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Fractal Revaluation of Bottom Depth of Magnetic Sources in Bida Basin, Nigeria from High-Resolution Aeromagnetic Data

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ABSTRACT

The recent high-resolution aeromagnetic (HRAM) data for the whole of Bida Basin in north-central Nigeria has been revaluated for depth to bottom of magnetic sources (DBMS) using the modified centroid method for fractal distribution of sources. Analysis of the HRAM map shows magnetic lineations due to tectonic features that may be connected to regional tectonic framework of West and Central Africa Rift Systems. The HRAM data were also divided into 28 overlapping blocks and each block was evaluated to obtain depths to the top and centroid of magnetic sources. Both depth values were consequently used to calculate the DBMS for each block. The results reveal that the DBMS varies between 5.41 and 19.29 km with an average of 12.01 km. Hence, this study would contribute to further explication of the geo-processes and rheology of Bida Basin in north-central Nigeria.

Key words: Basal depth, magnetic sources, fractals, Bida basin, Nigeria

INTRODUCTION

The revaluation of the depth to the bottom of magnetic sources (DBMS) from recently acquired high-resolution aeromagnetic data of the whole of Bida Basin, north-central Nigeria has been carried out in this study using fractal model. Nonetheless, earlier calculations of DBMS in the Earth's crust were executed through previously established mathematical procedures, namely: spectral peak method (Connard et al., 1983; Blakely, 1995), spectral centroid method (Bhattacharyya and Leu, 1975; 1977; Okubo et al., 1985; Tanaka et al., 1999), scaling spectral or power-law correction method (Maus and Dimri, 1996), and forward modelling of the spectral peak method (Finn and Ravat, 2004; Ravat et al., 2007), among others.

The mathematical scheme for fractal model of aeromagnetic analysis is derived from spectral centroid model (for an extensive description of the spectral centroid model, one may refer to Okubo et al., 1985; and Tanaka et al., 1999). One of the flaws of the spectral centroid model is the assumption of random and uncorrelated distribution of magnetic sources equivalent to white noise distribution because of its mathematical simplicity and non-availability of information about source distribution. However, in reality the source distribution follows correlated fractal distribution, which is referred to as scaling distribution (Maus and Dimri, 1996; Maus et al., 1997; Bansal and Dimri, 2014; Bansal et al., 2011; 2013; 2016; Kumar et al., 2017). Maus et al., (1997) gave an expression of the radial average of power spectrum (*P(k)*) of magnetic sources expressed in terms of scaling exponent and depth component as:

$$P(k)=C-2kZ_t-\text{tk}-\beta\ln(k)+\ln\left(\int_0^\infty[\cos h(tk)-\cos(tw)]\left(1+\frac{w^2}{k^2}\right)^{-1-\beta/2}dw\right) \quad (1)$$

where k is the wavenumber (2π/km), Z_t is the depth to the top, t is the thickness of slab, β is a scaling exponent due to source distribution, and C is a constant.

Following this, a fractal modification of the spectral centroid model (Bhattacharyya and Leu, 1975; Tanaka et al., 1999) was derived by Bansal et al., (2011) for the estimation of DBMS from aeromagnetic data for scaling distribution of sources. The new fractal model, like the spectral centroid model, computes the DBMS in three steps. Primarily, the depth to the top of magnetic sources is computed by correcting power spectrum for scaling distribution of sources as:

$$\ln(k^\beta P(k)) = A_1 - 2kZ_t \quad (2)$$

Next, the centroid depth is computed as:

$$\ln\left(k^\beta \frac{P(k)}{k^2}\right) = A_2 - 2kZ_0 \quad (3)$$

and finally, DBMS Z_b is estimated:

$$Z_b = 2Z_o - Z_t \quad (4)$$

The scaling component β depends on the geology or fractal distribution of susceptibility. Bouligand et al., (2009) conferred that the spectral peaks in power spectrum could only be found for low values of β, which disappears at higher values and therefore, reasonable values of scaling component should vary from 1.0 – 2.0 for 2D magnetic bodies and 2.5 – 3.5 for 3D distribution of sources. In

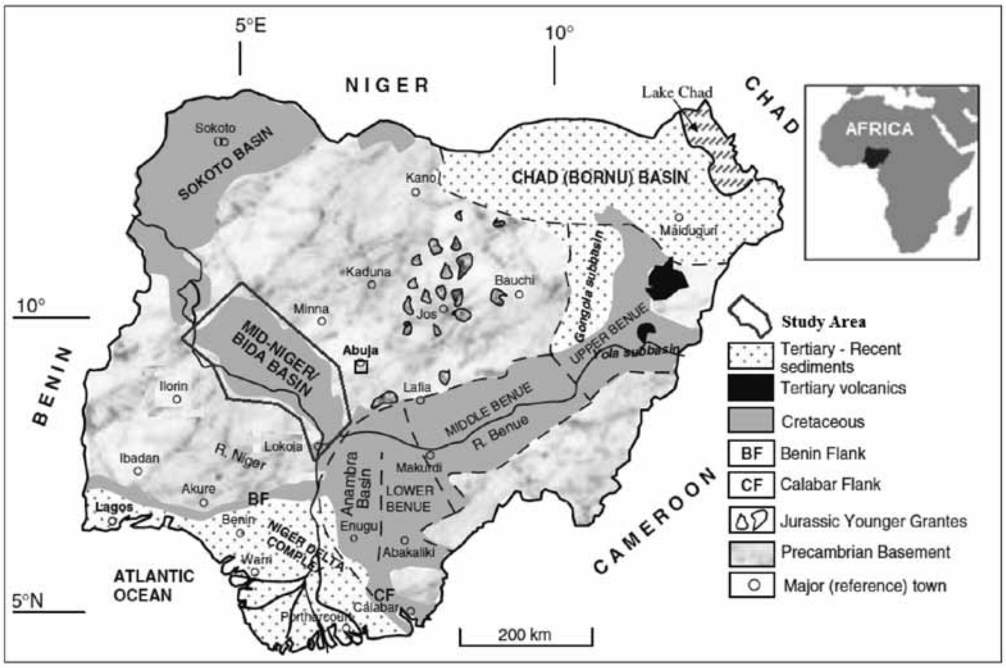

Figure 1. Geological map of Nigeria showing Bida Basin

furtherance, Bansal and Dimri (2014) revealed that scaling components of 2.4 – 4.6 would practically resolve 3D sources while lower scaling components reveal 1D and 2D source distributions. Salem et al., (2014) showed that scaling components ranging from 0 to 1.7 were effectively applied in the Central Red region of Egypt, whereas 0 to 4.0 were used by Kumar et al., (2017) for 2D structures in Central India. The results of Kumar et al., (2017) were however scattered and not correlated with depth and geology signifying complex tectonic nature of the region. Nevertheless, assigning a fixed scaling component value of 1 has been found to be reasonable in previous studies utilizing fractal technique in Austria, Germany, India, and Nigeria (Bansal et al., 2011; 2013; 2016; Gabriel et al., 2011; Bansal and Anand, 2012; Nwankwo, 2015). The value of 1 was used for 2D distribution of sources by assuming that these represent as scaling noise of 1/f type. Recent studies have led to improved DBMS estimations using fractal distribution of sources (Maus et al., 1997; Bouligand et al., 2009; Bansal et al., 2011; Salem et al., 2014). Consequently, it is expected that the application of fractal technique to the newly acquired high-resolution aeromagnetic data of the whole of Bida Basin in north-central Nigeria would yield better DBMS estimates.

Location and Geology of the Study Area

Bida basin (Figure 1) is located in the north-central region of Nigeria. It is bounded by latitudes $8^{0}00'$N and $10^{0}30'$N and longitudes $4^{0}30'$E and $7^{0}30'$E and covers an area of approximately 90,750 km^2.

The geology of Bida Basin has been described extensively by many researchers (Adeleye, 1974, 1976; Osokpor and Okiti, 2013; Jones, 1975; Kogbe et. al., 1983; Obaje, 2009; etc.). The basin is believed to be a gentle down-warped shallow trough filled with Campanian-Maestrichtian marine to fluviatile strata. Those with marine affinity, the limestones, often form cappings (under variable thickness of laterites) to the means of the basin. Some form prominent intermediate breaks of slope along the mesa walls (Osokpor and Okiti, 2013). The epeirogenic process responsible for the basin genesis seems closely connected with the Santonian tectonic crustal movements which mainly affected the Benue Basin and south-eastern Nigeria. The buried basement complex probably has a high relief (Jones, 1975) and the sedimentary formations have been shown to be about 2 km thick (Ojo and Ajakaiye, 1976) with a constituted post-tectonic molasse facies and thin marine strata, which are all unfolded.

The stratigraphy of the basin (Figure 2) consists of mainly Patti, Lokoja and Agbaja Formations (Ikumbur et al., 2013). Patti Formation is the only stratigraphic unit containing carbonaceous shale in the basin and is sandwiched between the older Campanian-Maastrichtian Lokoja Formation that contains conglomerates, sandstones and claystones; and younger Agbaja Formation that comprises mostly ironstones (Akande et al., 2005a; 2005b).

Tectonically, rift hypothesis has been proposed as the possible origin and evolution of the basin (Kogbe et. al., 1983; Adeniyi, 1985). Some investigators claim that the rifting in the Bida Basin started in the Upper Cretaceous

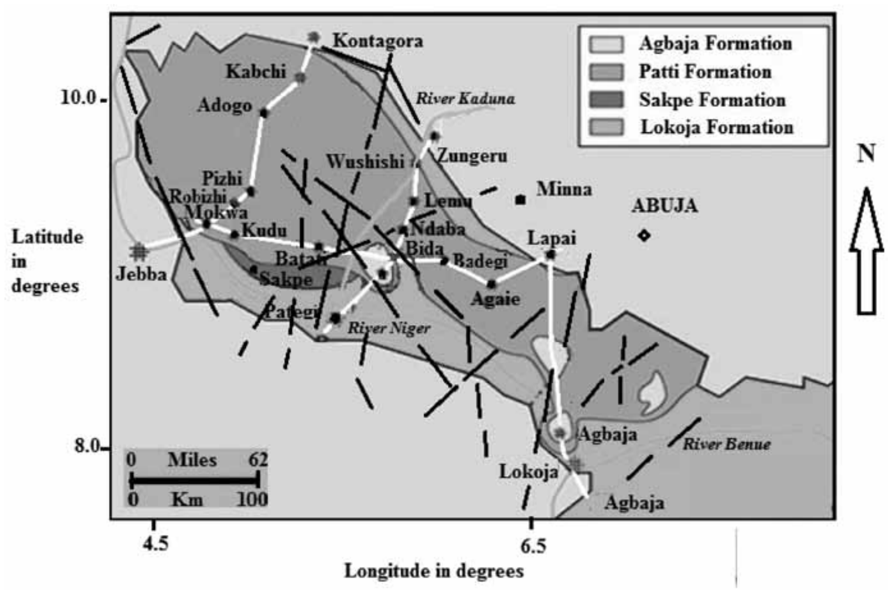

Figure 2. Geologic map of Bida basin showing stratigraphic sequence and lineaments (After NGSA, 1984; Obaje et al., 2015)

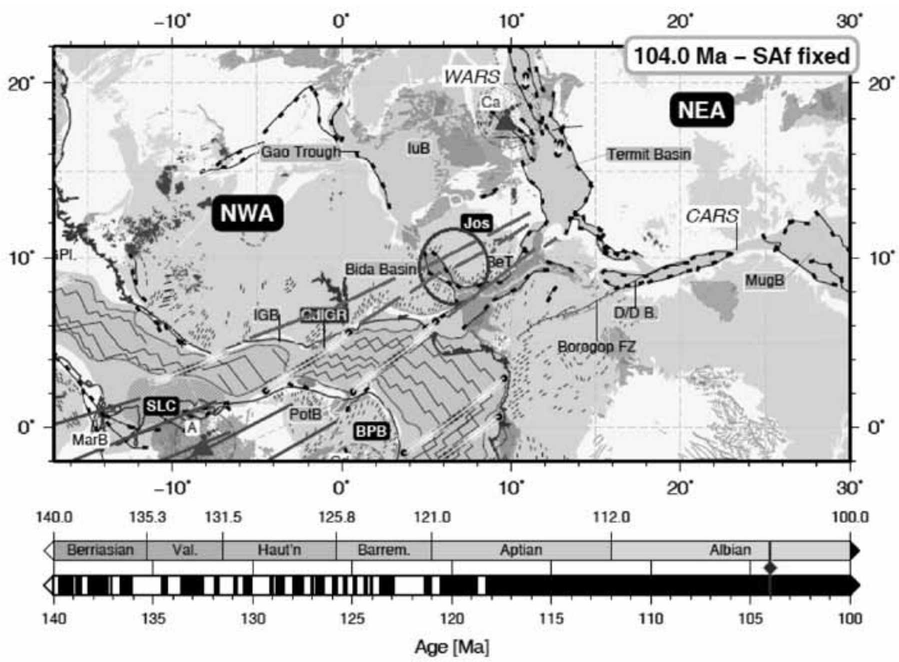

Figure 3. West African Rift System (WARS) and Central African Rift System (CARS) [After Heine et al., 2013]. Gray circle indicates position of Bida basin with extensions of inferred major fracture zones – St. Paul's, Romanche, and Chain drawn with broken lines. Ajakaiye et al., 1991 had earlier suggested these extensions.

but the entire process began originally from the Benue Trough in the Lower Cretaceous and eventually spread to other rifted basins like Gongola Trough, Yola Trough and Bida Basin (Udensi et. al., 2003). The origin of the basin is also said to be closely related to Santonian tectonic crustal movements, which affected the Benue Basin and south-eastern Nigeria (Ajakaiye et al., 1991; Ojo, 1990; Kogbe et al., 1983). The inland basins of Nigeria constitute one set of a series of Cretaceous and later rift basins in Central and West Africa whose origin is related to the opening of the South Atlantic (Figure 3). Ajakaiye et al., (1991) further suggested possible extension of St Paul and Romanche major fracture zones across the basin. Interpretations of Landsat imageries and geophysical data suggest that the basin is bounded by a system of linear faults trending NW-SE (Kogbe et al., 1983). Lineaments map (Figure 2) also reveals varied trends within the basin but dominantly trending NE – SW (NGSA, 1984).

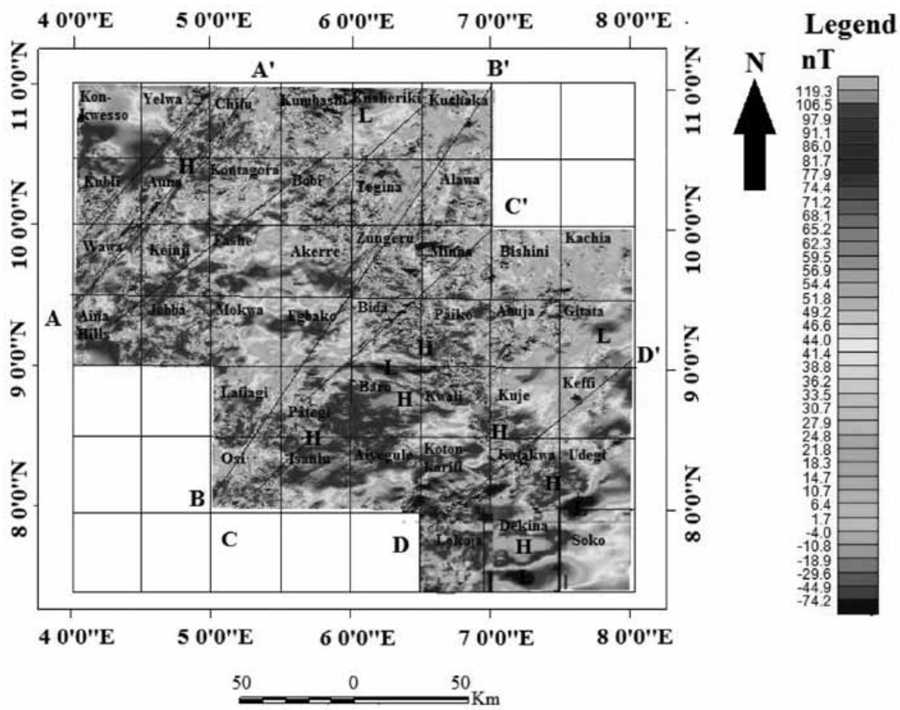

Figure 4. Residual Total Magnetic Intensity Map (RTMI) of entire Bida basin showing inferred lineaments (AA', BB', CC' and DD') – likely paleofracture zones. Magnetic high (H) and low (L) are also shown. A constant 33000 nT was removed as common background field.

Data Acquisition and Analysis

The regional airborne magnetic surveys over the entire Bida Basin and adjoining areas were carried out by the Nigeria Geological Survey Agency (NGSA) between 2004 and 2009. The field surveys were completed using 3 Fixed-wing aircrafts mounted with Scintrex CS3 Cesium vapour magnetometers having data recording interval of 0.1 seconds. The aircrafts were flown at a mean terrain clearance of 80 m with 500 m line spacing and nominal tie-line spacing of 2 km. The flight line and tie-line trends were 135 and 45 degrees respectively. The resulting magnetic data were processed and published as digital half degree high-resolution airborne magnetic (HRAM) intensity digital maps by the NGSA.

Forty three (43) HRAM maps (sheet number 117 - 122, 138 - 143, 159 - 166, 180 - 187, 203 – 208 and 224 – 229) on a scale of 1:100,000, covering a total area of 130,075 square km, were used in this work. The whole data, covering the entire Bida Basin and adjoining areas, were procured from NGSA and assembled into composite total magnetic field intensity (TMI) map (Figure 4). Regional correction, which was based on the International Geomagnetic Reference Field (IGRF-11), was made by the NGSA before the eventual publication as HRAM Maps.

The composite map was then divided into 28 overlapping blocks and each block covering a square area of 200 km x 200 km was analysed using fractal scheme. A window length (L) of 200 km was found suitable for the reason that magnetic source bodies having bases deeper than $L/2\pi$ may not be properly resolved by spectral method (Shuey et al., 1977). Moreover, a common rule of thumb is that the window size must be about 10 times the expected depth value (Ravat et al., 2007).

RESULTS AND DISCUSSIONS

Examination of the aeromagnetic data from Bida Basin confirms magnetic lineaments and regions, which were deduced as possible tectonic features. Geologic features usually depict magnetic signatures that make them easily recognizable. A major characteristic of magnetic contours is the fact that sudden break in lithology is shown by discontinuity (Ajakaiye et al., 1985; 1991; Udensi et al., 2003). Figure 4 shows series of lineaments and magnetic closures.

A previous study by Ajakaiye et al., (1991) showed that the onshore lineaments in West Africa are the extensions of the St Paul's, Romanche, Chain and Charcot regional fracture zones (Figure 3), which are believed to be part of major weakness in the crust that predate the opening of the Atlantic ocean and were reactivated in the early stages of continental rifting. Buser (1966) had earlier recognized the existence of paleostructures, which are linked to

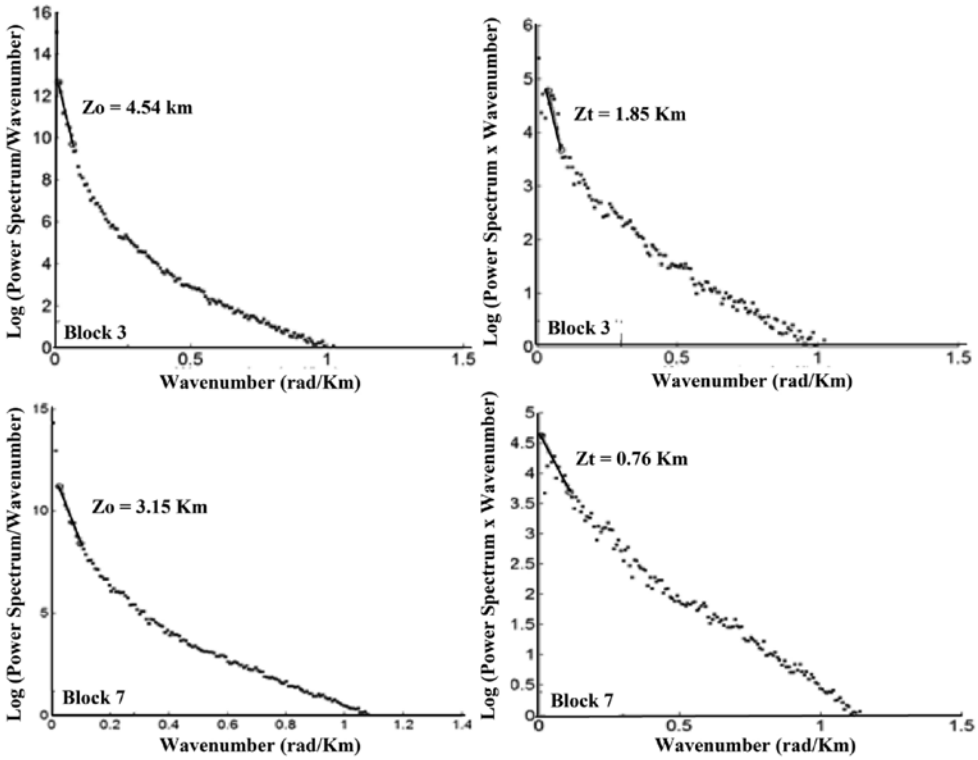

Figure 5. Radial averaged power spectral plots for blocks 3 and 7.

geological events like tectonic movement and intrusions. Consequently, it may not be unlikely that some of the observed major lineaments (BB′ and DD′), which trend NE-SW, in Figure 4 could be the St Paul's and Romanche paleostructures. Again, regions of magnetic lows and highs are revealed in the basin. These regions are marked H and L for magnetic high and magnetic low respectively in Figure 4. Conspicuous magnetic highs are located around Dekina, Baro and Pategi; while Bida, Dekina and Udegi have prominent magnetic lows. The low magnetic regions indicate the presence of deep-seated basic igneous intrusions into the basement beneath the basin. Basic igneous rocks are believed to have intruded the Basement Complex beneath the basin (Ojo, 1990). It could thus be inferred that the ancient fracture zones formed weak zones through which the magma that constituted the basic intrusions rose. The presence of large bodies of basic rocks indicated by these results suggests that a deep-seated rift may exist in the crust under the basin. Ojo (1990) further opined that the magnetic low anomalies may have been caused by predominantly basic rocks at depths which vary between 4 and 6 km well below the base of the sediments, which are generally not more than 2 km thick. The high magnetic regions may have resulted from thick sections of sedimentary ironstones. It is important to note that Bida Basin is the only sedimentary basin in Nigeria with abundant ironstones in its formational lithologies (Sakpe ironstone, Batati ironstone, Agbaja ironstone) and its other formations also contain measurable amounts of ferruginous components (Obaje et al., 2015).

Azimuthally averaged power and wavenumber-scaled power spectra for each of the 28 overlapping blocks were made and used to estimate the depths to bottom of magnetic sources (DBMS). Typical examples for blocks 3 and 7 are shown in Figure 5. The RHS of the figure shows the slope of the lower-wavenumber portion of the spectra, which leads to the estimation of the depth to the top of magnetic sources (Z_t); while the LHS shows the slope of the wavenumber-scaled spectra, which leads to the estimation of centroid depth (Z_o).

The estimated quantitative results are shown in Table 1. The table shows that the DBMS varies from 5.41 to 19.29 km with an average of 12.01 km. This depth information was subsequently used to generate a DBMS isotherm map for the basin as shown in Figure 6.

DBMS varies significantly in the study area. Figure 6 shows that the DBMS values in Bida Basin trend mostly NE – SW with the shallowest portion (less than 8 km) in the north-western part of the basin, and extends eastward while becoming deeper with its deepest depth (about 21 km) at the south-eastern part. In comparison with earlier results (Nwankawo and Sunday, 2017) obtained using conventional centroid method for the whole basin (Figure 7), the derived DBMS values using the modified model are found to be roughly 44% lower, which agrees with the submission of Bansal et al., (2011).

Table 1. Estimated DBMS Values

Blocks	Long (°E)	Lat (°N)	Depth to the top Z_t (km)	Centroid depth Z_o (km)	Depth to bottom Z_b (km)
1	5.00	10.50	0.47	5.3	10.13
2	5.50	10.50	0.39	4.09	7.79
3	6.00	10.50	1.85	4.54	7.23
4	6.50	10.50	0.77	5.33	9.89
5	4.50	10.00	0.85	6.52	12.19
6	5.00	10.00	0.74	5.30	9.86
7	5.50	10.00	0.76	3.15	5.54
8	6.00	10.00	1.24	4.43	7.62
9	6.50	10.00	1.20	4.85	8.50
10	4.50	9.50	1.71	7.10	12.49
11	5.00	9.50	0.55	3.98	7.41
12	5.50	9.50	0.84	5.71	10.58
13	6.00	9.50	0.43	5.65	10.87
14	6.50	9.50	0.66	5.95	11.24
15	7.00	9.50	0.90	7.66	14.42
16	7.50	9.50	0.56	9.09	17.62
17	5.50	9.00	1.05	8.45	15.85
18	6.00	9.00	0.40	7.65	14.90
19	6.50	9.00	1.44	7.13	12.82
20	7.00	9.00	1.35	5.94	10.53
21	7.50	9.00	2.90	6.69	10.48
22	5.50	8.50	0.94	7.05	13.16
23	6.00	8.50	1.07	7.11	13.15
24	6.50	8.50	1.43	8.22	15.01
25	7.00	8.50	0.96	7.25	13.54
26	7.50	8.50	1.78	9.29	16.8
27	7.00	8.00	1.51	10.4	19.29
28	7.50	8.00	2.24	9.78	17.32
			Average		12.01

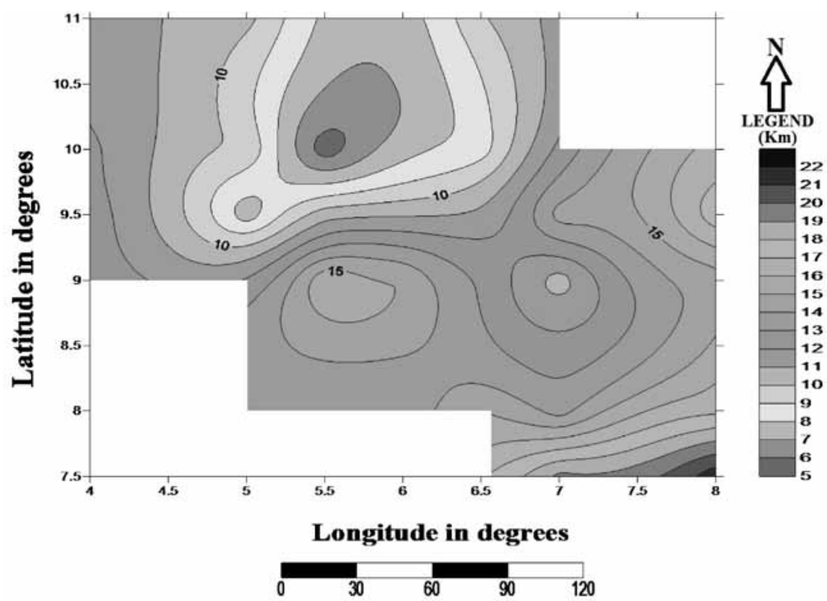

Figure 6. DBMS map of the study area (Contour interval 1 km).

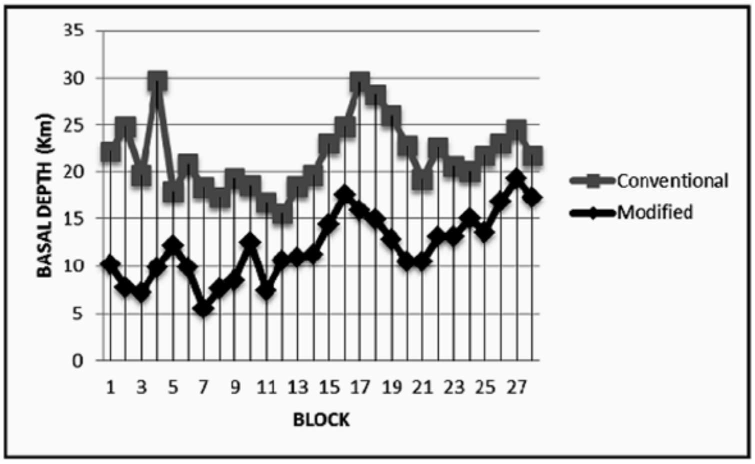

Figure 7. Comparison of DBMS values calculated using modified centroid for fractal distribution of sources with conventional centroid method.

CONCLUSION

The newly acquired high resolution aeromagnetic anomaly data over Bida Basin, north-central Nigeria has been studied using freshly developed fractal model to estimate the depths to bottom of magnetic sources (DBMS). The result shows that the DBMS varies between 5.41 and 19.29 km with an average of 12.01 km. Regions are observed in the basin with shallow DBMS (below 10 km). Further detailed studies are recommended in such regions. More so, the basin is the least studied of all Nigeria's inland basins.

To date, the basin has no information on seismicity, no exploratory wells have penetrated its sequences and subsurface data are limited (Obaje et al., 2009; 2015). Therefore, this study is expected to contribute significantly in the quantitative appraisal of the geo-processes and rheology of Bida Basin in north-central Nigeria.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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