the SW and basement crystalline rocks to the NE. Also, the Northern parts of the study area host a lot of igneous intrusions. The relatively high geothermal gradient and heat flow may be associated with the mineralogy, thermal and tectonic history of the area (Nwankwo et al., 2011).

6. Conclusions

Aeromagnetic data acquired over parts of north central Nigeria were analysed in order to characterise structural features and lineaments, sedimentary pile thickness, geothermal gradient and heat flow. The study area is underlain by the

Basement Complex rocks, Younger Granites and Cretaceous Middle Benue Trough sedimentary rocks. Depth to basement rock (sedimentary rock thickness) was evaluated by spectral analysis and source parameter imaging while structural/lineament characteristics were determined from the qualitative interpretation of residual magnetic field maps after data enhancement and the integration of the geology of the study area. Spectral analysis gave depth range of 0.33−0.73 km to the top of magnetic sources Z_t, with an average depth of 0.55 km; and depth range of 2.51−5.83 km to the magnetic centroid Z_o, with an average depth of 3.94 km. This compares with the depth range of 0.27−3.01 km obtained from SPI as depth to various magnetic sources. Z_o was interpreted as representing the average depth to basement rocks (sedimentary pile thickness) and its distribution shows that sedimentary pile thickness is greatest in the SW parts and decreases towards the NE of the study area. Structural lineament orientation obtained from the analysis of magnetic anomaly trends and local geology showed that the major structural lineament bearings are in the NE−SW, NW−SE and NNE-SSW, with minor NNW-SSE and E−W orientations. This conforms to the general trend of structures produced by the Pan African events. An average geothermal gradient of 82.87°Ckm^{-1} and heat flow of 207.19 mWm^{-2} were estimated, with a general increase in heat flow from the southern parts towards the northern parts of the study area. The relatively high geothermal gradient and heat flow, which holds good potential as sources for geothermal energy, may be associated with the mineralogical, thermal and tectonic history of the area.

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