Magnetic Basement Depth and Structure over Parts of Bida Basin, Nigeria Interpreted from 2-D Spectral Analysis and 3-D Euler Deconvolution

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Abstract

Background and Objective: Spectral analysis and Euler deconvolution of the residual field of the high resolution aeromagnetic data of part of Bida Basin were used to estimate the depths of anomalous magnetic sources of the area. This paper was aimed at the determination of magnetic basement depth of the area, the structural features associated with it and to infer favourable areas for possible mineral and petroleum exploration. Methods: High resolution aeromagnetic (HRAM) data of parts of Bida Basin within latitudes 8°00' N - 9°00'N and longitudes 6°30' E - 7°30'E, comprising Gulu, Koton-Karfi, Abaji and Kuje aeromagnetic sheets were acquired from the Nigerian Geology Survey Agency (NGSA). Several analytical techniques were used to digitally filter the data to improve signal-to-noise ratio. Results: The spectral analysis carried out using the residual data revealed a two layer depth model with the shallow magnetic layer depth ranging from 0.138 km to 0.935 km with an average value of 0.583 km. This depth layer is attributed to the surficial intrusion into the sedimentary fill, while the magnetic basement depth ranges from 1.86 km to 4.264 km with an average value of 2.723 km. Depth solutions using Standard Euler Deconvolution with a structural index of 0 (representing contacts) revealed depths generally below 0.250 km. The Euler deconvolution filter map was used to infer the locations as well as the depths to causative magnetic bodies using structural index 0. Structural interpretation of the HRAM data set revealed linear features with directional attributes of NW-SE, NE-SW, N-S and E-W directions with the NE-SW direction being dominant. Conclusions: The central part of the study area to its south-eastern part, especially around Abaji and environs is the most advisable area to undertake hydrocarbon exploration since the area has sedimentary thickness range of 3.3 - 4.4 km, which fall within the range of the oil window of a typical sedimentary basin. Similarly, the areas within the west and the south are potential areas of solid mineral exploration because of the shallow overburden thickness of 0.1 km.

Key words: Magnetic basement depth, Spectral Analysis, Euler deconvolution, Aeromagnetic data, Bida Basin.

INTRODUCTION

The Bida Basin, also known as the Mid-Niger Basin, is located within the West Central Nigeria. The study area is located between latitudes 8°00’N and 9°00’N and longitudes 6°30’E and 7°30’E. It is enclosed by four (4) aeromagnetic maps of the Geological Survey Agency of Nigeria with the major towns in the area including Gulu, Koton-Karfi, Abaji, and Kuje (parts of FCT). Airborne magnetic data are generally employed in mapping of fracture and fault systems of the basement rock which often controls the mineralization of any area (Ananaba and Ajakaiye, 1987; O’Leary, 1976). The contribution of airborne magnetic survey in the regional interpretation of linear features and other geological structures has been topical over the past few decades. Airborne magnetic method has therefore proven to be a veritable and potent tool for depth-to—magnetic source estimation and interpretation of geologic features that may lead to identification of mineral feed areas (O’Leary, 1976; Gunn and Dentith, 1997). Analysis of magnetic basement structures and depth can be delineated and mapped using magnetic data and have been applied in several key studies with great success (Gunn and Dentith, 1997). Within the past decades, interpretations using airborne magnetic data has moved from the study of solely regional basement structures to detailed examination of structures and lithologic variations in the sedimentary section (Opara, et al., 2012). In several basins worldwide, magnetic anomalies generally arise from secondary mineralization along the planes of fault/fractures and are most often revealed on aeromagnetic maps as surficial linear features (O’Leary et al., 1976; Ananaba and Ajakaiye, 1987; Ghazala, 1993). O’Leary et al. (1976) and Ananaba and Ajakaiye (1987), strongly suggested that most mineral deposits and their habits are generally related to some type of deformation of the lithosphere with most theories of ore formation and concentration in agreement with these tectonic or deformational concepts. Lineaments and their patterns are generally believed to be the most dominant factor controlling the occurrence of various mineral deposits worldwide (O’Leary et al., 1976; Ananaba and Ajakaiye, 1987).

Spectral analysis is very reliable for basement depth determination because its operations are carried out in the frequency domain (Telford et al., 1998). The method is therefore well established in its use in inferring depth to magnetic sources (Bhattacharya, 1966; Spector and Grant, 1970). Previous studies on the analysis of aeromagnetic data have been carried out in Bida Basin by Bemsen et al. (2013), Obi et al. (2015), Megwara and Udenso (2014), and Nwankwo et al., (2018).
Similarly, Megwara and Udensi (2014) carried out a structural analysis of the aeromagnetic data over the study area using the Werner and Euler deconvolution. The analyses which was carried out along profiles revealed depths to the magnetic sources of the range 0.01 km to 0.51 km with an average value of 0.128 km. It was also deduced that the lineament trend in the study area are mostly in the NNS–SSW and N–S directions with mineralization in the study area structurally controlled by these trends. Obi et al. (2015) did an aeromagnetic interpretation of southern Bida Basin using the Peter’s half slope and maximum slope method and revealed two depocenters at Kataerri and Datoraki with basement depths of 4.4 km and 4.8 km respectively. Bemsen et al. (2013) spectral analysis of aeromagnetic data over parts of the southern Bida Basin showed a two depth source model in the area. The deeper sources ranged from 2.81 to 3.24 km while the shallow sources ranged from 0.45 to 1.49 km with an average depth of 2.90 km. A spectral analysis of the northern Bida Basin as done by Nwankwo et al. (2008) revealed a depth range of 0.24 to 1.74 km for the shallow magnetic sources while magnetic basement depths values of 0.52 to 4.38 km were encountered close to the central parts of the basin. Structural analysis using aeromagnetic data was effectively demonstrated by similar works done by Daniel et al. (2015), Ugwuebede et al. (2013), Igwesi and Umego (2013), and Adetona and Abu (2013) within the lower Benue Trough around Nsukka, Okigwe, and Afikpo areas. Whereas in the Chad Basin, Anakwuba et al. (2011) and Chinwuko et al. (2012) carried out an in-depth structural analysis of its southern axis through the interpretation of aeromagnetic anomalies.

According to Obaje et al. (2011), the Bida Basin, also known as the Mid-Niger or Nupe Basin, is located in west-central Nigeria. The Bida basin is a NW–SE trending intra-cratonic structure extending from Kontogora in Niger State to Kogi State—slightly beyond Lokoja. The basin is bounded in the NE and SW by the basin complex and in the SE and NW by the Anambra and Sokoto basins respectively as shown in figure 1. Bida Basin is a gently down-warped trough whose origin is closely connected with the Santonian orogenic movement in southeastern Nigeria and the Benue valley, with its sedimentary fill comprising of post-orogenic molasses and thin unfolded marine sediments. The basin trends in the NW–SE direction in agreement with the NW extension of the Anambra Basin perpendicular to the main axis of the Benue Trough as shown in figure 1.

The Bida Basin and the Anambra Basin were both major depocentres during the third transgressive cycle in the late Cretaceous. Notable geologists that have worked in the area have divided this basin geographically into northern and southern Bida Basin, probably due to rapid facies changes across the basin (Obaje et al., 2004; Ojo, 1984). The northern and southern Bida Basins comprise of about 3km thick Campanian to Maastrichtian continental to shallow marine sediments. The southern Bida Basin comprises of the basal Campanian Lokoja Formation, followed by the Maastrichtian Patti Formation and then the youngest formation which is the Agbaja Formation (also Maastrichtian in age). Their lateral stratigraphic equivalents in the northern Bida Basin consist of the basal Bida Formation, then the Enagi Formation and lastly the Batati Formation (ironstone) as shown in figure 2.
Gravity studies (Ojo, 1984) carried out within the Bida Basin put the maximum thickness of the sedimentary pile at about 3.5 km in the central axis but a recent spectral analysis of the residual total magnetic field in the different sections of the basin showed an average sedimentary fill of about 3.4 km with basement depth of up to 4.7 km in the southern and central parts of the basin (Udensi and Osazuwa, 2004). In general, the depth to basement in the basin was believed to have decreased smoothly from the centre to the flanks of the basin.

In the present study however, Spectral Analysis and Standard Euler Deconvolution of the High Resolution Aeromagnetic data of the study area will be carried out to delineate the locations and depths of the anomalous magnetic sources. Similarly, the linear features and other structures associated with the study area will be delineated and its effects on mineralization in the study area will be deduced.

MATERIALS AND METHODS

Figure 3 shows the geology of the study area. It is covered by four (4) digitized high resolution aeromagnetic maps of sheets 206, 207, 227 and 228 of the scale 1:100,000, and a total area of about 12,100 km² covering the towns: Gulu, Koton-Karfi, Abaji, and Kuje (parts of FCT) respectively. These maps are among the maps flown by Fugro Airborne Surveys in 2006 and 2007 for the National Geological Survey Agency. Abuja and were acquired, analyzed, and interpreted. The aeromagnetic survey was flown along a series of NW-SE flight lines (perpendicular to dominant regional geologic strike) spaces at 500 m with 2000 m tie line spacing in the NE – SW direction. Data were recorded at very small intervals of 0.1 s each with 80 m normal flight height. The geomagnetic gradient was removed from the data using January 2005 IGRF model referenced to the World Geodetic System, 1984 ellipsoid.

The aeromagnetic maps were digitally filtered using the nonlinear filter (NLF). The nature of filtering applied to the airborne magnetic data in the present study was chosen to eliminate certain wavelengths. Analytical methods used in this study include trend surface analyses, Reduction-to-Pole, 2-D spectral inversion and 3-D Standard Euler Deconvolution. The regional gradients were removed by fitting a plane surface to the data by multi- regression least square techniques. The regional-residual separation of magnetic anomalies was carried out using the third degree trend surface analysis method (Mandal et al., 2013). Similarly, in this study, the analytical signal module in Hilbert transform was used as the basis for carrying out reduction-to-pole (RTP) transformation of the HRAM data (Mandal et al., 2013). Spectral Analysis was carried out on the residual data of the study area to estimate the shallow magnetic depth sources as well as the magnetic basement depths. Spectral analysis as a method of estimating the depths to magnetic sources is well established and therefore sufficiently understood (Spector and Grant, 1970). They show that when a statistical population of a potential field source exists at around a specific source depth, then the expression of those sources on a plot of the natural logarithm of energy against wave number is a straight line having a slope of 2z; where z is the inferred depth.

The two dimensional Fourier Transform pair may be written as shown in equation 1 (Bhattacharya, 1966; Opara, 2011)

\[ G(u, v) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(x, y) e^{-j(ux+vy)} dxdy \]  

(1a)

and

\[ g(x, y) = \frac{1}{4\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G(u, v) e^{-j(ux+vy)} dxdy \]  

(1b)

Where u and v are the angular frequencies in the x and y directions respectively. The use of this method involves issues that are inherent in the application of the Discrete Fourier Transform (DFT). These include the problem of aliasing, truncation effect or Gibbs’ phenomenon and the problem associated with even and odd symmetries of the real and imaginary part of the Fourier transform. According to Kearey et al (2002), aliasing can be overcome by having the sampling frequency of the digitized magnetic field interval to be at least twice as high as the highest frequency component present in the sampled function. The truncation effect can be reduced by applying a cosine taper to the observed data before Fourier Transform. However, in this work, these problems were taken care of by the software used in the analysis.

Finally, 3-D standard Euler deconvolution method which is based on Euler’s homogeneity equation (Equation 2) was used to estimate the depth as well as locations of anomalous magnetic bodies. The 3-D Euler Deconvolution method is used for both locating and inferring depths to subsurface geologic structures.
which give rise to magnetic anomalies. The Euler homogeneity equation is an equation that relates the magnetic field and its gradient components to the location of the source, with the degree of homogeneity n, which may be interpreted as a structural index (Thompson, 1982). The structural index is a measure of the rate of change with distance of a field. In combination, the structural index and the depth estimates have the potential to identify and calculate depth estimates for a variety of geologic structures such as faults, magnetic contacts, dykes, sills, etc (structural index 0 for contacts, structural index 1 for sills and dikes, structural index 2 for horizontal cylinders and pipes, and structural index 3 for spheres). A solution is only recorded if the depth uncertainty of the calculated depth estimate is less than a specified threshold and the location of the solution is within a limiting distance from the center of the data window (Whitehead and Musselman, 2008).

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

(2)

Where B is the regional value of the total magnetic field and \((x_0,y_0,z_0)\) is the position of the magnetic source, which produces the total magnetic field M measured at \((x,y,z)\). N is the structural index (Thompson, 1982; Reid et al., 1990). The structural index, N, is a measure of the rate of change of the magnetic field with distance from the source. In other words it is the fall-off-rate and it is inversely proportional to the source dimensions. However, in this study only structural index 0 (contacts) was used because of the predominance of magnetic contacts in the area as observed from field mapping.

**RESULTS AND DISCUSSION**

The total magnetic field intensity map of the study area is shown in Figure 4 as a contour map and is contoured in nano tesla (nT). The map revealed magnetic field intensity values of 7868-8100 nT with very high magnetic intensity values shown in the areas underlain by the migmatitic gneiss and biotite granite respectively. Similarly, figures 5 and 6 shows the first degree regional and residual fields respectively. The regional fields showed values ranging from 7925-8100 nT and generally revealed regional trends of NE-SW direction. The residual field map revealed values ranging from -92.8nT to 139.9nT indicating that extremely low magnetic residual values were observed within the southeastern section of the map and coincided with the area underlain by the Nupe Formation. Lineaments on aeromagnetic maps are very discernible and generally reveal the form and dimensions of individual structures (including folds, faults, joints, veins, lithologic contacts, and other geologic features). These lineaments and their patterns on aeromagnetic maps generally include traces of major regional lineaments, intersection of major lineaments, lineaments associated with circular features, etc (O’Leary et al., 1976; Ananaba and Ajakaye, 1987; Opara et al., 2012). Their analysis most often leads to the location of mineral deposits. Lineament analysis and structural interpretation of the HRAM data set revealed linear features with directional attributes of NW-SE, NE-SW, N-S and E-W directions with the NE-SW direction being dominant.
Spectral analysis of the residual field data was therefore carried out to estimate the depths to the anomalous magnetic sources. In this work, the study area has been divided into 16 overlapping blocks and spectral analysis done on each blocks with a window dimension of 27.5 km x 27.5 km. Fourier analysis was used to transform the digitized aeromagnetic data from the space domain to the wave number (frequency) domain where energy (or amplitude) spectral analyses were carried out. The results of the various spectral windows are shown in Table 1 below. The results of the spectral analysis of the residual field of the high resolution aeromagnetic data revealed a two-depth-source model represented as $D_1$ and $D_2$. $D_1$ represents the depths to the shallow magnetic sources while $D_2$ represents the depth to the deeper sources identified as magnetic basement depth. The shallow magnetic layer depth ranges from 0.138 km to 0.935 km with an average depth value of 0.583 km. This depth layer is attributed to the surficial intrusion into the sedimentary fill. Similarly, the magnetic basement depth ranges from 1.86 km to 4.264 km with an average value of 2.723 km. This basement depth values are associated with basement and intra-basement features and deformation.

Table 1: Summary of the spectral depths of the study area.

Fig. 7a: Coloured contour of the shallow magnetic depth (D1).

Fig. 7b: 3-D map of the shallow magnetic depth (D1).
Fig. 7c: Contour map of the magnetic basement depth (D2).

Fig. 7d: 3-D map of the magnetic basement depth (D2).
Fig. 8: Standard Euler Deconvolution Depth Solution Plot Draped on the coloured Total Magnetic Intensity Contour Map of the Study area. (Structural Index=0.0).

Figures 7a and 7c show contours of D₁ and D₂ depths which help to infer D₁ and D₂ depths at every point of the study area. Contouring was improved by the colour application on the maps of figures 7a and 7c. By this improvement, areas of high or low basement depths can be easily identified. Basin architecture and basement morphology of the study area were clearly depicted through the 3-D contour maps of the shallow magnetic depth (D₁) and the magnetic basement depth (D₂) as shown in figures 7b and 7d. From figure 7a, the shallow magnetic depth, D₁ ranges from 0.138km to 0.935km with an average depth of 0.532km as shown in table 1. From figure 7b, the 3-D map of this layer, it is not advisable to undertake solid mineral exploration in the region in between the west and the south west of the study area which falls within the koton-Karfi sheet. Though this area has D₁ depth values of 0.1 to 0.3 km which is the shallowest overburden thickness in the study area, such range of thickness of sedimentary fill is somewhat much to excavate. From figure 7c, the magnetic basement depth, D₂ is attributed to intrusions into the basement surface and ranges from approximately 1.9 km to 4.3 km with an average basement depth of 2.723km. Onyedim (2006), revealed that if the magnetic units in the basement occur at its surface then the contour of depth, D₂ will map the basin floor morphology. Figure 7d, the 3-D map of the basement magnetic depth gives the basement morphology, the host of the sedimentary fills. It is most advisable to undertake hydrocarbon exploration from the central part of the study area to its south eastern part; Abaji and environs mainly in Abaji sheet of our study area where depths of 3.3 – 4.3 km enough for petroleum geothermal window were encountered. The north eastern area of the study area is part of the basement complex from the geology map of the area in figure 3 and has D₂-depths of the range of 2.3 km – 2.7 km which makes it to be of less potential for petroleum exploration.

The Euler deconvolution map of figure 8 shows the locations and depths of subsurface anomalies using structural index 0. Solution depths to the magnetic contacts from this map were generally below or equal to 250 meters. The shallow depth solution of ≤ 250m is a pointer that the topmost Agbaja Formation is a great host of magnetic substances.

The results of this work are in line with the following works of Ojo (1984). He did a gravity study of the Bida Basin and got an estimated maximum thickness of the sedimentary sediments at about 3.5km in the central axis. Kogbe (1989), inferred that the total thickness of Cretaceous sediments in the eastern portion of southern Nigeria is about 3.3 km. Udensi and Osazuwa (2004), showed that an average sedimentary fill of the southern and central parts of the basin is about 3.4 km with basement depth of up to 4.7 km through a spectral analysis of the residual maps of the total magnetic field maps in different sections of the basin. In general, the depths to basement in the basin increase center-ward from the flanks of the basin.

Conclusion:
2-D Spectral analysis has been used to effectively estimate the shallow magnetic depth range and the deep magnetic depth range of the study area. The 3-D Euler deconvolution filter was used to infer the locations and depths to causative magnetic bodies using structural index 0. The shallow magnetic layer readings are of the depth range of 0.138 km to 0.935 km with an average value of 0.583 km, attributed to the surface intrusive and intrusion into the sedimentary fill, while the deep magnetic layer, the magnetic basement surface, is of the depth range of 1.86 km to 4.264 km with an average value of 2.723 km.

Furthermore, the study shows that the area in-between the west and the south west of the study area play host to the shallowest depths to the intrusive and intrusions but it is not advisable to undertake solid mineral exploration in this area because of the overburden thickness above 0.1 km is much for excavation. The central part of the study area to its south-eastern part, Abaji and environs is the most advisable area to undertake hydrocarbon exploration since the area has magnetic basement depth range of 3.3 – 4.4 km, which fall within the range of oil window of a typical sedimentary basin. The Euler deconvolution filter map shows solution depths to the magnetic contacts to be generally below or equal to 250 meters. The shallow depth solution is a pointer that the topmost Agbaja Formation is a great host of ironstones.

Future Studies:
Solid mineral and hydrocarbon exploration require precise information for intensive and cost effective exploration. In future works, it is suggested to identify more precisely the location of the geologic structures responsible for the magnetic anomalies by the use of located Euler deconvolution and higher structural indices of 1 – 3. Located Euler deconvolution is a combination of standard Euler deconvolution and analytic signal filter maps. Ground magnetic survey and possibly reflection seismic survey are recommended within the Ajaji area, central of Abaji sheet, to ascertain the thickness of about 4 km sedimentary fill for better oil exploration.
REFERENCES


