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Evaluation of Depth to Magnetic Basement over Some Parts of the Nupe Basin, Nigeria by Source Parameter Imaging Method Using Aeromagnetic Data

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ABSTRACT

The IGRF corrected aeromagnetic data over some parts of Bida Basin, Nigeria was acquired from the Geological Survey Agency of Nigeria and interpreted, using the Oasis Montaj software, with the aim of determining the approximate depths to magnetic basement rocks. The study area is situated within latitude $8^0$00'N - $10^0$00'N and longitude $4^0$30'E - $7^0$00'E and covered by 10 aeromagnetic data sheets which were digitized and assembled to produce a combined aeromagnetic data file for the study area. The data was filtered using vertical, horizontal and generalized derivatives as well as grid analysis. The first order derivative was used as it is much more sensitive to noise at higher order derivatives. Depths of basement rock were delineated within the study area using the Source Parameter Imaging (SPI) method with the output grids from the filtering process serving as input grids for SPI processing. The results of the depth estimates revealed depth solutions ranging from about 60.225m to 3.447km. Three regions were zoned as having the highest depth with the first zone comprising the Enagi surface cover in the northwestern portion of the basin covering areas around Kutigi, Kudu, Robizi, Bokani, Pizhi, Adogo, and Lemu. The second zone is made up of a deep N-W trending trough comprising the Pattishabakolo area and extending to areas around Wuya, Badeggi, Ndaba, Egbati, and Again. The third zone falls within the South-East trench encompassing areas around Gulu, Kandi, Enwan, Muye, Germany, Ahoko, and Agbaja. These regions were, therefore, recommended for hydrocarbon search.

INTRODUCTION

The quest for resource control and agitations for secession have been on the increase in Nigeria in recent times. Numerous cases of pipeline vandalism activities, orchestrated by some people who think their resources are being taken away from them by force, abound. Genuine or not, these anxieties have grave consequences on the economic development of Nigeria as well as her unity. Nigeria's economy is largely dependent on export and domestic sales of oil and gas upon which over 170 million people depend. As the hydrocarbon potential of the Niger Delta is becoming depleted, there is need to further explore the other sedimentary basins of Nigeria. The Bida basin is one of those inland basins of Nigeria that might have high hydrocarbon accumulation potential as well as mineral deposits of economic interest.

Nigeria is blessed with abundant natural resources that if well harnessed, every part of the country would develop its resources and be self-sustaining largely, thereby minimizing or even eradicating the tensions that could cross the elastic limit if proper care is not taken. At this point, it will be very difficult or even impossible for the country to be restored to her original cohesive state. The first step to being taken towards averting this dangerous trend, which when successful would untimely lead to national development, is to make use of the exploration industries whose basic tool is exploration geophysics. In this paper, we utilized one of the geophysical exploration techniques, the Source Parameter Imaging (SPI), to delineate probable areas for mineral and hydrocarbon search. This study will serve as a reconnaissance tool for oil and mineral prospecting as well as to upgrade the geophysical data in the basin.

The Source Parameter Imaging method of depth estimate would delineate and characterize regions of thick sedimentary formations from those of uplifted or shallow basement and determine the depths to the magnetic sources within the Bida basin. The results could be used to deduce whether or not the basin has the potential for hydrocarbon accumulation or mineral deposits concentration.

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 the basement to be 3.39 km with a maximum depth of 4.5km. Ojo and Ajakaiye (1989) delineated the presence of a positive gravity residual center 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. They estimated the maximum thickness of sediments to range 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 with depths to basement varying between 4.0 km and 6.0 km. 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 2.50 km to 3.75 km, 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 the 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 Bida (Mid-Niger or Nupe) Basin is one of the seven inland basins of Nigeria containing sediment-fills of Cretaceous to Tertiary ages. The others are Niger Delta, Anambra, Benue Trough, Chad, Sokoto and the Dahomey (Benin) Embayment (Obaje, 2009). Figure 1 is the geological map of Nigeria showing the various geologic formations of Nigeria while Figure 2 is the geology and location map of the Bida basin and its environs.

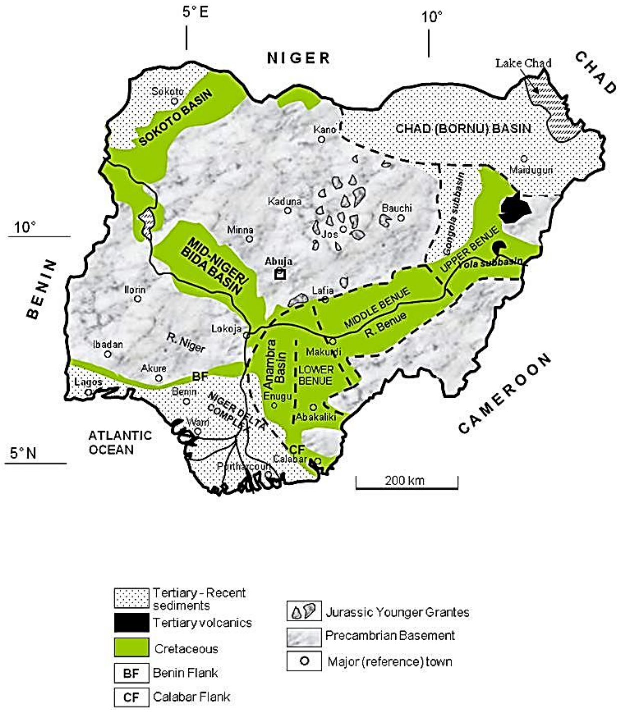

Figure 1: Geological map of Nigeria showing the major geological components (After Obaje, 2009).

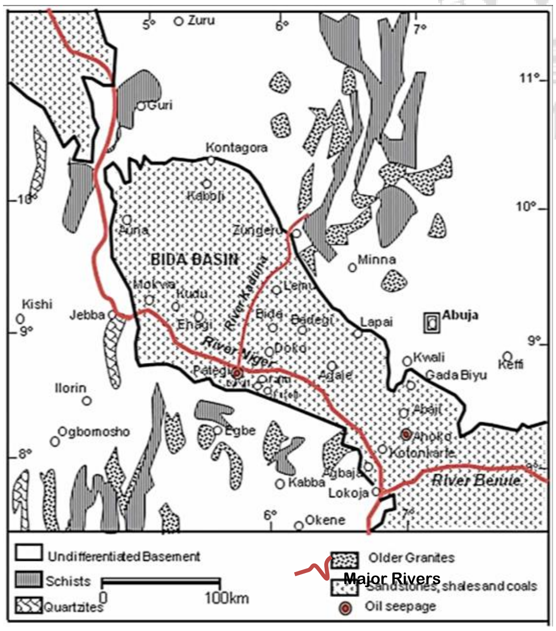

Figure 2: Geology and Location Map of Bida Basin and its Surroundings (Obaje, 2009)

The basin is surrounded in the northeast and southwest by the basement complex while it merges with Anambra and Sokoto basins in the sedimentary fill comprising post-orogenic molasses facies and a few thin unfolded marine sediments (Adeleye, 1989). Akande *et al.* (2005) also described the basin as a gently down-warped trough whose genesis may be closely connected with the Santonian orogenic movements of southeastern Nigeria and the nearby Benue valley. A study by Ojo (1990) revealed an E-W magnetic low, which dominates the modern section of the basin in terms of deep-seated structures and the existence of deep-seated rift, which might exist in the crust due to the presence of large bodies of identified rocks. The basin consists of the Bida Sandstone and the Lokoja formation, which was produced during the Campanian, the Sakpe, Enagi, Batati, Patti and Agbaja formations that were created during the Maastrichtian. The Bida Formation is divided into the Doko Member and the Jima Member. Adeleye (1974) made a detailed study of the Doko and Jima Members and reported that the Doko Member is about 183m thick and shows the localized development of cross-stratification while the Jima Member 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). Adeleye (1989) and Obaje (2009) also view the member as having to poorly sort and exposed pebbly, sub-arkoses and quartzose sandstones with granular to sub-granular grains, which are thought to have been deposited in a braided alluvial fan setting. The sandstones of the Jima Member (Jima Sandstone subfacies), according to Adeleye (1989), are dominantly quartzose, non-arkosic and brownish. Thin intercalations of poorly sort, hard, whitish, argillaceous sandstones are locally present in the lower parts of the Jima subfacies. Adeleye (1989) observed various types of concretions occurring in the sandstone facies from spherical to sub-spherical, sausage-shaped, irregular and compound shapes. Shiny, blackish ferruginous mineral, possibly goethite/haematite, form the cement and some weak to strong concentric growth shells are displayed.

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. Other subsidiary lithologies include sandstone-siltstone with some claystones. Fossil leaf impressions and rootlets have been found in the formation. The formation ranges in thickness between 30m and 60m. Mineral assemblage consists mainly of quartz, feldspars, and clay. The Batali formation constitutes the uppermost units in the sedimentary sequence of the Bida Basin. It consists, according to Obaje *et al.* (2013), of argillaceous, oolitic and goethitic ironstones with ferruginous claystone and siltstone intercalations and shaly beds, which occur in minor proportions some of which have yielded near-shore shallow marine to fresh water fauna.

The Lithologic units in Lokoja Formation range from conglomerates, coarse to fine-grained sandstones, siltstones, and claystones in the Lokoja area (Akande *et al.*, 2005). Subangular to subrounded cobbles, pebbles and granule sized quartz grains in the units are frequently distributed in a clay matrix. The outcrops of the Patti Formation occur between Koton-Karfe and Abaji. This formation consists of sandstones, siltstones, claystones, and shales interbedded with bioturbated ironstones with the argillaceous units predominating in the central parts of the basin.

The Agbaja Formation forms a persistent cap for the Campanian - Maastrichtian sediments in the Southern Bida Basin as a lateral equivalent of the Batati Formation on the northern side of the basin. It consists of sandstones and claystones interbedded with oolitic, concretionary and massive ironstone beds in this region.

2. MATERIALS AND METHODS

The 2009 IGRF corrected aeromagnetic data was acquired from the Nigeria Geological Survey Agency through the Ibrahim Badamasi Babangida University, Lapai Hydrocarbon Research Project which granted a third party access for the use of the data, while Oasis montaj 9.1 Software was used for the analysis and the Source Parameter Imaging as a depth determination method.

2.1 The Source Parameter Imaging Method

The Source Parameter Imaging (SPI) method, developed by Thurston and Smith (1997), is a technique that uses an extension of the complex analytic signal to estimate magnetic depths. It is a profile or grid-based method whose grid solutions show the edge locations, depths, dips and susceptibility contrasts. The method utilizes the relationship between source depth and the local wavenumber (k) of the observed field, which can be calculated for any point within a grid of data through horizontal and vertical gradients (Thurston and Smith, 1997) with the depth usually displayed as an image. The accuracy of the method has been shown to be +/- 20% in tests on real data sets with drill hole control (Salako, 2014). This accuracy is similar to that of Euler deconvolution; however, SPI has the advantage of producing a complete set of coherent solution points.

The complex analytic signal $A_1(x,z)$ as defined by Nabighian (1972) is expressed as:

$$A_1(x,z) = \frac{\partial M(x,z)}{\partial x} - j\frac{\partial M(x,z)}{\partial z} \tag{1}$$

where M(x,z) is the magnitude of the anomalous total magnetic field, j is the imaginary number, and z and x are Cartesian coordinates for the vertical direction and the horizontal direction perpendicular to strike, respectively. Nabighian (1972) showed that the horizontal and vertical derivatives comprising the real and imaginary parts of the 2D analytic signal are related by:

$$\frac{\partial M(x,z)}{\partial x} \Leftrightarrow -j\frac{\partial M(x,z)}{\partial z} \tag{2}$$

where ⇔ signifies a Hilbert transform pair. The local wavenumber, k_1, is defined by Thurston and Smith (1997) as:

$$k_1 = \frac{\partial}{\partial x} tan^{-1}\left(\frac{\partial M}{\partial z} / \frac{\partial M}{\partial x}\right) \tag{3}$$

The analytic signal uses the Hilbert transform pair such that the Hilbert transform and the vertical derivative operators are linear. Therefore, the vertical derivative of equation (2) yields:

$$\frac{\partial^2 M(x,z)}{\partial z \partial x} \Leftrightarrow -j\frac{\partial^2 M(x,z)}{\partial z^2} \tag{4}$$

This can be used in defining the analytic signal based on second order derivatives

$$A_2(x,z) = \frac{\partial^2 M(x,z)}{\partial z \partial x} - j\frac{\partial^2 M(x,z)}{\partial z^2} \tag{5}$$

Which yields the second order local wave number k_2 given by

$$k_2 = \frac{\partial}{\partial x} tan^{-1}\left(\frac{\partial^2 M}{\partial z^2} / \frac{\partial^2 M}{\partial z \partial x}\right) \tag{6}$$

The first and second – order local wavenumbers are used to determine the most appropriate model and depth estimate independent of any assumption about a model.

Nabighian (1972) provided the vertical and horizontal gradients of a sloping contact model as:

$$\frac{\partial M}{\partial z} = 2KF_c sind \frac{h_c \cos(2I-d-90)+xsin(2I-d-90)}{h_c^2+x^2} \quad (7)$$

and

$$\frac{\partial M}{\partial x} = 2KF_c sind \frac{x \cos(2I-d-90)-h_c sin(2I-d-90)}{h_c^2+x^2} \quad (8)$$

where K is the susceptibility contrast at the contact, F is the magnitude of the earth`s magnetic field (the inducing field), c = 1 – $\cos^2 i \sin^2 \alpha$, α is the angle between the positive *x*-axis and the magnetic north, I is the ambient- field inclination, tan I = Tani/cosα, d is the dip (measured from the positive *x*-axis), h_c is the depth to the top of the contact and all trigonometric argument are in degrees.

The coordinate systems are defined such that the origin of the profile line (x = 0) is directly over the edge. Reford and Sumner (1964) as provide the expression of the magnetic field anomaly due to a dipping thin sheet:

$$M(x,z) = 2KF_{cw} \frac{h_t \sin(2I-d)-xcos(2I-d)}{h_t^2+x^2} \quad (9)$$

Where w is the thickness and h_t is the depth to the top of the thin sheet.

For a long horizontal cylinder, Murthy and Mishra (1980) as gave the expression for the magnetic field anomaly:

$$M(x,z) = 2KF_S \frac{(h_h^2-x^2)\cos(2I-180)+2xh_h sin(2I-d)}{\left(h_h^2+x^2\right)^2} \quad (10)$$

Where S is the cross-sectional area and h_h is the depth to the center of the horizontal cylinder.

Substituting (7) (8) (9) and (10) into the expressions for the first- and second order local wavenumber and simplifying, we obtain:

$$k_1 = \frac{(n_k+1)h_k}{h_k^2+x^2} \quad (11)$$

and

$$k_2 = \frac{(n_k+2)h_k}{h_k^2+x^2} \quad (12)$$

Where n_k is the SPI structural index (subscript k = c, t or h), n_c =1 and n_h = 2 for the contact, thin sheet, and horizontal cylinder models respectively. The SPI structural index is defined so that for the thin sheet and contact models, the numerical values are identical to the numerical values of the Euler structural index defined by Reid *et al* (1990).

2.2 The Aeromagnetic Data

The need to re-invigorate the solid minerals sector necessitated Federal Government of Nigeria to embark on the provision of quality geosciences data through an airborne geophysical survey programme. This resulted in the generation of geophysical data in many places including the airborne magnetic survey of 2007 to 2009, which included the Bida Basin shown as Block D4 in Figure 3. The surveys were mostly flown at 500 m line spacing and 80 m mean terrain clearance generating about 2 million line-km data. Raw aeromagnetic data on sheets covering the sedimentary cover of the Bida Basin shown as D4 in Figure 3 were obtained and merged for a composite interpretation.

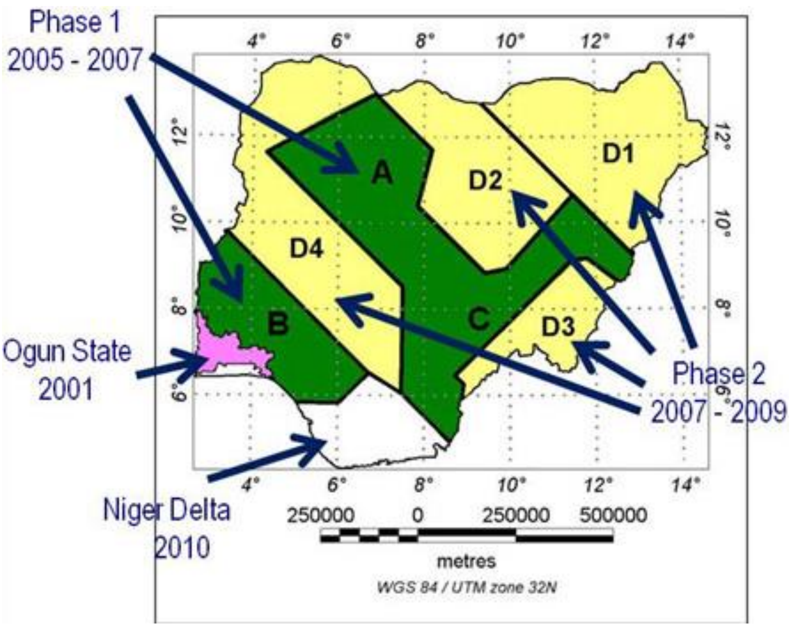

Figure 3: Map of Nigeria showing the Phases of Airborne Survey and duration (Source: NGSA).

3. RESULTS

3.1: Result of Reduction of Magnetic Pole (RTP).

Reduction to the pole (RTP) is a standard part of the magnetic data processing method, especially for large-scale mapping. RTP operation can transform a magnetic anomaly caused by an arbitrary source into the anomaly that the same source would produce if it were located at the magnetic pole and magnetized by induction only. RTP also helps in the interpretation of magnetic data by removing the influence of magnetic latitude on the anomalies.

Oasis montaj 9.1 software was used to reduce the total magnetic field intensity data to the pole and the result is shown in Figure 4.2. From the map, a negative broad and deep-seated magnetic anomaly could be observed around areas bounded by latitudes $8^{0}45'$ N - $9^{0}00'$ N and longitudes $5^{0}30'$ E - $6^{0}50'$ E. This region is shown in blue colour on the RTP map and corresponds to areas around south of Patigi, Baro and north of Gulu. Sandwiching this region are broad and deep-seated positive magnetic anomalies covering areas around latitudes $8^{0}00'$ N to $8^{0}15'$ N and longitudes $6^{0}00'$ E to $7^{0}00'$ E below and situated on magnetic sheets covering areas around the southern parts of Kotonkarfe and Kirri; and latitude $9^{0}00'$ N to $9^{0}30'$ N and longitude $5^{0}15'$ E to $6^{0}00'$ E above covering areas around the extreme north of Baro, Gulu and Patigi as well as southern Egbako. There are also some deep pockets of negative and positive anomalies scattered around the region, which could be attributed to the nature of the region, which is known to be dominated by sandstones, and siltstones, which are nonmagnetic, and ironstones, which are magnetic in nature. The yellow bands represent the transition between these regions and clearly show the edges of the shapes of the anomalies.

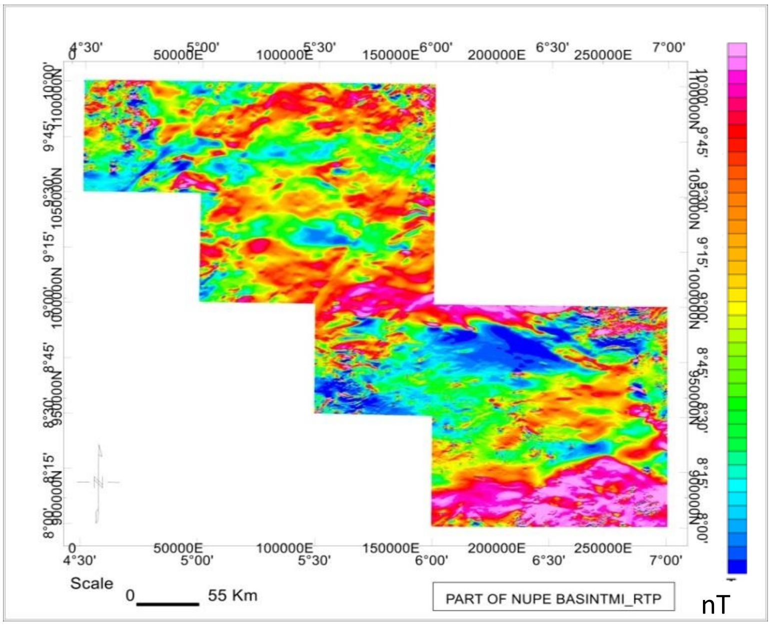

Figure 4: 2009 IGRF Corrected TMI data of Parts of Bida/Nupe Basin Reduced to Pole.

3.2: Result of Application of Analytic Signal

To obtain the analytic signal that shows the structures within the basin, the computed x-, y- and z- derivatives were used in Oasis Montaj as input grids so that the amplitude is independent of the direction of magnetization. The result of the amplitude domain analytic signal is shown in Figure 5 where areas in purple color, signifying high amplitudes, ranging from 0.344 to 0.218 cycles, result due to outcrops of magnetic rocks while moderate depths are represented in red color and range from 0.218 to 0.096 cycles. These are areas of shallow depths, which could be attributed to intrusions of the magnetic basement into the sedimentary basin. The regions with the lowest amplitudes connote deeper regions, which arise due to the intrusion of the magnetic basement into the sedimentary basin at greater depths. This region has a range of amplitudes from 0.096 – 0.064 cycles and is shown in yellow and green colors and trends in the NW-SE direction.

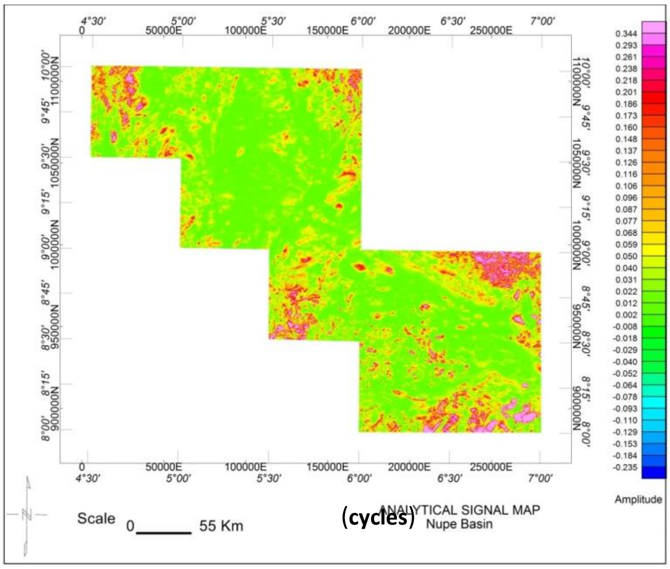

Figure 5: Analytic Signal Map of Bida/Nupe Basin

3.3: Source Parameter Imaging (SPI) Result

The Source parameter imaging method calculates source parameters for gridded magnetic data and assumes either a 2D slopping contact or a 2D dipping thin sheet model that is based on the complex analytic signal. The SPI depth to the magnetic basement was determined using Oasis montaj 9.1 software and employing the first vertical derivatives and horizontal gradients. This model, as generated from the software, was displayed as an image and the depth estimates for each anomaly were determined. Figure 6 shows the processed and interpreted aeromagnetic data showing the depth to basement in coloured legend over the Bida/Nupe basin, with the blue color indicating the areas with the lowest total magnetic field intensity and the purple color indicating regions with the highest total magnetic field intensities.

The results of the depth estimate from the application of Source Parameter Imaging method in the study area revealed depth solutions ranging from about 60.23m to 3.35km within the study area. On the SPI depth grid shown in Figure 6, the pink areas indicate the shallowest portions of the basin while the blue portions highlight the deepest pockets. The trend of the deep pockets is observed to lie from NW to SE, which corroborates the observed trend of the direction of the basin itself. Figure 7 shows a profile plot of SPI depth against lateral distance showing an average estimated depth of about 3.6km. It is, however, worth noting that since this estimate is only for one profile cutting across only a few places in the basin, the average depth might be lower.

The interpreted aeromagnetic map is divided into three zones according to their extents and depths as shown in Figure 8. These zones are easily identified by the deep blue coloration, which indicates the deepest zones with the purple to red coloration showing the shallowest areas. Because the TMI data was subjected to filtering, the high values could be largely associated with the formational geology of the sedimentary fill, which is discernable with the knowledge of the geology of the area and to some extent due to exposed magnetic minerals.

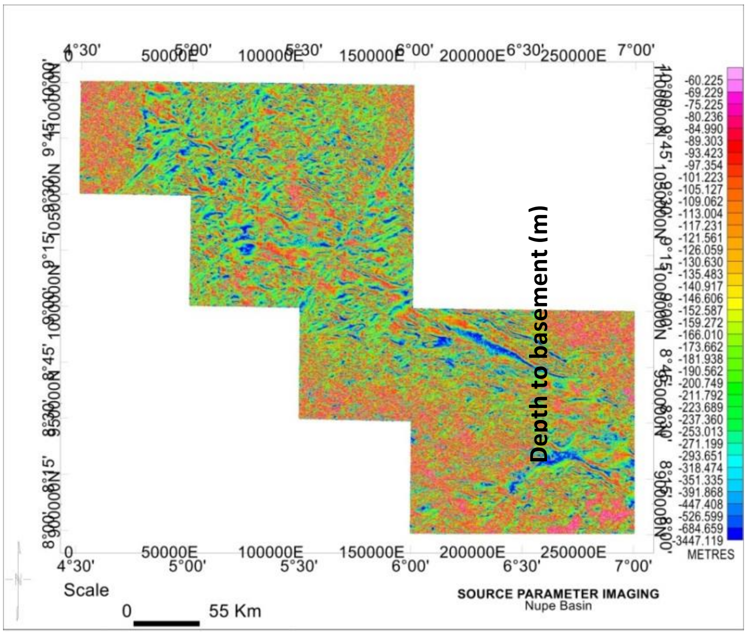

Figure 6: Interpreted Depth to Basement from the 2009 IGRF Corrected Aeromagnetic Data of Bida/Nupe Basin using SPI.

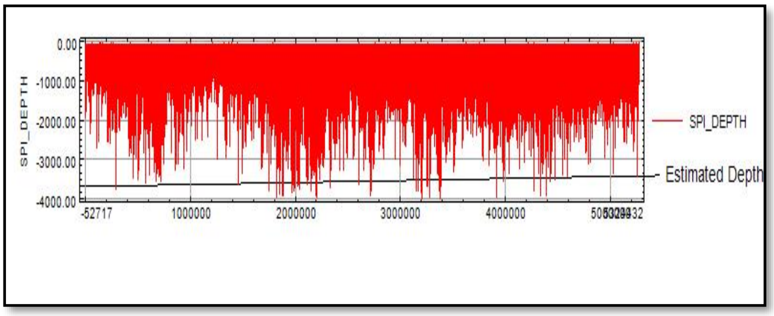

Figure 7: SPI Depth Profile Map

It was also observed from the grid statistics that a greater portion of the basin has its depth ranging from 293.65m to 684.66m, an indication that the basin is generally shallow in nature. This result corroborates the findings of Olaniyan *et al*. (2012), who used the SPI method to delineate depths ranging from 217m to 4571m within the basin, further noting that 90% of the depth solutions ranged from 217m to 1500m. The observed deep pockets scattered within the basin, and shown in blue color, might be either due to magnetic basement located at such magnificent depths or possibly due to the presence of intrusions and outcrops of ores, which host iron minerals. This is because Obaje et al. (2013), Adeleye (1974) and Nwajide (2013) as consisting of iron ores, which are highly magnetic in nature have reported the basin. The results have also shown a good agreement with the geological mapping interpretation conducted by Obaje *et al.* (2013), except that the aeromagnetic interpretations have widened the scope of some geomagnetic signatures.

The first zone, based on coordinate matching with the geological of the area, is an expansively broad region, which, according to Obaje *et al.* (2013), comprises the Enagi surface cover in the northwestern portion of the basin covering areas around Kutigi, Kudu, Robizi, Bokani, Pizhi, Adogo and Lemu. The area extends from around latitude $8^0$45' N - $10^0$00'N and longitude $5^0$60'E - $6^0$00'E. The second zone is made up of a deep N-W trending trough comprising the Pattishabakolo area and extending to other areas in Niger state around Wuya, Badeggi, Ndaba,

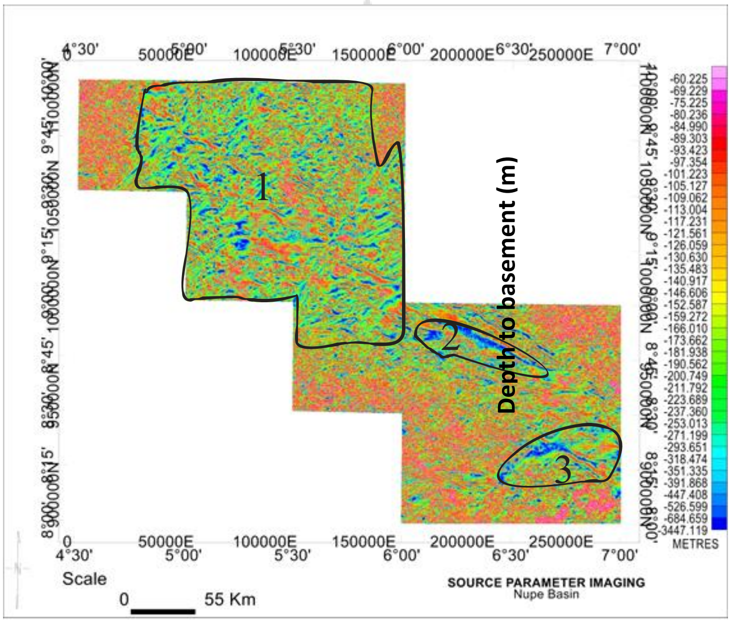

Figure 8: Zones indicating the deepest areas in Bida/Nupe Basin

Egbati and Agaie. It is located within latitude $8^0$45' N - $9^0$00'N and longitude $6^0$15'E - $6^0$45'E.The third zone falls within the South-East trench encompassing areas around Gulu, Kandi, Enwan and Muye in Niger state; some areas around the FCT and Gerinya, Ahoko, and Agbaja areas in Kogi state which extend from around latitude $8^0$15' N - $8^0$30'N and longitude $6^0$30'E - $7^0$00'E. Most parts of zones 2 and 3 are expected to be filled with the Batati iron

Formation but for the fact that the Formation could be isolated outliers as described by Obaje *et al.* (2013). It is, therefore, likely that the depths to the basement are independent of geological formational relationship or most portions of the Batati Formation might have been eroded thereby paving way for the low magnetic signatures observed within the associated zones.

The interpreted aeromagnetic data has delineated the depth to basement rocks within the basin to range from 60.23m to 3.45km as shown in the legends of Figures 6 and 4.8. This is in close agreement with the depths to basement in the region as reported by Ojo (1990), who put the depths at between 4km and 6km; Udensi and Osazuwa (2004) who reported an average of 3.39km with a maximum of 4.50km; Olaiyan *et al*. (2012) who obtained values between 2.50km and 3.75km; Ofor *et al*. (2014) who had a range from 1.50km to 4.70km, Ojo and Ajakaiye (1989) whose depth values varied from 1.00km to 2.00km and Obi *et al*. (2015) who delineated depths from 0.2km to 4.2km.

4. SUMMARY AND CONCLUSION

Aeromagnetic data of some areas around the Bida/Nupe Basin of Nigeria were acquired and interpreted with the aim of determining the approximate depths to the magnetic basement. The aeromagnetic data was acquired from the Geological Survey Agency of Nigeria and analyzed using the Oasis montaj 9.1 Software from Geosoft, South Africa. The total magnetic field intensity data was first reduced to the pole to show how the anomalies would have been if the data was collected at the magnetic pole. First vertical derivative, horizontal derivatives in x -, y - and z – directions filters were applied to the data to which was then used in the Source Parameter Imaging method to estimate the depth to magnetic basement.

The depth to basement estimated using the source parameter imaging method gave a range of values from 60.23m to 3.47km. The regions that produced the least depth were those on magnetic sheets covering areas around Kainji, Northern Patigi and around Gulu East. The moderately deep areas were observed to be in the vicinities of the magnetic sheets covering Mokwa, Fashe, Egbako, and Akere, whereas areas around the magnetic sheets containing Baro, Gulu West and the Northern part of Kotonkarfe were observed to be of great depth. The aeromagnetic interpretation gave a range of depth from 60.225m to 3.447km which corroborate the findings of Olaniyan *et al*. (2012), Ofor *et al*. (2014), Ojo and Ajakaiye (1989), Megwara and Udensi (2014) and Obi *et al*. (2015) who respectively estimated the depths to basement to be within the ranges of 1km – 1.5km, 1.55km - 4.70km, 1km – 2km, and 0.01km – 0.5km and 0.2km – 4.2km.

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