



RESEARCH PAPER

## Geophysical Interpretation of Ground Magnetic Data over some Northern parts of the Bida Basin, North Central Nigeria

<sup>1</sup>Tsepav, M.T. and <sup>2</sup>Mallam A.

<sup>1</sup>Department of Physics, Ibrahim Badamasi Babangida University, Lapai, Nigeria

<sup>2</sup>Department of Physics, University of Abuja, Abuja, Nigeria

### ABSTRACT

Total magnetic field intensity data was acquired on the ground using the G5 Proton precession magnetometer in seventeen different locations on at least, four E-W or N-S traverses at station spacing of between 9.0m and 90m along each traverse. Diurnal correction was first applied, after which the Savitzky-Golay smoothing and filtering techniques were applied to smoothen and filter unwanted signals. Regional Magnetic Field Intensity was also calculated for each of the surveyed areas using the World Magnetic Model calculator and then removed from the smoothed data to obtain the residual magnetic field. The raw data, diurnal corrected data and the diurnal corrected-filtered data as well as the residual magnetic anomaly were plotted as contour maps for a qualitative interpretation while the residual anomalies were plotted against the distances traversed on each profile for a qualitative interpretation. The results of these interpretations revealed the residual magnetic intensity values ranging from -277.59 in Batati to 165.84nT in Babban Rami. The negative magnetic values were attributed to thick overburden while the positive values were ascribed to shallow overburdens except where magnetic ironstones were responsible for such high values. The depths to basement rocks varied from 0.0012km in Sakpe to 2.545km in Enagi with an average depth of 135m..

**Keywords:** Ground Magnetic Survey, OriginPro8, Residual Anomaly, Smoothing, Filtering Depth to Basement.

### INTRODUCTION

Mathematical models for the earth's magnetic field showing its shape and intensity across the surface of the earth have been developed, and the target of magnetic surveys is usually to bring out the unexpected anomalies from such models. A high magnetic anomaly indicates that the measured field strength is higher than the predicted value by the global model, while a low magnetic anomaly shows that the measured field strength is lower than the value predicted by the global model (Mariita, 2009).

Anomalies in the earth's magnetic field are caused by the differences in the magnetisation of rocks in the Earth's crust and could be of remanent or induced nature. According to Mariita, (2009), sedimentary rocks generally have a very small magnetic susceptibility compared to igneous or metamorphic rocks, which tend to have much higher magnetite content. Most magnetic studies are planned to map the geologic structures in the basement rocks which are the crystalline rocks that lie beneath the sedimentary layers or to detect magnetic minerals directly.

Magnetic survey is therefore aimed at investigating subsurface structures on the basis of the anomalies in the earth's magnetic field resulting from the magnetic properties of the underlying rocks. Generally, the magnetic susceptibility of rocks varies according to the type of rocks therefore for rocks with high magnetic susceptibilities; the local magnetic field will be strong. On the other hand, where they have low magnetic susceptibilities, the magnetic field will be weak.

Nigeria has enormous mineral resources that are fairly distributed and if genuinely utilized, the economy will be boosted. One of the ways of achieving this task is to harness the abundant natural resources that abound in most parts of the country. The depleting nature of the existing petroleum reservoir and hence the products

Received 29 October, 2016

Accepted 02 December, 2016

Address Correspondence to:

[tsemato@yahoo.com](mailto:tsemato@yahoo.com)

derived from it is also a point of concern, as there is the possibility that the existing quantity may be exhausted in the nearest future. There is, therefore, the need to explore for more reserves of hydrocarbon to complement and supplement the existing quantity. Consequently, a proper geophysical prospecting which would be aimed at ascertaining the presence of these minerals and the associated geomagnetic features and determining whether or not they are in commercial quantities, and subsequent exploitation is of paramount interest. The research therefore, aims at carrying out a geophysical interpretation of the total magnetic intensity over some parts of the Northern Bida Basin of Nigeria with a view to evaluating the depth to basement rocks that trigger magnetic anomalies in the area and identifying the causative objects of the magnetic anomalies and their extent for informed deductions.

Bida Basin is located predominantly in Niger State of Nigeria with extensions into Federal Capital Territory, Abuja, Kwara and Kogi States. The region is endowed with abundant mineral resources and there is also the likelihood of hydrocarbon and hence petroleum occurrence in the basin (Obaje, 2009). Figure 1 shows the geology and location map of the Bida Basin and its surrounding environment.

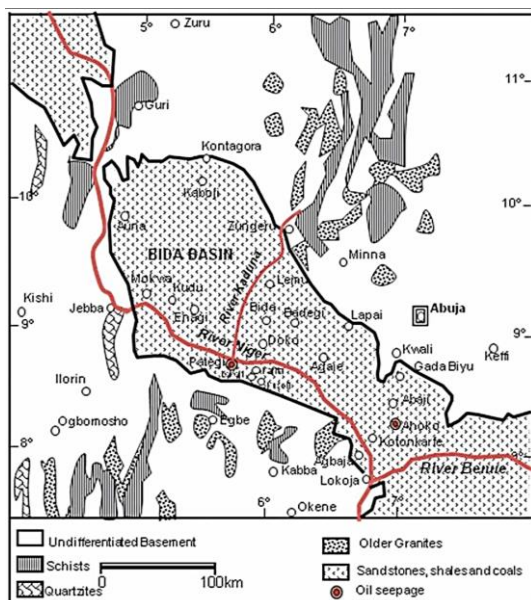


Figure 1: Geology and Location Map of Bida Basin and its Surroundings (Obaje, 2013)

Geophysical works have been conducted in the basin using magnetic and other methods.

Udensi, and Osazuwa, (2004) used statistical analysis to estimate the average depth to basement to be 3.39km with a maximum depth of 4.5km. Ojo, and Ajakaiye, (1989) delineated the presence of a positive gravity residual centre in the basin. They attributed this to the presence of a shallow metamorphic basement of high density and intermediate composition which they deduced was probably of schist. They also observed negative anomalies which were ascribed to relatively great thicknesses of sediments. The area was estimated to be of low sinking with maximum thickness of sediments lying between 1.0 km and 2.0 km. Ojo, (1990) investigated a major east-west magnetic low whose deep seated structures dominate the southern part of the basin. The depths to basement varied between 4.0km and 6.0km. Udensi, (2001) identified the landward prolongation of St. Paul and Romanche fracture zones as lineaments passing through the northern and southern parts of Bida basin. In the spectral determination of depths to magnetic rocks in the Bida Basin, Udensi and Osazuwa (2004) were able to corroborate the interpretations of Ojo (1984) and Ojo and Ajakaiye (1989) that outlined the basin as being bounded by a system of linear faults. Olaniyan *et al.*, (2012) used manual and automatic depth estimation methods to determine the depth to basement within the Bida basin to be generally shallow with depths between 1km and 1.50km with some deep pockets around Mokwa, Kudu, Kotonkarfe, Auna, Akerre and Bida, ranging from 2.50km to 3.75km which could be reservoirs for hydrocarbon potentials. Ofor *et al.*, (2014) carried out a study of Pategi and Egbako areas of the lower Bida basin and revealed two prominent layers; with average values of 0.59km and 3.1km. Megwara, and Udensi, (2014) also carried out structural analysis using aeromagnetic data over parts of southern Bida basin and the surrounding basement rocks to highlight trend characteristics of magnetic lineaments and determine the depth to magnetic sources which they found to be within the range of 0.01km to 0.51km with an average value of 0.128km.

### Geology of the Study Area

The geology of Nigeria, as recorded in Obaje, (2009), consists of three major litho-petrological components: the Basement Complex, the Younger Granites, and the

Sedimentary Basins. The Basement Complex, which is of Precambrian age is made up of the Migmatite-Gneiss Complex, the Schist Belts and the Older Granites; the Younger Granites comprise several Jurassic magmatic ring complexes centered on some parts of north-central Nigeria, while the Sedimentary Basins, containing sediment-fill of Cretaceous to Tertiary ages comprise the Niger Delta, the Anambra Basin, the Lower, Middle and Upper Benue Trough, the Chad Basin, the Sokoto Basin, the Mid-Niger (Bida-Nupe) Basin and the Dahomey (Benin) Embayment (Obaje, 2009). Figure 2 is the geological map of Nigeria showing the various geologic formations.

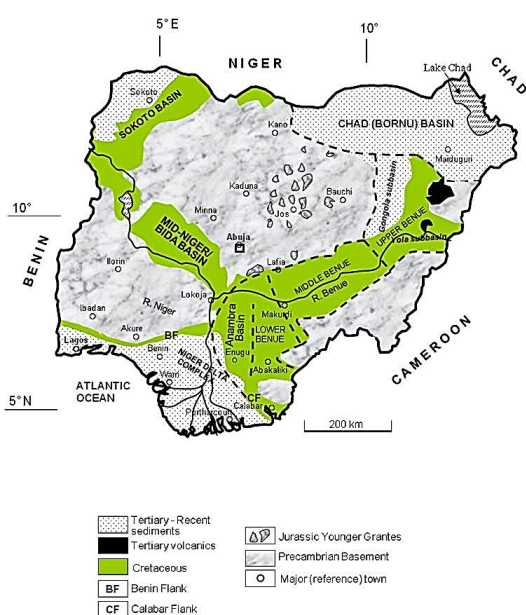


Figure 2.2: Geological map of Nigeria showing the major geological components (After Obaje, 2009).

The Bida Basin is divided into North and South. The Northern Bida Basin, where the study area is located, consists of four formations: the Bida formation which was produced during the Campanian and the Sakpe, Enagi and Batati formations which were created during the Maastrichtian. The Bida Formation, also called the Bida Sandstone is divided into two members, namely the Doko Member and the Jima Member. Adeleye (1974) reported that the Doko Member is about 183m thick and shows localized development of cross-stratification. The Jima Member, according to him, is about 90m thick and predominantly sandy with extensive cross-stratification. The Doko Member, located 16km south of Bida is the basal unit and consists of 80m of massive

and flat bedded arkoses and coarse to medium sandstone with breccia horizons (Olaniyan *et al.*, 2012).

The sandstones of the Jima Member (Jima Sandstone subfacies), according to Adeleye (1989), are dominantly quartzose, non-arkosic and brownish. Thin intercalations of poorly sorted, hard, whitish, argillaceous sandstones are locally present in the lower parts of the Jima subfacies.

The Sakpe Formation comprises mainly oolitic and pisolitic ironstones with sandy claystones locally, at the base, followed by dominantly oolitic ironstone which exhibits rapid facies changes across the basin at the top (Adeleye, 1973).

The Enagi Formation as described by Obaje, (2009), on the other hand, consists mainly of siltstones and correlates with the Patti Formation in the Lokoja sub-Basin. The Batati formation constitutes the uppermost units in the sedimentary sequence of the Bida Basin. It consists, according to Obaje, (2013), of argillaceous, oolitic and goethitic ironstones with ferruginous claystones and siltstone intercalations and shaly beds.

## METHODOLOGY

The magnetic field generated by current is characterized by the magnetic induction,  $\mathbf{B}$  (Tesla); but when the field passes through magnetic materials which also contribute their internal magnetic fields, ambiguities can arise about which part of the field comes from the external currents and which comes from the material itself. If  $\mu$  is the permeability of the material, then for a medium, other than vacuum, the strength of the field varies with the type of material and  $\mathbf{B}$  is related to the magnetic field strength,  $\mathbf{H}$  through the relation:

$$\mathbf{B} = \mu \mathbf{H} \quad (1)$$

But  $\mu = \mu_0 \mu_r$   
where  $\mu_r$  and  $\mu_0$  are the relative permeability of the medium and the permeability of free space respectively.

$$\therefore \mathbf{B} = \mu_0 \mu_r \mathbf{H}$$

This can be written in the form:

$$\mathbf{B} = \mu_0 \mathbf{H} + \mu_0 (\mu_r - 1) \mathbf{H} \quad (2)$$

If the material does not respond to the external magnetic field by producing any magnetization, then  $\mu_r = 1$  and

$$\mathbf{B} = \mu_0 \mathbf{H}$$

The implication is that to obtain a flux density,  $\mathbf{B} = \mu \mathbf{H}$ , an additional field strength induced by  $\mathbf{H}$  is needed. Therefore

$$\mathbf{B} = \mu \mathbf{H} = \mu_0 (\mathbf{H} + \chi \mathbf{H})$$

$$\text{or } \mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M}) \quad (3)$$

where  $\mathbf{M} = \chi \mathbf{H}$  is the induced flux density known as the intensity of magnetisation.

The magnetic susceptibility,  $\chi$  determines the degree of magnetization of a material in response to an applied magnetic field.

The Earth's magnetic field is understood to consist of two parts with the larger component believed to originate from convection of liquid iron in the Earth's outer core (Campbell, 1997). It is monitored and studied using a global network of magnetic observatories and various satellite magnetic surveys (Langel and Hinze, 1998). According to Nabighian *et al.*, (2005), this field changes slowly with time and is believed to undergo collapse, often followed by reversal, on a time scale of about  $10^5$  years. The other part comes from the interaction of the ionosphere with the solar radiation. Figure 3 shows the world's geomagnetic map indicating the contoured total magnetic field intensities across the continents and oceans.

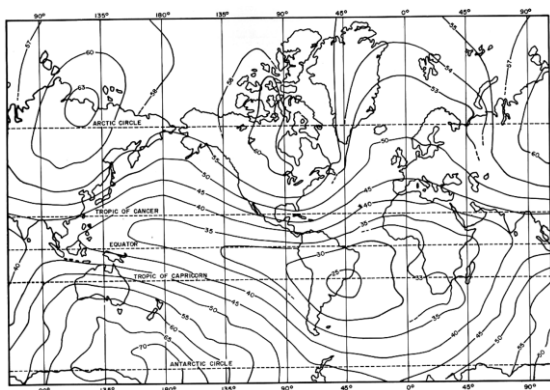


Figure 3. World geomagnetic Field Intensity [ $\times 10^3$ ] nT (After Roux, 1980)

The magnetic scalar potential,  $A$  due to a continuous distribution of matter in a medium like the Earth could be calculated at an external point,  $P$  as shown in Figure 4.

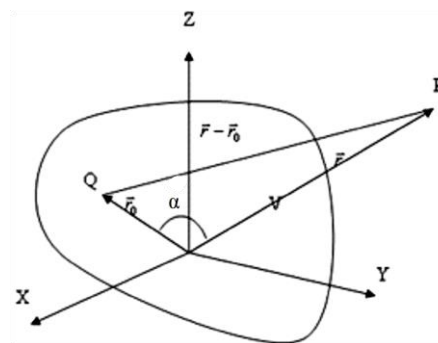


Figure 4: Magnetic scalar potential (Parasnis, 1986).

If, in Figure 4, the material that fills the volume,  $V$  has a continuous distribution of magnetic dipole moment per unit volume, then it can be shown that for  $P$  enclosed within  $V$ , the magnetic potential  $A$  is:

$$A = - \int_{V-V'} \mathbf{J} \cdot \nabla \left( \frac{1}{r-r_0} \right) d^3 r_0 - \int_{V'} \mathbf{J} \cdot \nabla \left( \frac{1}{r'-r_0} \right) d^3 r_0 \quad (4)$$

where  $\mathbf{J}$  is the current density.

The first term is nonsingular, therefore it is harmonic everywhere.  $\mathbf{J}$  may be made constant by making  $\mathbf{r}'$  small enough in the second term.

$$\Rightarrow \nabla^2 \cdot A = - \int_{V'} \nabla \cdot \mathbf{J} \cdot \nabla \left( \frac{1}{r-r_0} \right) d^3 r_0 \quad (5)$$

Using Gauss Theorem,

$$\nabla \cdot A = - \int_s \nabla \cdot \mathbf{J} \cdot \hat{n} \cdot \nabla \left( \frac{1}{r-r_0} \right) d^2 r_0 \quad (6)$$

$$\therefore \nabla \cdot A = 4\pi \nabla \cdot \mathbf{J} \quad (7)$$

Equation (7) is the required potential equation within regions occupied by magnetic bodies.

Several methods of analyzing magnetic data abound. For instance, Nabighian (1974) developed the concept of two dimensional analytic signal also referred to as energy envelope of magnetic anomalies. Roest *et al.* (1992) showed that the amplitude of the three dimensional analytic signal at location  $(x, y)$  can be derived from the three orthogonal gradients of the total magnetic field using the Equation:

$$|A(x, y)| = \left[ \left( \frac{dT}{dx} \right)^2 + \left( \frac{dT}{dy} \right)^2 + \left( \frac{dT}{dz} \right)^2 \right]^{\frac{1}{2}} \quad (8)$$

where  $|A(x, y)|$  is the amplitude of the analytic signal at  $(x, y)$ ,  $T$  is the observed magnetic field at  $(x, y)$ .

The analytic signal anomaly over a two dimensional magnetic contact located at  $(x = 0)$  and at depth,  $h$  is described according to Nabighian (1972) as:

$$|A(x, y)| = \alpha \frac{1}{(h^2 + x^2)^{\frac{1}{2}}} \tag{9}$$

The constant,

$$\alpha = 2M \sin D (1 - \cos^2 \{I\} \sin^2 \{A\}) \tag{10}$$

represents the amplitude factor and

$h, M, D, I,$  and  $A$  respectively represent the depth to the top of the contact, the strength of magnetization, the dip of the contact, the inclination of the magnetization vector and the direction of the magnetization vector.

The analytic signal described by Equation (9) is a bell shaped function with the directional terms contained in the amplitude factor  $\alpha$  (MacLeod, *et al.*, 1993). The shape of the analytic signal is dependent only on depth (MacLeod *et al.*, 1993) and hence it can be shown that the analytic signal over a two dimensional magnetic dike can be described by the equation:

$$|A(x, y)| = \alpha \frac{1}{(h^2 + x^2)} \tag{11}$$

Parasnis, (1986) developed a depth determination method which aims at asymmetric profiles but simplifies tremendously for a symmetric profile. The method adopts the analytic signal method by making use of the properties of the bell-shaped anomaly curve to determine the depth to such anomalous bodies. According to this method, for an asymmetric profile, the depth to the top of a magnetic anomaly is:

$$z = \sqrt{(-x_1 \cdot x_2)} \tag{12}$$

where  $x_1$  and  $x_2$  are respective distances from the horizontal zero line to the minimum and maximum peaks of the anomaly considered as shown in Figure 5(a).

For a symmetric anomaly, the depth becomes half of the width of the anomaly at half the maximum value Figure 5(b)

$$z = \frac{w}{2} \tag{13}$$

where  $w$  is the full width at half maximum.

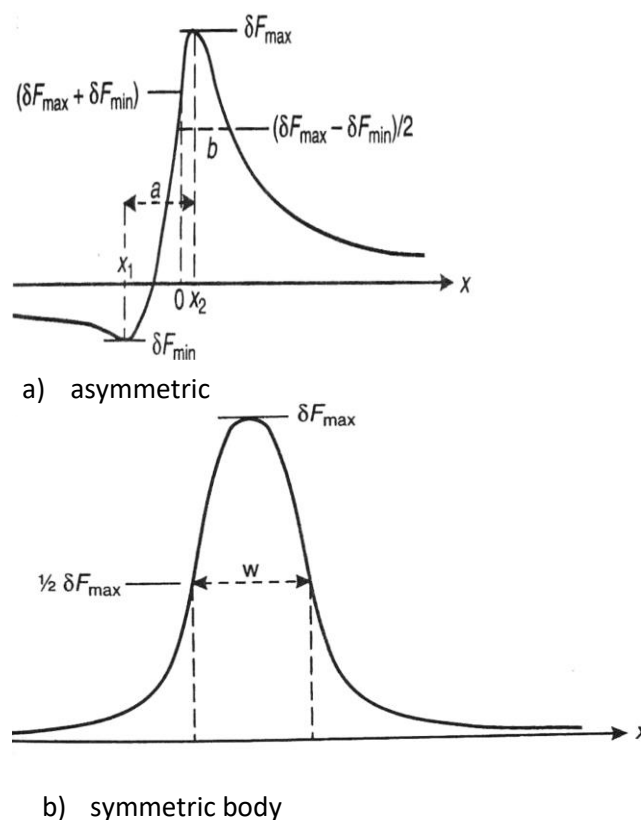


Figure 5: Parasnis' method of determining the depth to the top of symmetrically and asymmetrically magnetized body (Reynolds, 1987)

When the anomaly becomes symmetric, it approximates a Gaussian function which is represented by the equation of a normal curve of the form:

$$y = y_0 + \frac{A}{w_1 \sqrt{\frac{\pi}{2}}} e^{-2\left(\frac{x-x_c}{w_1}\right)^2} \tag{14}$$

where:

$y_0$  = offset,  $x_c, y_c$  = centre of the normal curve,  $A$  = area and  $w =$  width of the Gaussian  
 Anomaly =  $\frac{w}{\sqrt{\ln 4}}$

where  $w$  is the full width at half maximum (FWHM) which is the parameter of interest in depth determination using Parasnis' method.

**Data Collection**

The G5 Geotron proton precession magnetometer was used to measure the total magnetic field in seventeen (17) different places within the Bida basin of Nigeria The areas covered were Pattishabakolo, Doko, Batati, Jima, Kutigi, Sakpe, Atsu-Gulu, Muye,

Ekpagi-Agaie, West Bida, Enagi, Lemu Wushishi, Kontagora, Babban Rami, Makera and Mokwa. Four (4) traverses running East - West or North – South, depending on the orientation of the geologic features, were established in a grid of varying dimensions across these locations. The measurements were carried out along the traverses at station spacing varying from 9.0m to 90.0m depending on the extent of the geologic object of interest. The total magnetic field measurements were acquired with the sensor held on a 2m pole above the ground at every measurement together with the time of measurement and coordinates of the station. The Garmin Oregon 550 GPS was used to measure the coordinates of the stations as well as to ensure that the profiles were straight and as nearly parallel as possible.

The first station on each traverse was taken as the base station for every area surveyed, and due to the large size of the survey, the base station was re-occupied to repeat the measurement at the end of readings for every two consecutive traverses. Field notes were taken of the coordinates and features of geologic interest while total magnetic field intensity readings as well as date and time of measurements, signal strength, line number, station number and total number of readings were recorded in the magnetometer's memory for subsequent retrieval.

### Data Analysis

Origin Pro8 software was used in the data processing and interpretation. It is a contouring, graphing and statistical package developed by OriginLab Corporation, Northampton, USA and can be used for generating maps, graphs, matrix conversion and gridding; regression, curve fitting and for mathematical and statistical operations. Other functions of the software include signal processing like data smoothing and filtering as well as image processing and analysis.

The data was first corrected for diurnal drifts after which smoothing was applied to the resulting data to remove unwanted signals using OriginPro8 Software. Because of its superiority over other methods such as the Fast Fourier Transform and Adjacent Averaging methods, the Savitzky-Golay filter method of OriginPro 8 which performs a local polynomial regression

around each data point and creates a new, smoothed value for each data point was used in data filtering. The method tends to preserve features of the data, such as peak height and width.

To obtain the residual magnetic anomalies, the regional effects were removed from the diurnal-corrected filtered total magnetic field intensity. This was done by first finding the average International Geomagnetic Reference Field (IGRF) for each of the survey sites using the World Magnetic Model (WMM) calculator developed by Noah Hassler (2015), and then subtracting the resulting value from each data point.

The residual magnetic anomalies were contoured and then plotted against the distances traversed. To evaluate the approximate depths to magnetic basement, the residual anomaly curves were gauss fitted either in linear or multi peaks mode depending on the identified anomalous peaks.

## RESULTS AND DISCUSSION

The total magnetic field intensity data covering the surveyed areas is presented in the form of contoured magnetic map in Figure 6. The diurnal-corrected and diurnal corrected-filtered total magnetic field intensity data were also contoured as shown in Figures 7 and 8 respectively. Figure 9 is the 2D contour map of the residual magnetic anomaly over the surveyed area while the 3D view of the residual magnetic anomaly is shown in Figure 10. Figures 11 (a) – (c) show the graphs comparing the diurnal-corrected total magnetic field intensity (DC) to diurnal-corrected-filtered total magnetic field intensity (DCF) for some profiles in the areas surveyed. This is important as the effects of the filtering clearly bring out the true shape of the anomalous structures. Figures 12 (a) – (c) represent some of the gauss fitted profile plots. The results of the fitting were the generation of the full width at half maximum which, according to Parasnis, (1986), when halved, gives the approximate depth to basement.

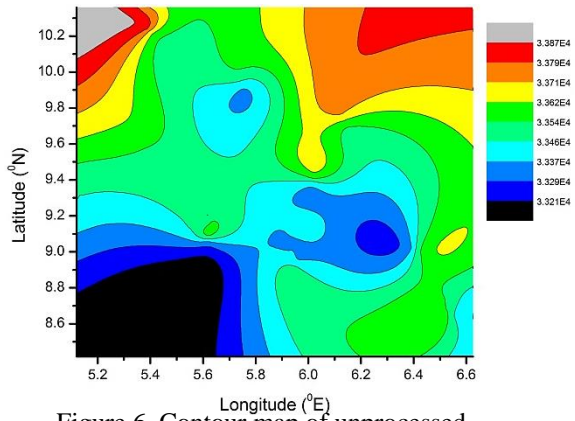


Figure 6. Contour map of unprocessed Total Magnetic Field Intensity

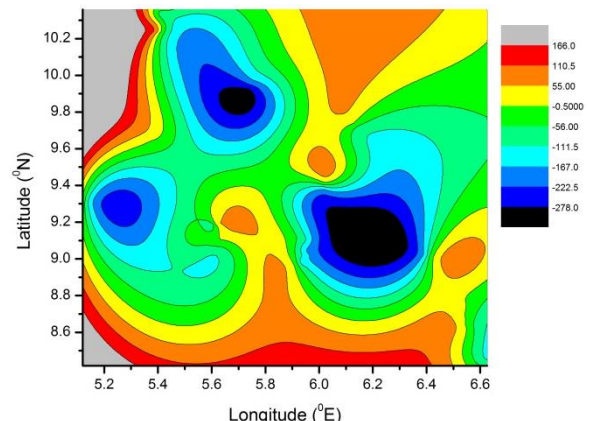


Figure 9: Contour map of Residual Magnetic Field Intensity

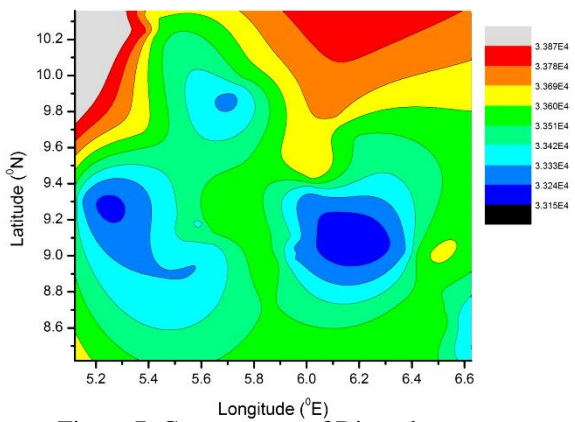


Figure 7. Contour map of Diurnal - Corrected Total Magnetic Field Intensity

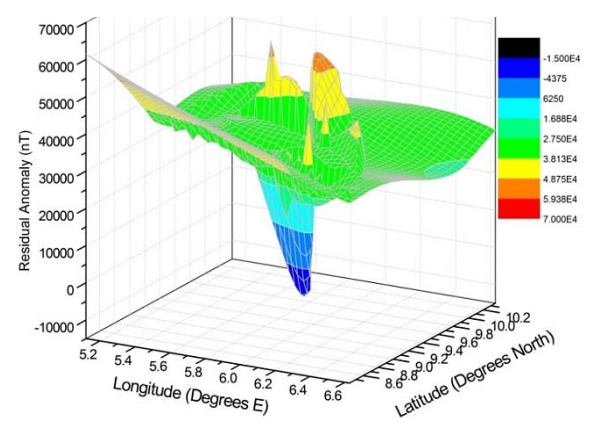


Figure 10: 3D Surface Map of the Residual Magnetic Anomaly in the Survey Area.

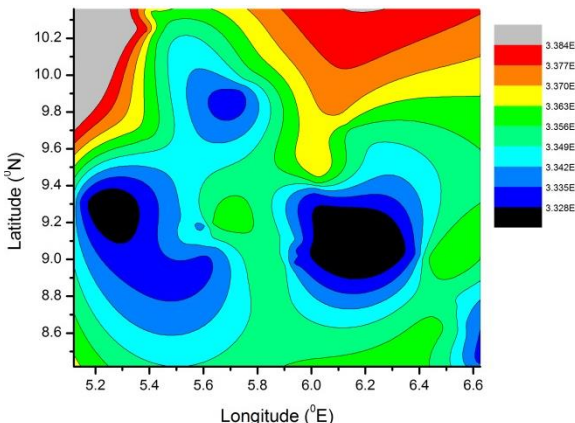


Figure 8. Contour map of Diurnal - Corrected-Filtered Total Magnetic Field Intensity

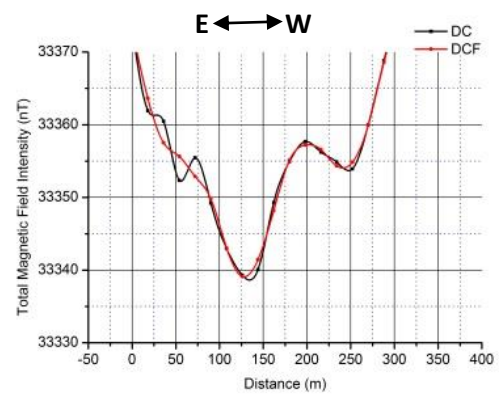


Figure 11(a): DC and DCF for Profile 3 in Pattishabakolo

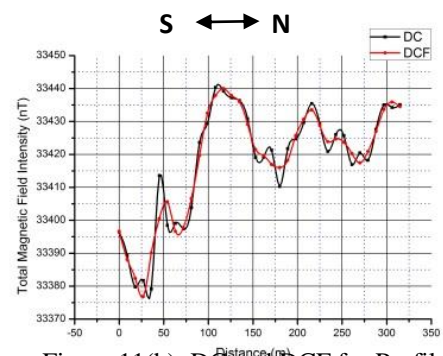


Figure 11(b): DC and DCF for Profile 3 in Batati

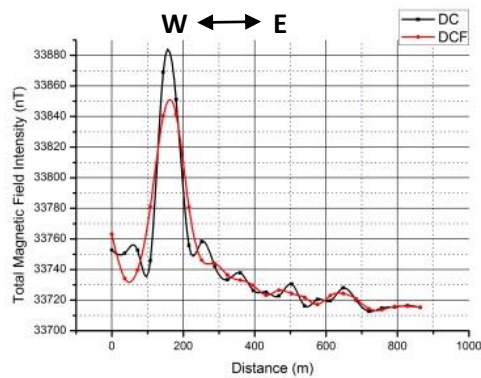


Figure 11(c): DC and DCF for Profile 1 in Babban Rami

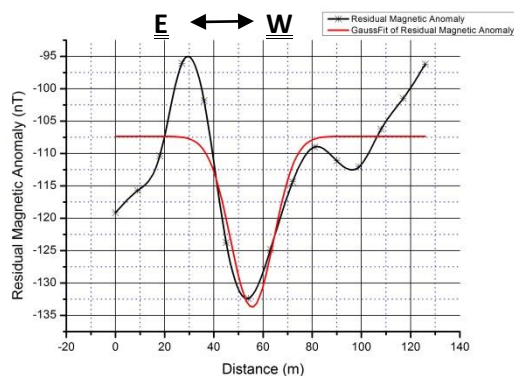


Figure 12 (a): Residual Anomaly graph for Profile 6 in Pattishabakolo

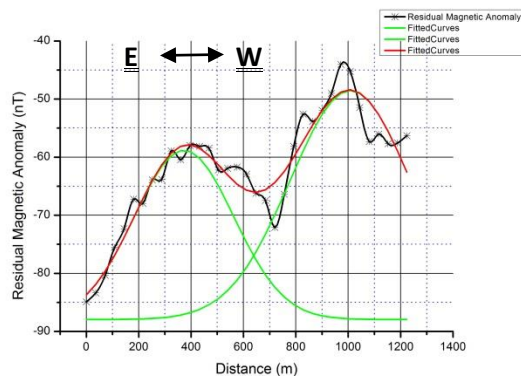


Figure 12(b): Residual Anomaly graph for Profile 4 in Kontagora

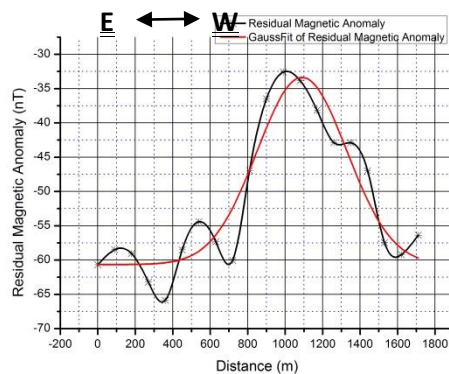


Figure 12 (c): Residual Anomaly graph for Profile 2 in Sakpe

## DISCUSSION

The structural trends shown by the presence of the fractured zones on the map, which are also evidently revealed on the profiles point to the fact that the surveyed area might have been subjected to intense tectonic activities as suggested by Adepelumi *et al.*, (2008). These features are also visibly shown on the 3D surface map. Features such as dykes, fractures, shear zones and/or faults are visible expressions of residual forces produced after rocks have been subjected to deformation, and they also serve as confirmation of occurrence of tectonic events in an area.

Out of the eight traverses made in Pattishabakolo, magnetic anomaly amplitudes in the area were generally negative, ranging from -192.77nT on profile 2 to -91.43nT on profile 7. The lowest magnetic anomaly values were observed along traverses 1, 2, 3 and 5 and might be the result of deep seated basement rocks, since the overlay in the area is reported by Obaje, (2013) to be predominantly of nonmagnetic sediments. These zones may have been heavily fractured, jointed and/or sheared, and may contain grabens with sediment fills similar to those reported by Oga and Mamah, (2014).

Traverses along the profiles in Doko showed negative magnetic anomalies ranging from a minimum value of -150.11nT to a maximum of -82.50nT. Magnetic signatures of noticeable geophysical concern were observed along traverses 1, 2 and 3 which indicated some relative anomalous magnetic highs that could be attributed to uplifts of denser rock in structures such as anticlines, reverse faults or horsts.

The profiles in Batati present magnetic anomalies that portray the area as the deepest among the areas surveyed in the basin, as the highest negative values were noticed between the range of -277.59nTon profile 4 and -200.83nT on profile 1. Obaje *et al.*, (2013) has however, reported the area to contain ironstones, a fact that could have made the anomalies to be positive, but the reverse is the case. The implication is that the depth to basement here would have been deeper were it not for the magnetic ironstones. The iron contents might have increased the magnetic anomalies and therefore appeared to have



reduced the thickness of the overburden. Profile 1 has shown a signature that could conveniently be described as a vertical fault at around 40m to 50m when moving in the S-W direction.

Jima area has magnetic anomalies range of between -134.48nT and -39.53nT on profiles 4 and 2 respectively. The anomaly values here are all negative, indicating that the area has a very thick overburden. This discerning fact derives its support from reports by Nwajide, (2013) and Obaje *et al.*, (2013) who reported the geology of the areas as comprising non-magnetic sandstones of the Bida formation, as well as field observations which revealed the nonmagnetic sandstones. Relative magnetic anomaly highs were observed on traverses 2, 3 and 4 at about 140m, 80m and 30m respectively in the N –S direction.

Kutigi and Babban Rami had a similar distribution of magnetic anomalies, having negative values as minimum and positive values as maximum. The lowest recorded magnetic anomaly in Kutigi was -213.51nT on profile 2 while the highest value was 155.28nT on profile 3 with each of the profiles showing some positive magnetic anomalies at one point or the other. While profile 3 exhibited virtually positive magnetic anomaly values, others showed both negative and positive values. In Babban Rami, the minimum magnetic anomaly value was observed at the beginning of profile 4 as -7.07nT while the maximum value of 165.84nT was noticed at profile 1. Profiles 1 and 4 had only positive values while profiles 2 and 3 had both negative and positive magnetic anomalies. It has been reported by Nwajide, (2013) that Kutigi member belongs to the Batati upper ironstone formation and this might likely be the reason for the overtly high magnetic anomaly values experienced within the region. It is also likely that the Babban Rami area might be the extension of the Kutigi member of the Batati ironstone. When compared to the magnetic anomalies in Batati, it would be noticed that the anomaly values in Kutigi and Babban Rami are higher, a fact that could be attributed to the level of ferruginisation of the ironstones which might be higher in these areas than in Batati.

Adeleye, (1974) and Nwajide, (2013) described Sakpe area as consisting of the lower ironstones of the Campanian age. The presence of these ironstones coupled with great depths to

basement rocks might have been largely responsible for the relatively low negative magnetic anomalies observed in the area. The magnetic anomalies in this region ranged from a minimum value of -66.74nT on profile 1 to a maximum value of -10.74nT on traverse 4. It is very likely that the overburden thickness in this area is great but could not be exactly ascertained based on magnetic observations because of the magnetic minerals present in the ironstones which gave rise to the observed magnetic signatures.

The Atsu area, near Gulu, along Gulu - Baro road showed some negative and positive magnetic anomalies on profiles 1 and 2 while profiles 3 and 4 showed only positive magnetic anomalies. The minimum magnetic anomaly value was observed on profile 2 to be -46.54nT while a maximum of 48.39nT was observed on profile 4. The area is thought of as being an extension of the Sakpe lower ironstone as reported in Nwajide, (2013), so the positive values here may not necessarily mean that the area has a shallow depth to basement as a result of the underlying rocks being non-magnetized but for the fact that the area is underlain by ironstones which have magnetic minerals.

At Muye, the residual magnetic anomalies varied from -114.39nT to -11.16nT on profile 1. The discernably negative values could be as a result of the underlying rocks being non-magnetized and hence suggesting that the overburden is of great thickness. No visible exposures of rocks were observed in the area, however, clayey to sandy environments were discerned which are non-magnetic and might likely be responsible for the low anomaly values.

Ekpagi, near Agaie and Bida West showed some striking semblances in the residual magnetic anomaly values distribution in the sense that they both have high minimum negative anomalies and low negative maximum anomalies. While Ekpagi had a minimum magnetic anomaly value of -203.42nT and a maximum of -60.98nT, Bida West had minimum and maximum values of -187.93nT and -83.84nT respectively. These areas are reported by Nwajide, (2013) to be dominated by the about 80m thick Bida sandstones of the Campanian age. These sandstones are likely the thick un-magnetic overburden that gave rise to the negative magnetic anomalies in these areas.

Enagi, Lemu and Kontagora exhibited negative minimum residual magnetic anomalies of -61.07nT, -131.46nT and -91.22nT respectively, with maximum negative corresponding values of -14.65nT, -19.48nT and -15.93nT. While Enagi area has been reported by Nwajide, (2013) to consist of non-magnetic, 70m thick, siltstones which might be responsible for the low magnetic anomalies recorded in the area, the low magnetic anomaly values observed in Lemu area may likely be the result of the overlay which comprised the coarse grained sandstones which had a little iron impregnation. Kontagora area, according to Obaje, (2009), borders the Precambrian Basement Complex and the overlying Cretaceous sediments. Even though the area surveyed had exposures of sandstones, there is the likelihood that the depth to basement is shallow which might be the possible reason for the low negative residual magnetic anomalies range from -91.22nT to -15.93nT.

The rock formations noticed in Wushishi area of the Basin indicate that the area could lie on the boundary between the Precambrian Basement Complex and the overlying Cretaceous sediments as quartzite which is of basement origin and Schist which is a metamorphic rock were noticeably present. This might be the cause of the generally low magnetic anomalies and the positive anomalies witnessed in the area. Profiles 2, 3 and 4 revealed magnetic anomalies between about -35nT to 30nT, an indication that the depth to basement in the area is likely shallow and a likely confirmation of the fact that the area is close to the basement complex as indicated on the geologic map of the Basin. On profile 1 of the area, the minimum and maximum magnetic anomaly values of -140.16nT and 54.26nT were respectively observed at about 750m and 300m in the E-W direction. This sharp variation on a single profile might be due to a dyke or a channel. The presence of a N-S stream noticed around might give credence to this assertion.

Makera area showed entirely positive magnetic anomalies ranging from 7.76nT to 36.17nT. Though there were no visible rocky exposures to be identified for confirmation of the types of rocks likely to be present in the area, the area is thought of as being an extension of the Bida sandstone but with claystones overlay. The positive magnetic anomalies observed are a

clear indication that the area has a shallow depth to basement.

Mokwa area had a minimum magnetic anomaly of -68.18nT and a maximum value of 11.84nT which were obtained on traverses 4 and 1 respectively. Normal folding and/or faulting signatures were generally observed on the profiles except that profile 3 showed a distinct insignia of a sharp dislocation around 400m in the N-S direction which might be due to a vertical fault.

The maps in Figures 6, 7 and 8 generally show the same trend except for the fact that the magnetic features are enhanced by the diurnal correction and filtering processes. Figure 9 also shows striking similarities with the observed trends but it brings out the magnetic anomalies more succinctly.

From Figure 8 three deep areas were discerned on account of their low total magnetic field intensity values. They are areas bounded by latitude 8.74<sup>0</sup>N and 9.42<sup>0</sup>N and longitude 5.92<sup>0</sup>E and 5.40<sup>0</sup>E; latitude 8.60<sup>0</sup>N and 9.50<sup>0</sup>N and longitude 5.20<sup>0</sup>E and 5.70<sup>0</sup>E as well as latitude 9.62<sup>0</sup>N and 10.00<sup>0</sup>N and longitude 5.52<sup>0</sup>E and 5.80<sup>0</sup>E. In Figure 9, the magnetic anomalies are clearly isolated from the regional field with the low anomaly values shown between latitude 8.80<sup>0</sup>N and 9.46<sup>0</sup>N and longitude 5.96<sup>0</sup>E and 6.40<sup>0</sup>E; latitude 9.10<sup>0</sup>N and 9.40<sup>0</sup>N and longitude 5.20<sup>0</sup>E and 5.40<sup>0</sup>E and latitude 9.64<sup>0</sup>N and 10.22<sup>0</sup>N and longitude 5.50<sup>0</sup>E and 5.85<sup>0</sup>E. On the mineral resources map of Nigeria developed by the Nigerian Geological Survey Agency (NGSA), 2005, these areas are predominated by claystones, sandstones and siltstones which contain non-magnetic minerals such as quartz, feldspar, silica, calcite clay, dolomite and micas which might be responsible for the low magnetic intensity values.

Areas with large negative magnetic anomaly values might also be associated with weak zones, faulting and/or shearing, which may be favourable to hydrogeological prospectivity and for hydrocarbons search. The areas where ironstones were identified such as areas around Sakpe and Batati could be further surveyed for iron ores that can be used for the production of steel and iron. Magnetic minerals such as limonite, hematite, magnetite which are oxides of ironstones; siderite which is a carbonate of

ironstone or chamosite which is ironstones with silicate are likely to be found here.

Figure 10 is a 3D surface view of the areas showing the identified areas that are likely hydrocarbon deposits, as indicated by low total magnetic field intensity values, and the likely iron ores as flagged by high total magnetic field intensity values. These variations in the total magnetic intensity field could be attributed to the topography and depth of the basement rocks as well as orientation of the rocks at varying depths.

Depths to basement estimated using the half width method for each profile in the various areas surveyed revealed a maximum depth of about 2.545km in Enagi, 1.11km in Gulu and 1.03km in Babban Rami with the rest having depths to basement values of less than 1km. On the other hand, minimum depths were evaluated to be 0.0012km in Sakpe, 0.0023km in Pattishabakolo and 0.0093km in Doko. These depths may not necessarily be due to the formational sediments of the overburden but the presence of magnetic ironstones which dominate the basin and might likely have given the impression of a shallow depth. The overall average depth to basement within the surveyed areas was found to be about 0.135km which could have been more, were it not for the presence of magnetic ores within the basin. This collaborates the findings of Olaniyan et al., (2012), Ofor *et al.*, (2014), Ojo and Ajakaiye, (1989) and Megwara and Udensi, (2014) who respectively estimated the depths to be within the ranges of 1km – 1.5km, 1.55km - 4.70km, 1km – 2km and 0.01km – 0.5km.

## Conclusion

The interpretation of the ground magnetic data of some parts of Bida basin has successfully delineated areas of high and low magnetic anomalies which are associated, in most cases, with thick and thin overburdens for low and high magnetic anomalies respectively. There are, however, some areas which showed high magnetic anomalies but were geologically identified with thick sedimentary overburdens. This could be attributed to the presence of magnetic minerals such as limonite, hematite, magnetite, siderite and chamosite which are of ironstones origin. The survey has successfully delineated the extent of magnetic signatures underlying the study area and their approximate

burial depths which by implication revealed the thicknesses of overburden in each of the places surveyed. The dykes and horsts are likely to be associated with very high positive magnetic anomalies and might have been caused by multiphase intrusions emplaced over time. Zones of weakness, dislocations, fracturing and/or shearing were also delineated across the entire breadth of the survey area and could be result of residual forces arising from deformation which is suggestive of the fact that intense tectonic activities may have taken place in the area in the past. Based on the results of the study, locations within the survey with high potentials for geotechnical, hydrogeological and hydrocarbon activities can be undoubtedly inferred. It is however recommended that higher resolution equipment and methods such as superconducting quantum interference devices (SQUIDs), seismic and better interpretation tools be used for improved results. Test wells could as well be dug in the low magnetic areas and samples of the rocks obtained for a geochemical analysis to confirm the assertion of hydrocarbon presence within the basin and the likely quantity. For geotechnical purposes, the areas with high magnetic anomalies could suffice as these are associated with shallow overburdens and hence the likelihood of sustaining massive structures. If hydrogeological activities are to be conducted within the basin, areas identified as having dislocations and/or associated with transform zones, which could be in the form of cracks or faults are highly recommended. The areas where ironstones were identified such as areas around Sakpe and Batati could be further studied using geochemical analysis for magnetic minerals such as limonite, hematite, magnetite, siderite and chamosite which are of ironstones origin.

## REFERENCES

- Adeleye, D. R. (1974). Sedimentology of the fluvial Bida Sandstones (Cretaceous) Nigeria. *Sedimentary Geology*, 12, 1-24. [http://dx.doi.org/10.1016/0037-0738\(74\)90013-X](http://dx.doi.org/10.1016/0037-0738(74)90013-X).
- Adeleye, D. R., (1973). Origin of ironstones, an example from the middle Niger Basin, Nigeria. *Journal of Sedimentary Petrology* 43, 709–727.

- Adeleye, D. R., (1989). The Geology of the middle Niger basin. In: Kogbe, C.A. (Ed.), *Geology of Nigeria*, second ed. Elizabethan Publishing Co., Lagos, 335–338.
- Adepelumi A. A, Ako B. D, Ajayi T. R, Olorunfemi A. O, Awoyemi M. O and Falebita D.E, (2008). Integrated geophysical mapping of Ifewara transcurrent fault system, Nigeria. *Journal of African Earth Sciences*, 52: 161-166.
- Campbell, W. C., (1997). Introduction to geomagnetic fields: Cambridge University Press, p280.
- Langel, R. A., and W. J. Hinze, (1998). The magnetic field of the Earth's lithosphere: The satellite perspective: Cambridge University Press.
- MacLeod, I. N., Jones, K., and Dai, T. F. (1993). 3-D analytic signal in the interpretation of total magnetic field data at low magnetic latitudes. *Exploration Geophysics*, 24(4), 679.
- Mariita, N.O. (2009). The Magnetic Method. Presented at Short Course IV on Exploration for Geothermal Resources, organized by UNU-GTP, KenGen and GDC, at Lake Naivasha, Kenya.
- Megwara J. U. and Udensi E. E. (2014). Spectral Analysis Using Aeromagnetic Data: Case Study of Parts of Southern Bida Basin, Nigeria and the Surrounding Basement Rocks. *Earth Science Research*, 3 (2), 27- 42
- Nabighian M. N., Grauch V. J. S., Hansen R.O., LaFehr T. R., Li Y., Peirce J. W., Phillips J. D. and Ruder M. E., (2005). Historical Development of the Magnetic Method in Exploration. *Geophysics*, 70, (5), 33 – 61.
- Nabighian, M. N. (1972). The analytic signal of two dimensional bodies with polygonal cross section: Its properties and use for automated anomaly interpretation. *Geophysics*, 37, 507–517.
- Nabighian, M. N. (1974). Additional comments on the analytic signal of two dimensional magnetic bodies with polynomial cross section. *Geophysics*, 39, 85–92.
- NGSA, (2005). Mineral Resources Map of Nigeria
- Nwajide C.S. (2013). *Geology of Nigeria's Sedimentary Basins*. CSS Books limited Lagos, p 565.
- Obaje N. G., (2009). *Geology and Mineral Resources of Nigeria*, Lecture Notes in Earth Sciences. Springer Dordrecht Heidelberg, London New York. Pp 221.
- Obaje, N. G., Balogu, D. O., Idris-Nda, A., Goro, I. A., Ibrahim, S. I., Musa, M. K. Dantata, S. H., Yusuf I., Mamud-Dadi, N. and Kolo I. A (2013). Preliminary Integrated Hydrocarbon Prospectivity Evaluation of the Bida Basin in North Central Nigeria. *Petroleum Technology Development Journal*, 3 (2).
- Ofor, N. P., Adam, K. D. and Udensi, E. E. (2014). Spectral Analysis of the Residual Magnetic Anomalies Over Pategi and Egbako Area of the of the Middle Niger Basin. *Nigeria. Journal of Natural Sciences Research*, 4(9), 44-50.
- Oga V and Mamah LI, (2014). Ground magnetic survey in Otukpo area of Benue State, Nigeria. *Journal of Natural Sciences Research*, 4(6): 76-82.
- Ojo, S. B. (1990). Origin of a major magnetic anomaly in the Middle Niger Basin, Nigeria. *Tectonophysics*, 85, 153-162. [dx.doi.org/10.1016/0040-1951\(90\)90410-A](https://doi.org/10.1016/0040-1951(90)90410-A)
- Ojo, S.B., (1984). Middle Niger Basin revisited magnetic constraints on gravity interpretations. A paper presented at the 20th Nigeria Mining and Geosciences Society Conference, Nsukka, Nigeria, *Conference proceedings*, pp. 52–53.
- Ojo, S.B., Ajakaiye, D. E., (1989). Preliminary interpretation of gravity measurements in the middle Niger Basin area, Nigeria. In: Kogbe, C.A. (Ed.), *Geology of Nigeria*, second ed. Elizabethan Publishing Co., Lagos, pp. 347–358.
- Olaniyan O., Abbah U., Nwonye N., Alichu A. and Udensi E.E., (2012). Interpretation of Total Magnetic Intensity Field over Bida Basin. Nigerian Geological Survey Agency. *Occasional Paper No. 15*. 3p.

- Parasnis D.S., (1986). Principles of Applied Geophysics. 4<sup>th</sup> edition, Chapman and Hall, London, pp 382.
- Reynolds, John M. (1987). An Introduction to Applied and Environmental Geophysics. John Wiley and Sons, Ltd., 2nd ed. p 681.
- Roest, W. R., Verhoef, J. and Pilkington, M. (1992). Magnetic interpretation using the 3D analytic signal. *Geophysics*, 57, 116–125.
- Roux A. T., (1980). The Magnetic Method. Geophysical Field Manual for Technicians. South African Geophysical Association, No1.
- Udensi, E. E., and Osazuwa, I. B., (2004). Spectra determination of depths to magnetic rocks under the Nupe basin, Nigeria. Nigeria Association of Petroleum Explorationists (NAPE) Bulletin 17, 22–27.
- Udensi, E.E., (2001). Interpretation of the total magnetic field over the Nupe basin in West Central Nigeria using aeromagnetic data. Ph.D thesis Dept of Physics ABU, Zaria, Nigeria.