Use of Magnetic anomaly data to delineate subsurface structures and depth characterization of Lafiaji and its environs, Northcentral Nigeria

Taofeeq Olanrewaju Lawal\textsuperscript{a}, John Sunday\textsuperscript{b}, korede Fawale\textsuperscript{c}, Muyideen Salami\textsuperscript{d} and Taiwo Adewumi\textsuperscript{a}

\textsuperscript{a}Department of Physics, University of Ilorin, Kwara State, Nigeria; \textsuperscript{b}Department of Science Lab. Tech, Polytechnic Ilorin, Kwara State, Nigeria; \textsuperscript{c}Department of Science Lab. Tech, Federal Polytechnic, Ado-Ekiti, Nigeria; \textsuperscript{d}Department of Physics, Faculty of Computing and Applied Science, Baze University, Abuja, Nigeria; \textsuperscript{e}Department of Physics, Faculty of Science, Federal University of Lafia, Nigeria

\begin{abstract}
As part of the effort to have updated knowledge about the metallic source location, subsurface structures and depth information responsible for mineralization in Lafiaji and its environs, North-central Nigeria, a magnetic data of the area has been analyzed using combinations of mathematical techniques. These techniques include Total Horizontal Derivatives (THD), Tilt Derivatives (TD), CET grid technique, Euler Deconvolution (ED), and Fourier technique. Reduction to equator (RTE) was performed on the magnetic data and subjected to the mathematical techniques. The TD, THD and CET techniques revealed various striking subsurface structures moving in NE, SW, NW SE, EW direction and forms banded gneisses and muscovite schist that are intimately linked through the crustal progress going on in the basement rock of the area. The ED solutions did not only reveal various structural sources but also determines the best index with the average depth values of various metallic sources. Also, the result from the spectral analysis ranges from 1.40 km - 3.50 km. In conclusion, this study did not only demonstrate the usefulness of HRAM data in revealing the nature and extent of subsurface structural features and depth information but also shows intense tectonic deformation of the basement structures responsible for mineral exploration.
\end{abstract}

1. Introduction

The magnetic method has been described as a non-destructive and efficient potential field method that measures spatial differences in the strength of the earth’s field at the exact location (Kearey et al. 2013). The method can be acquired on the earth’s surface as a land or ground method, above the earth’s surface as an aeromagnetic method and on the sea as a marine-borne magnetic survey. Among the three ways by which method is carried out, an aeromagnetic survey has advantages over the ground and marine magnetic survey because of its ability to cover wide hectares of land and its movement along a rugged terrain within a very short time (Telford et al. 1990). The aeromagnetic survey has resulted in a tremendous acquisition of several data some years back and these data are used in the investigation of subsurface structures responsible for minerals and hydrocarbon explorations (Kearey et al. 2013). Applications of magnetic surveys are not limited to detections of hidden ore sources in the mineral’s investigation only but have also received a nod in reconnaissance survey for studying of subsurface structural features (such as faults, joints, folds, contact, etc.), engineering and environmental investigation, geothermal and hydrocarbon signatures (Reeves 2005). Several studies have shown that aeromagnetic data can be interpreted using derivatives (such as horizontal, vertical, and total), CET, Euler deconvolution, 2D Fourier transform (Balogun 2019; Reid et al. 1990; Ozebo et al. 2015; Lawal et al. 2016; Lawal and Nwankwo 2017; Awoyemi et al. 2017; Elkhateeb and Abdellatif 2018). All these mathematical techniques reveal trends in the subsurface geological lithologies and estimate depths to magnetic sources evolved from the susceptibility difference of the underlying rocks. In this case, this work is of the view of using HRAM data in revealing the nature and extent of subsurface structural features, depth information, and shows intense tectonic deformation of the basement complex responsible for mineral deposits.

2. The study area

The study area is made up of Lafiaji, Pategi, Osi, and Isanlu all lay in the southern Bida Basin of Nigeria (Figure 1). The survey area spans between the longitude and latitude 5\degree 00’ – 6\degree 00’ East 8\degree 00’ – 9\degree 00’ North and the equivalents in Eastings and Northings are 718,400–831,200 mE and 883,800–997,900 mN within the Zone 31 of Northcentral Nigeria. The length and breadth of the study area are 110,000 m by 110, 000 m with an elevation ranging from 60.57 m to 548.87 m (Figure 3), with the lowest value occupying very little space (light blue to dark blue) found
3. The geological build-up of the area

Geologically, the study area which lies in the Northcentral region of the basement complex of Nigeria (Figure 1) has been reported by (Obaje 2009); (Megwara and Udensi 2014) to form part of the Pan African mobile belt which falls among the West African and Congo Cratons. It is intruded by Younger granites and is below the Cretaceous and Younger dregs which form a larger section Bida basin. Among the four Petrolithological units of the Southwest Nigerian Precambrian basin complex, Migmatite–Gneiss complex and schist belt are notable complex geology in the area. The Migmatite–Gneiss complex found to have intruded by a suite of granitic sources which are of age ranges between PanAfrican to Eburnean. Adjacent to Migmatite–Gneiss is the schist belt which is of low graded Younger metasediments dominated belts trending North-south direction. The belt is made up of greater protérozoic supercrustal cover that has been enclosed into Magmatic gneiss quartizite complex. Lithologically, the belt is believed to be of coarse to fine-grained elastics, pelitic, muscovite schist. Twenty per cent of the rocks associated with Migmatite–Gneiss complex includes migmatite, banded gneiss, biotite gneiss, etc. of age that intrudes, the older granitoids of Pan-African age are observed in the Southwestern portion of the area, while the North and some segments of the southeastern region of the area are made up of more than 80% of younger metasedimentary rocks (e.g. muscovite schist, sandstone, and shales) also of pan-African age (Figure 2).

8 (Wang et al. 2019) to produce RTE map (Figure 4b).

4. Materials and methods

4.1. Description of data

Data used include magnetic data of sheet numbers 203, 204, 224, and 225 obtained from the Geological Survey Agency of Nigeria. The survey to acquire the data was carried out between 2003 and 2009 via an airplane flown at an 80 m high, a line spacing 500 m, a mean terrain clearance 80 m, a 500 m tie line spacing, and flight direction is in NW-SE. International Geomagnetic Reference Field (IGRF, 2010) was deducted from the acquired survey data (Figure 4a). RTE correction was also carried out on the merged Total magnetic anomaly data because of the variation in declination and inclination of the earth magnetic field from the geomagnetic equator to the magnetic pole, such that the peaks of anomalies due to subsurface are shifted from directly over the source and the anomalies become highly asymmetric (Xiong 2008; Hinze et al. 2013; Saada 2016; Lawal and Nwankwo

Figure 1. Geological map of Nigeria showing the study area.
Therefore, RTE correction as discussed in the work of (Xiong 2008) was adopted by using the value $-4.053^\circ$ for the declinations and $-12.072^\circ$ for the inclinations for this area using Oasis Montaj software, version 8.3.

### 4.2. Analysis of magnetic data

Magnetic Data analysis involves the application of enhanced mathematical techniques on the RTE map. The techniques include are Total Horizontal Derivatives (THD), Tilt Derivatives (TD), and Center for Exploration Targeting grid and porphyry (CET), Euler Deconvolution (ED) and Fourier transform analysis. The THD and TD give information about the contact location of source bodies at depth, while SED reveals both depth and various sources bodies within the study area, the CET gives information about the lineament structures with their directions and identifying potential zones for mineral deposits and Spectral analysis reveals knowledge of the magnetic source depth only.

### 5. The euler deconvolution (EDT), the THD, the TD, fourier technique and the CET grid technique

The EDT method is a technique that reveals the information about the positions, nature, and depth of...
Figure 3. Digital elevation model of the study area showing the topography.

magnetic sources present in either profiles or gridded potential field data (e.g. magnetic) (Thompson 1982; Reid et al. 1990). This method is a three in one approach because of its ability to determine the nature, position, and depth of source bodies. Although unlike some enhanced mathematical techniques such as Continuous wavelet transform which requires no a prior information about geometry (Chamoli et al. 2006), EDT requires small information about geometry by defining the structural indices. EDT is based on obtaining Euler 3D homogeneity equation is related to magnetic field data given as (Reid et al. 1990; Lawal et al. 2016)

\[ (x - x_0) \frac{\partial M}{\partial x} + (y - y_0) \frac{\partial M}{\partial y} + (z - z_0) \frac{\partial M}{\partial z} = \eta(\beta - M) \]  

(1)

And \((x_0, y_0, z_0)\) are the location of a magnetic source whose total field magnetic anomaly at the point \((x, y, z)\) is \(M_0\beta\) is the regional field of the magnetic anomaly and \(\eta\) called structural index \([S.I]\) which measures the rate of the field changes against its distance. The S.I presume various value for dissimilar types of anomalous source bodies, e. g. for S.I = 0.0 is an indication to magnetic contact, thick step; for S.I = 1.0 is an indication to sills/dykes; for S.I = 2.0 is an indication to homogenous cylinder/pipe and lastly S.I = 3.0 is an indication to spheres.

The THD has been described to outline the edges and horizontal extent of anomalous source bodies. (Balogun 2019) describes the technique as the simplest way of obtaining contact locations of magnetic sources that are linear and continuous. Its sensitivity to noise in magnetic data is very low because the mathematical expression is a square of derivatives in first-order. The expression for THD is given in equation 2.

\[ [THD] = \sqrt{\left(\frac{\partial F}{\partial x}\right)^2 + \left(\frac{\partial F}{\partial y}\right)^2} \]  

(2)

F is the derivative magnetic field in the directions of x and y. To obtain structural features, the maximum values aligning linearly can be interpreted as lithological contrast and faults. Also, when the derivative attains maximum over locations where magnetic susceptibility are greatest and highlights of magnetic discontinuities perpendicular to the direction of derivations are observed, it is an indication of edges of geological structures (Salawu et al. 2019).

The TD technique is used to map shallow geological features (e.g. faults, dikes, etc.) by revealing the edges of magnetic source bodies. (Oruç 2011) reported that the technique was discovered firstly by (Evjen 1936) and later developed by (Verduzco et al. 2004). They defined the technique as an arctangent of the fraction of First Vertical Derivatives (FVD) to THD of the magnetic field data. Mathematically, the expression can be written as:
Tilt derivative has been interpreted to have assisted in estimating fault zones, dykes, contact locations that are linear and very continuous at depth, and also reveals areas of anomalous features that are least affected by noise (Salem et al. 2007). (Oruç 2011) reported that the amplitudes of the tilt angle derivative range from $-\pi/2$ to $\pi/2$ radian due to the inverse function of the trigonometric tangent. The TD also doubles as an automatic gain control filter by equalising the amplitude output of the RTE TMI anomalies across the grid or profile magnetic data which is dependent on the depth of the buried source only (Balogun 2019).

Fourier transform is a mathematical technique used to transform any function from the time (or space) domain into the wavenumber or frequency domain. The mathematical technique has been used extensively in the area of geophysics because of the ease of convolving functions and filtering the data in the wave-number domain. The technique is used to decompose geophysical anomalies by analysing the frequency content in the data. In aeromagnetic data interpretation,
the Fourier technique has been applied by (Spector and Grant 1970) on the magnetic anomalies of a rectangular block due to vertical prisms of various ensembles. In their work, they were able to reveal how the thickness, width, and depth of anomalous sources influence the nature of the spectrum. To obtain information about the depth of anomalous sources, two slopes will be observed from the plot of the logarithm of energy against wave number; with the low wavenumber portion corresponding to the deep-seated magnetic sources and high wavenumber, portion corresponds to superficial stationed anomalous sources. Therefore, Spector and Grant (1970) showed that this mathematical technique is related by the equation:

\[ \ln \left( P_{\Delta T}(k) \right)^{1/2} = \ln A - |k|Z_0 \]  

(4)

Where the average energy spectrum is \( P_{\Delta T} \), wave-number is \( K \), \( A \) is fixed, \( Z_0 \) represents depth to the peak of the anomalous source which can be derived through a straight line drawn on the elevated wave-number section of the plot of the natural log of energy against the wavenumber. The CET grid technique is useful in the identification of linear discontinuities and detection of edges within gravity and magnetic field data (Kovési 1991). To achieve this usefulness, Holden et al. (2011) presented the steps such as the textural approach which places interest on the locations of complex texture that are connected with discontinuities in magnetic data. Also, the phase symmetry which reveals laterally continuous line – like regions of discontinuities and amplitude thresholding which uses the output results of phase symmetry to delineate structures and reduces the regions containing discontinuities into line – like structures.

6. Results and discussion

6.1. RTE Map

The enhanced RTE map is presented in Figure 4b. In contrast with the TMI map (Figure 4a), it will be observed that there was a shift in the position of the anomalies in a north-ward direction since the study area is located in a low latitude section of the magnetic equator. From the RTE map, various shapes of magnetic anomalies are positioned over their causative sources and the map is divided into regions positive (high magnetic) anomalies with a relief of about 114 nT and negative (low magnetic) anomalies with a relief of −15 nT. These anomalies appear elongated, circular, semicircular in shape, and the majority of these anomalies are heading in the NE–SW, and E–W direction with their alignment in a continuous manner is noticeable in the South East, Northwest and Northcentral region of the study area. There are few other anomalies noticeable in Northeast and part of Southwest trending in NW–SE, and N–S direction. Also on the map are both low and high magnetic anomalies which seem to obstruct the connection of the Northern oblique band margin, which displays the northern segment to the west. This assertion is observed in the Northcentral region of the area. The positive magnetic deviations found on the map are an indication of low magnetic susceptibility which can be regarded as upliftment of basement rock that is caused by high magnetic content rich in basic intrusions. These intrusions are associated with a shallow sedimentary basin. These anomalies are indications of concealed ores and geological features. The negative anomalies are a reflection of subsurface faulted regions of the basement complex which has been overflown with rocks or set of faults or fracture line trending on the which controls the underlying rocks in the area. Rocks associated with these anomalies are biotite granites, migmatite gneiss, etc.

6.2. The THD map

Figure 5 which the THD map reveals the subtle anomaly texture of the RTE anomaly map. These textures are maxima where there are discontinuities in the values of known anomaly values. Also on the map are elongated maximum amplitudes which are an indication of structural discontinuity that are often referred to as linear geological features. The THD also reveals that edges of maxima values aligning linearly are indications of lithological contrast and faults. The derivative attained maximum over locations where magnetic susceptibility are greatest and highlights of magnetic discontinuities perpendicular to the direction of derivations are observed, this is an indication of edges of geological structures and they are located in the Northeast and Southwest region of the area. Also in the figure are short and long linear features that distinguish the edges of magnetic sources. The long linear features which are continuous and of less predominant are trending NE–SW direction represents lithological boundaries that can be interpreted as a major fracture/fault, contact lines. The short linear and curvilinear features with their orientation trending mostly in Northwest–Southeast, and East-west direction are also within the lithological boundaries of metallic source bodies of muscovite schist, banded granite Gneiss, and migmatites, respectively. These also suggest fracture zones resulting from tectonics of similar intensities and of similar depth to the basement that can be influenced by the rate of deposition and thermal subsidence.

6.3. The tilt derivative map (TD)

The Tilt Derivative map shown in Figure 6 revealed superficial and deep-rooted basement structures. On this map, there are closely spaced contours of values ranging from −0.79 to 0.79–radian band which usually reveal approximate shallow target metallic sources, while spaced contours of the same band will reveal an approximate deeper metallic sources target. Also, the 0–radian tilt angle contours on the map are regions
of magnetic discontinuities, contact defining the boundaries of magnetic origin objects that are regarded as lineaments structures on the RTE map. These lineaments structures trend Northeast–Southwest, East-west, and North–South respectively. More so, this TD map suggests that N–C, S–W, and N–W regions are relatively deeper from the assertion of – 0.79 to 0.79-radian band earlier mentioned. This means that rocks found in this area are influenced by deformations resulting from the activities of tectonics that have taken place during the Pan – African plate margin.

6.4. The standard euler deconvolution map (SED)

The results of the SED technique obtained when applied to the RTE map using Structural Indices (S.I) of 0, 1, and 2 are shown in Figures 7 to 9. For S.I = 0, Figure 7 shows solution result for some of the trends and edges of contact and thick step trending majorly

Figure 5. The total horizontal derivative map.

Figure 6. The tilt derivative map.
Figure 7. Euler solutions of RTE map $S.I = 0$.

Figure 8. Euler solutions of RTE map $S.I = 1$. 
Figure 9. Euler solutions of RTE map $S.I = 2$.

Figure 10. A layout block diagram for the spectral analysis of the study area.
Figure 11. Radially average spectrum plots blocks B8 (top left), B22 (top right), B30 (bottom left) and B42 (bottom right).

Figure 12. Depth to the source of magnetic anomalies.
in NE–SW direction, while few of these sources are trending E–W, N–S and NW–SE, respectively. For S.I = 1, Figure 8 shows solution result for some trends and edges of dykes and sills clustered in the N–C region trending majorly Northeast–Southwest direction just like S.I = 0. In the case of S.I = 2 shown in Figure 9 shows the solution result for rod and homogenous cylinder. It also clustered around the N–C region and moves the Northeast–Southwest direction. Because of this, S.I = 0 gives better solutions because the solutions are clustered and distributed all over the study area while S.I = 2 and 3 are not. The clustering and distribution of all solutions obtained for S.I = 0 shown in Figure 7 represent lithological features that confirmed highly deformed muscovite schist rocks while the granite gneiss rocks are possible intrusive dykes. The depth to delineate structural features obtained using the SED technique varies from 200 m to 1500 m is a suggestion that certain mineral deposits are structurally controlled within the area.

### 6.5. The spectral analysis

To obtain depth information about the location of the metallic source bodies, we have divided the study area into 49 overlapping blocks with each block having a distance of about 15 km (Figure 10). Figure 11 shows some of the mean natural logarithm plots of the overlapping blocks used in obtaining information about the depth of the deep and shallow seated structures. When these depth values are contoured, we obtain Figure 12 with values ranging from 1.40 to 3.50 km. The deep-seated structures with values ranging from 2.20 to 3.50 km are found in parts of N–E, S–E, S–W, and N–C represent depths to Precambrian basements where pegmatite intrusions, quartz, vein are cross-cutting the host rocks. Also on the map are depth values spanning from 1.40 to 1.90 km observed in the part of N–W, N–E, S–W and S–S region of the study area and this indicate downward subsidence controlled by fractures/fault which makes muscovite schist a major mineral deposit in the area. The muscovite in igneous rocks is usually associated with quartz, potassium feldspars, biotite and amphibole minerals.

### 6.6. The CET grid techniques

The CET grid technique applied to the RTE map reveals lineament structures (Figure 13), while (Figure 14) shows the orientation of the lineament plot which also follows the same pattern as deduced in Figure 5, 6, 7, 8 and 9. These structures are an
indication of minerals occupying the area that is covered with cretaceous sandstone except for regions in the Northwest and Northeast whose rocks have been deformed. It can also be observed from the lineament map that the majority of the prominent structures trending Northeast–Southwest while fewer ones are trending in Northwest–Southeast, East–West, and North–South direction. These movements reveal the effects of deep heterogeneity of the earth’s crust which represents fractures – faults influencing the mineral potential of the region.

7. Conclusion

In this study, High-resolution Aeromagnetic data have been analysed and interpreted using combinations of enhanced mathematical techniques so that updated information about the metallic source locations, edges, lineaments, trends, and depths to metallic sources responsible for mineralisation potential lithological structures in the southern Bida basin of Nigeria. The RTE map reveals variations and distributions of anomalies of various sizes concealed as shear and weak zones characterised by positive and negative (high and low magnetic) anomalies trending majorly in Northwest–Southeast, and East–West direction. These positive anomalies are caused by basement rock uplift of high basic igneous intrusions associated with shallow sediments while negative anomalies are reflections of subsurface sections of the basement-complex which has been overflow with sediments and rocks associated with these minerals are biotite granite. On the other hand, the Total horizontal derivative map reveals long and short linear features distinguishing the edges of magnetic source bodies. The long linear features are continuous and less prominent trend NE–SW, NW–SE direction and they represent lithological boundaries that can be interpreted as major fracture/faults lines. While the short linear and curvilinear structures with their direction are trending mostly in Northwest–Southeast, East–West is also concentrated within the lithological boundaries of metallic source bodies of Muscovite shist and Band Granite gneiss. The tlt derivative map reveals some spherical shape anomalies that have closely spaced contours around the Northcentral, Northwest, and South-western regions of the area which is suggestive of granite gneiss. This map also shows a network of discontinuities defining boundaries of metallic objects observed on the THD map. These discontinuities are intra-basement lineaments trending Northeast–Southeast, Northwest–Southeast, East–West, and North–South, respectively. From Figure 12, it shows that the west, east and northeastern section of the area have magnetic basement depth ranging from 0.75 to 1.9 km, while Southeast, Northwest and Southwestern regions of the area have magnetic basement depth to be deeper and the values range between 2.5 km and 3.2 km. The changes in depth values across the study area are an indication of downward subsidence controlled by fractures/fault which makes Muscovits schist a major mineral source in the area. The standard euler deconvolution results show different solutions for various degrees of structural indices (S.I = 0, 1, 2) and different subsurface structural features (such as contacts, dykes, cylinders, and spheres) with their depth values ranging from 200 to 1500 m. It shows that these structures are believed to be housed in the subsurface region controlled structurally in Northwest–Southeast, East–West and North–South direction. Also, lineament map which reveals several lineament structures trending in all directions with the prominent once trending NE–SW represents subsurface features that are controlled structurally by underlying tectonic activities responsible for mineral deposits. These mineral deposits occur as loosely stratified sources which consist of quartz, feldspar, tantalite, kaoline, marble, columbite, etc. most of these minerals are oriented in the NE–SW direction. Their direction implies that there is a presence of Northeastern movement of currents flowing for the sediments before the advent of deposition. Information about the lineament structures shows characteristics which confirm the presence of fluvialite regime for the deposition of sediments under the influence of low energy conditions and little transportation. In view of the above, the study has confirmed the presence of pegmatite rich zones and the abundance of pipe-like, cylindrical, spherical structures that act as a prospective region for mineralisation purposes. Therefore, detailed geochemical studies are required in other to know the full composition of these minerals. Also, a ground gravity survey modelling aided by Seismic survey could help understand the effects of high magnetic anomalies.

Figure 14. Rose plots of the lineament map for the study area.
which are suspected of mineral ores and hydrocarbon deposits in areas with 2.4 km sedimentary thickness.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Taofeq Olanrewaju Lawal http://orcid.org/0000-0002-8381-9294

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