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Spectral depth analysis for determining the depth to basement of magnetic source rocks over Nkalagu and Igumale areas of the Lower Benue Trough, Nigeria

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Structural interpretation of aeromagnetic data over Nkalagu-Igumale area of the Lower Benue Trough of Nigeria was carried out to determine the depth to magnetic basement and delineate the basement morphology and the structural features associated with the basin and their trends. The aeromagnetic data were subjected to series of computer based image and data enhancement techniques before spectral analysis. Results of the 2-D spectral analysis revealed two depths source models with the depth model (D1) for deep magnetic source bodies which are associated with intra-basement discontinuities and faults ranging from 2.15 to 5.25 km while the depth model (D2) of the shallow magnetic source bodies range from 0.35 to 0.99 km. From an economic viewpoint, the results indicate possible mineralization and existence of a reasonable Cretaceous sedimentary thickness in the area which is deep enough for hydrocarbon accumulation. The average sedimentary thickness obtained in the area is 3.75 km.

Key words: Benue Trough, depth to magnetic basement, aeromagnetic data, spectral analysis, intrusive bodies.

INTRODUCTION

Magnetic method is a measurement of the earth's magnetic field intensity, typically involving the total magnetic field and/or vertical magnetic gradient, horizontal or vertical component or horizontal gradient of the magnetic field (Biswas et al., 2017). Anomalies in the earth's magnetic field are caused by induced or remnant magnetism. Induced magnetic anomalies are the result of secondary magnetization induced in a ferrous body by the earth's magnetic field. The shape, dimensions and amplitude of an induced magnetic anomaly is a function of the orientation, geometry, size, depth and magnetic susceptibility of the body, as well as the intensity and inclination of the earth's magnetic field in the survey area (Biswas, 2016; Biswas and Acharya, 2016). For exploration purposes, both ground and aeromagnetic data have been used to investigate the presence of

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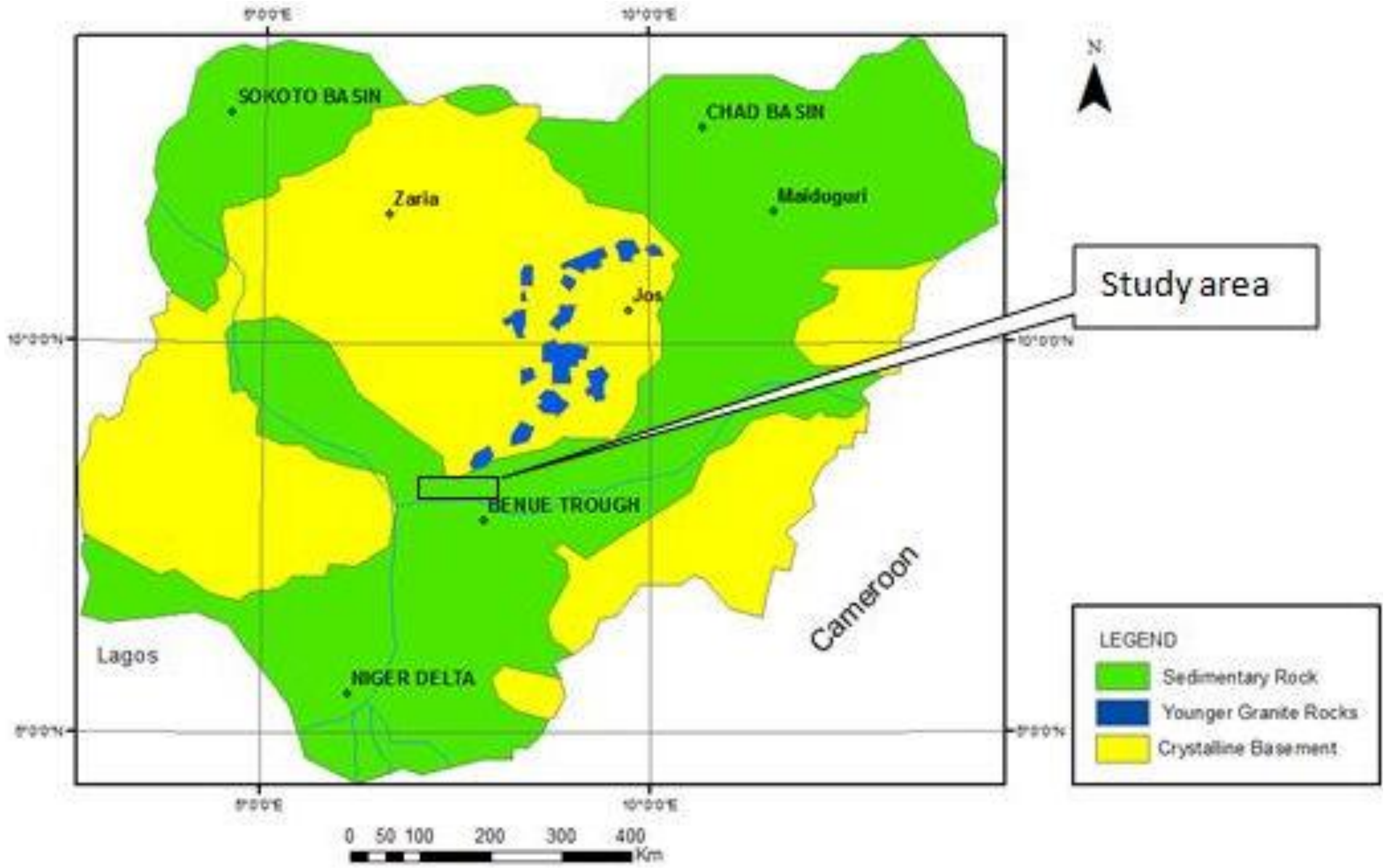

Figure 1. Map of Nigeria showing the study area.
Source: Jatau and Nandom (2013).

mineral deposits in combination with gravity. In the mining industry, both gravity and magnetic methods are still widely used as exploration tools for mapping subsurface geology and to estimate ore reserves for some massive ore bodies (Mandal et al., 2015; Biswas and Sharma, 2016). Nowadays, aeromagnetic surveys are very useful for determining depths to magnetic source rocks of the anomalies over an area, and utilized the principle that the magnetic field measured at the surface can be considered an integral of magnetic signatures from all depths. These anomalies arise as a result of the interactions between the magnetic field and the rocks of the earth crust and also from secondary mineralization along the fault planes in many sedimentary basins. The average depth to sources of ensembles (sedimentary thickness) across the geological area can be obtained from the energy (power) spectrum of the surface field when plotted against frequency in a logarithmic scale. Interpretation of aeromagnetic data can be done quantitatively and qualitatively. Quantitative interpretation involves making numerical estimates of the depth and dimensions of the sources of the anomalies and this often takes the form of modelling of the sources which could in theory, replicate the anomalies recorded in the survey (Biswas, 2015, 2016; Biswas et al., 2017). The computational efficiency and storage capacity of modern digital computers now enable the utilization of a wide range of sophisticated mathematical techniques for data processing and interpretation. Fourier spectral analysis as a mathematical technique has attracted increasing attention in recent years as a powerful tool for the interpretation of potential field data (magnetic anomalies).

The study area lies within the southern portion of the Lower Benue Trough and consists of Sheet 302 (Nkalagu sheet) and Sheet 288 (Igumale sheet) bounded within longitudes 7° 30’ and 8° 00’ East and latitudes 6° 30’ and 7° 00’ North and covering an area of about 6000 km^2. Figure 1 shows the map of Nigeria and location of the study area.

The Lower Benue Trough as a rift system and aulacogen (Olade, 1976) is an area of importance in terms of economic mineral deposits. Consequently, this has inspired a lot of interest on geophysical investigations by many researchers (Ofoegbu and Onuoha, 1991; Obi et al., 2010; Ugwu and Ezema, 2012) to re-examine the economic potentials of this mineral belt using different

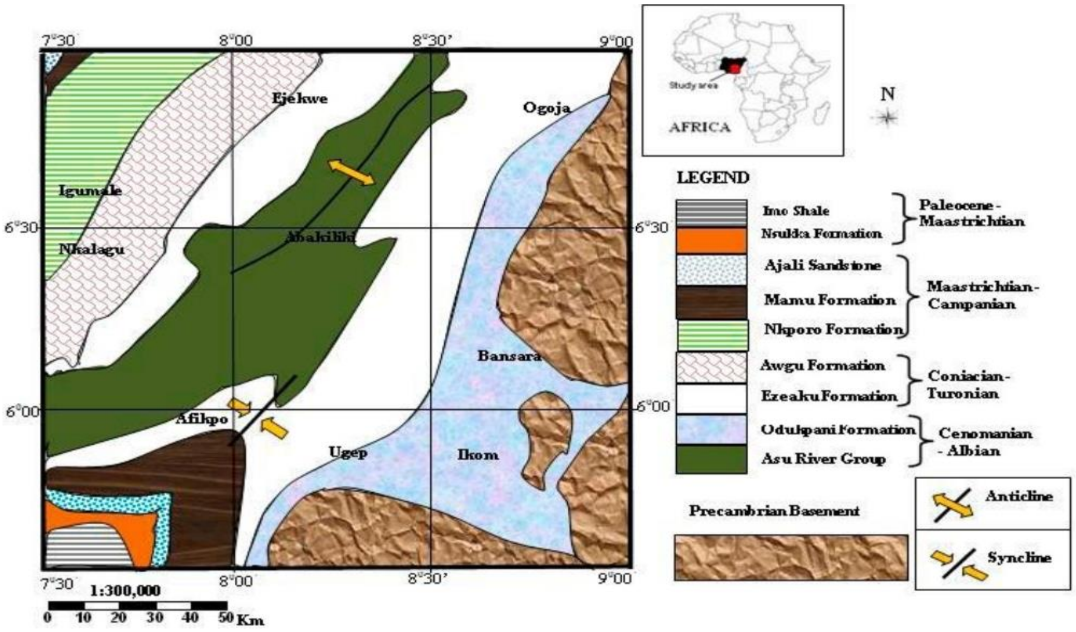

Figure 2. Geological map of some parts of Lower Benue Trough, including the study area.
Source: Onuba et al. (2013).

geophysical methods. Previous magnetic anomaly studies over the Lower Benue Trough has shown that the anomalies in the area can best be explained in terms of the combined effects of deep lying basement and intermediate intrusions at both shallow and deep depths (Ofoegbu, 1984, 1985; Ofoegbu and Onuoha, 1991; Ugwu and Ezema, 2012). Ofoegbu (1985) estimated the sedimentary thickness in the Lower and Middle Benue Trough to vary between 0.5 and 7.0 km. Some of the anomalies were interpreted in terms of dykes and volcanic plugs (Ofoegbu, 1984; Ugwu and Ezema, 2012). Previous studies also suggested that Benue Trough has a typical network of fractures and lineaments with dominant trends of NE-SW direction. The intrusive bodies are of variable thickness and different directions of magnetization, which suggest that although they are derived from a common basic mantle material, they were probably emplaced at different polarity epochs (Ofoegbu, 1984).

To contribute to a better understanding of the depth and nature of mineralization, geology and development of the tectonic history in the Lower Benue Trough, we have considered the use of spectral analysis of the aeromagnetic data over Nkalagu and Igumale areas to compute for depths to magnetic sources.

Geology of the study area

The geology and evolution of the lower Benue Trough is now fairly well documented (Wright, 1968, 1976; Nwachukwu, 1972; Olade, 1975; Ofoegbu, 1985; Obaje, 2009). The lower Benue Trough which is underlain by a thick sedimentary sequence was formed as a result of series of tectonics and repetitive sedimentation in the Cretaceous time. The depositional history of the Benue Trough is characterized by phases of marine regression and transgression (Reyment, 1965; Short and Stauble, 1967; Murat, 1972). The major component units of the lower Benue Trough include the Anambra Basin, the Abakaliki Anticlinorium and the Afikpo Syncline. The oldest sediment of the sequence belongs to the Asu River Group which unconformably overlies the Precambrian basement complex that is made up of granitic and magmatic rocks (Ofoegbu and Onuoha, 1991). The Asu River Group whose type outcrops in Abakaliki has an estimated thickness of about 2000 m (Ofoegbu, 1985) and is Albian to Cenomanian. It comprises of argillaceous sandy shales, laminated sandstone units and minor limestones with an interfingering of magnetic volcanics (Nwachukwu, 1972). The shales are fissile and highly fractured. Deposited on top of these Asu River Group sediments in the area are the Upper Cretaceous Eze-Aku shales. The Turonian Eze-Aku shales consist of nearly 1000 m of calcareous flaky shales and siltstones (Reyment, 1965). The geological map of the study area is shown in Figure 2.

MATERIALS AND METHODS

Two aeromagnetic maps were acquired from the Nigerian Geological Survey Agency (NGSA). They are Sheets 302 (Nkalagu) and 288 (Igumale). The data were acquired along a flight line trend of 135° with a spacing of 500 m and an average flight elevation of

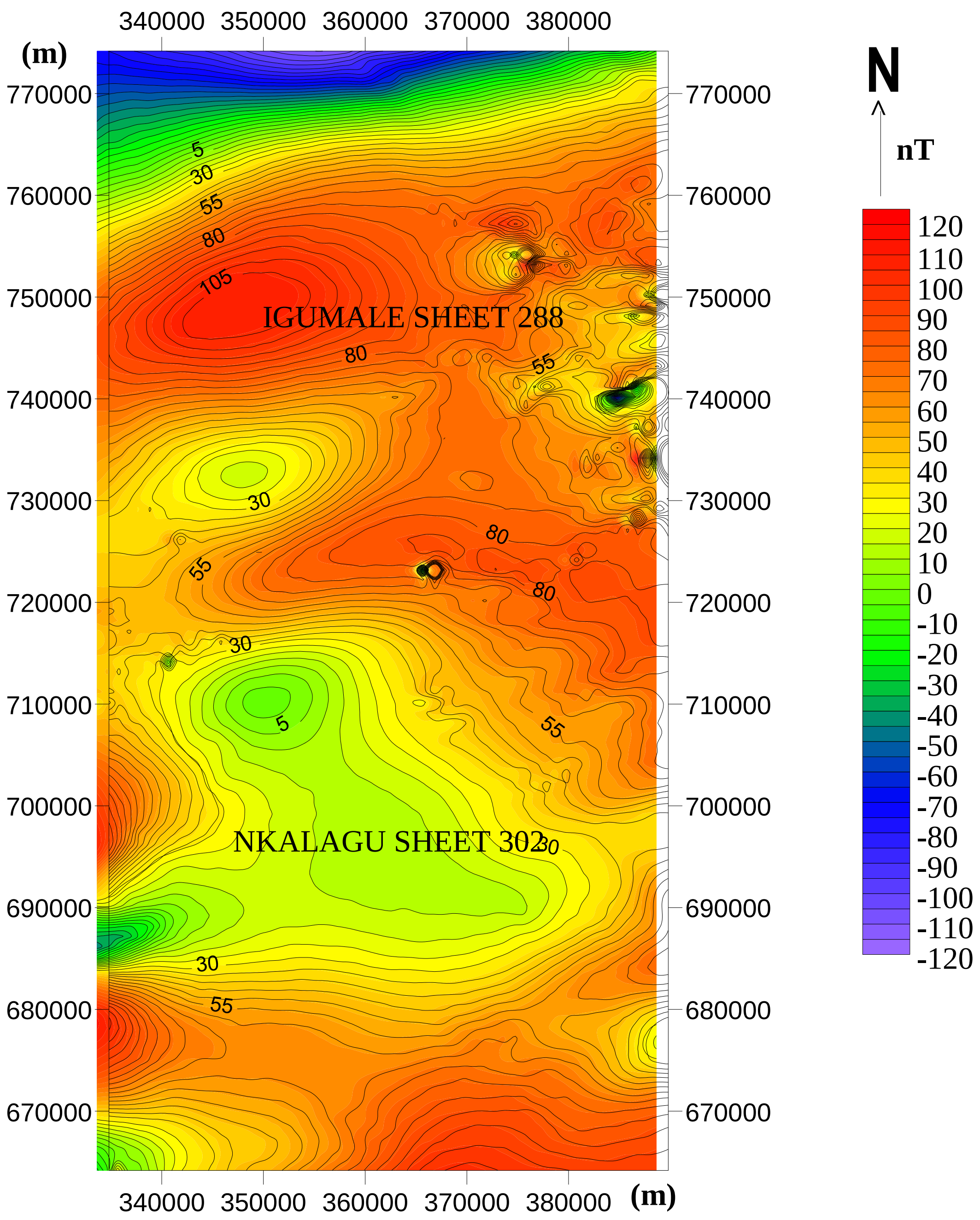

Figure 3. Total magnetic field intensity map of the study area.

75 m, while the tie lines trend and spacing are 225° and 500 m, respectively. The data were made available in digital form on scale of 1:100,000.

The geomagnetic gradient was removed from the data using the International Geomagnetic Reference Field (IGRF). The data sheets of Nkalagu (302) and Igumale (288) were combined using Microsoft Excel 2010 to form the study area covering a total area of about 6000 km^2. The combined sheet was used to produce the total magnetic field intensity (TMI) map (Figure 3) of the study area employing WINGLINK Software and Surfer 10 binary grids. The regional-residual separation was done by polynomial fitting. Here, all the regional fields were calculated as two-dimensional first degree polynomial surfaces. Figure 4 shows the residual anomaly map of the study area after the regional-residual separation. The residual field was also gridded into horizontal and vertical derivatives (Figures 5 and 6). The 3-D surface anomaly map of the study area is also shown in Figure 7.

In order to calculate the depth to basement of the study area using spectral analysis, the study area was divided into six profiles with 18 cells containing 18 × 18 data points. In doing this, it was ensured that essential parts of each anomaly were not cut off in the cells as each cell was made to contain more than one maximum, as suggested by Hahn et al. (1976). To achieve this, the cells were made to overlap each other using Excel 2010 program by applying

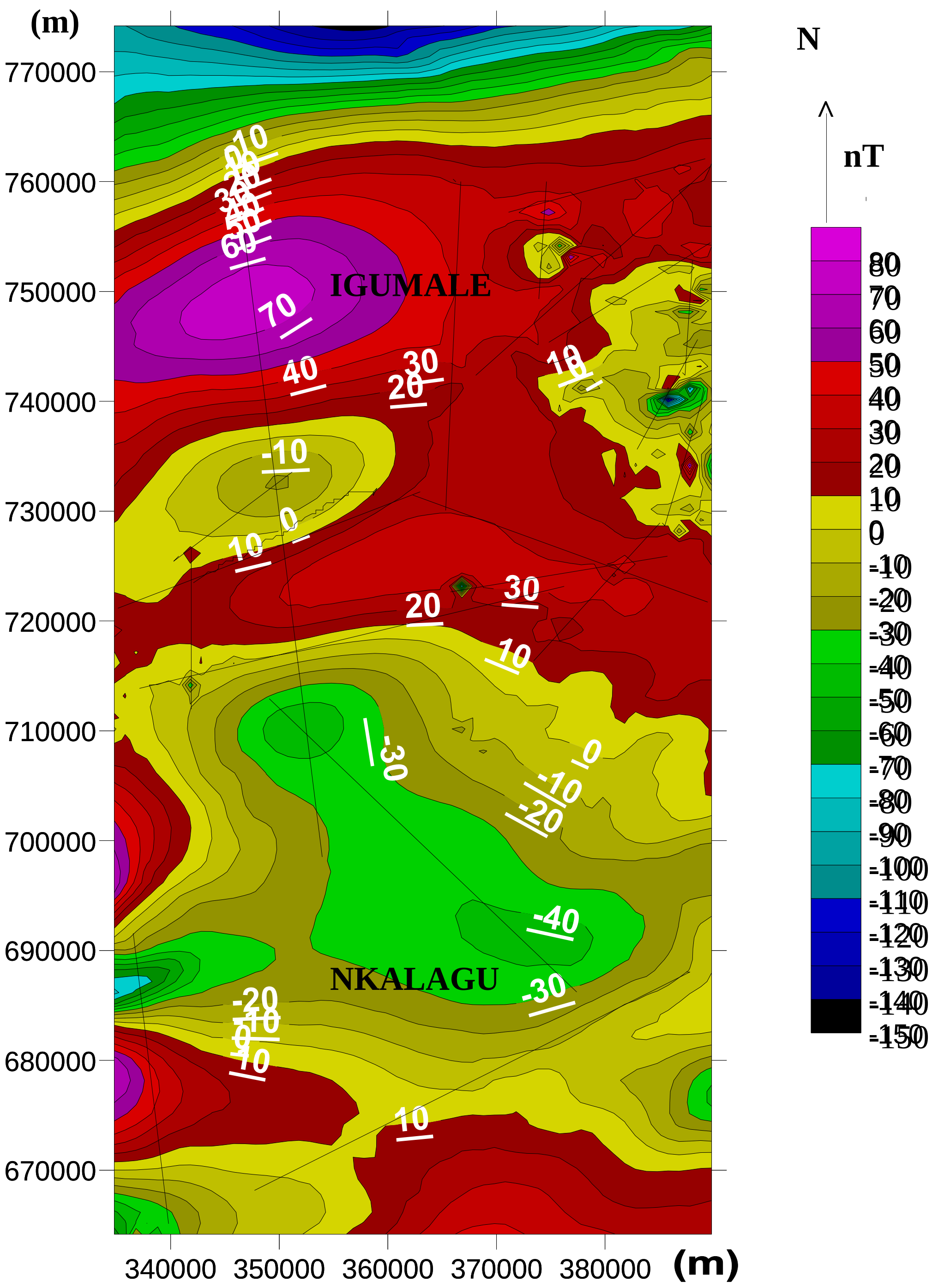

Figure 4. Residual anomaly map of the study area.

inequality formulas in which degree of overlap was insignificant. The Excel software which has the Fourier mathematical algorithm was used to compute the Fast Fourier Transform (FFT) magnitude and FFT frequency. The energy (magnitude) which is in logarithmic scale was plotted against logarithm frequency to produce a decay-curve segment which decreases in slope with increasing frequency. The depths to sources of ensembles were obtained by manually fitting a straight line to each linear interval of the logarithmic energy-decay curve which yields a negative slope. The line of the first linear interval was fit from the deviation of the decay curve from the vertical axes of the logarithmic energy. The second line of the second linear interval was drawn from the deviation of the decay curve from the line of the first linear interval. This was done sequentially such that there is no other possible linear interval between the first and second linear intervals.

Smoothing was done to the signals to filter and determine a trend (linear curvature) on the decay curve by removing high frequency noise. The effect of this filter was to average the value at a given grid

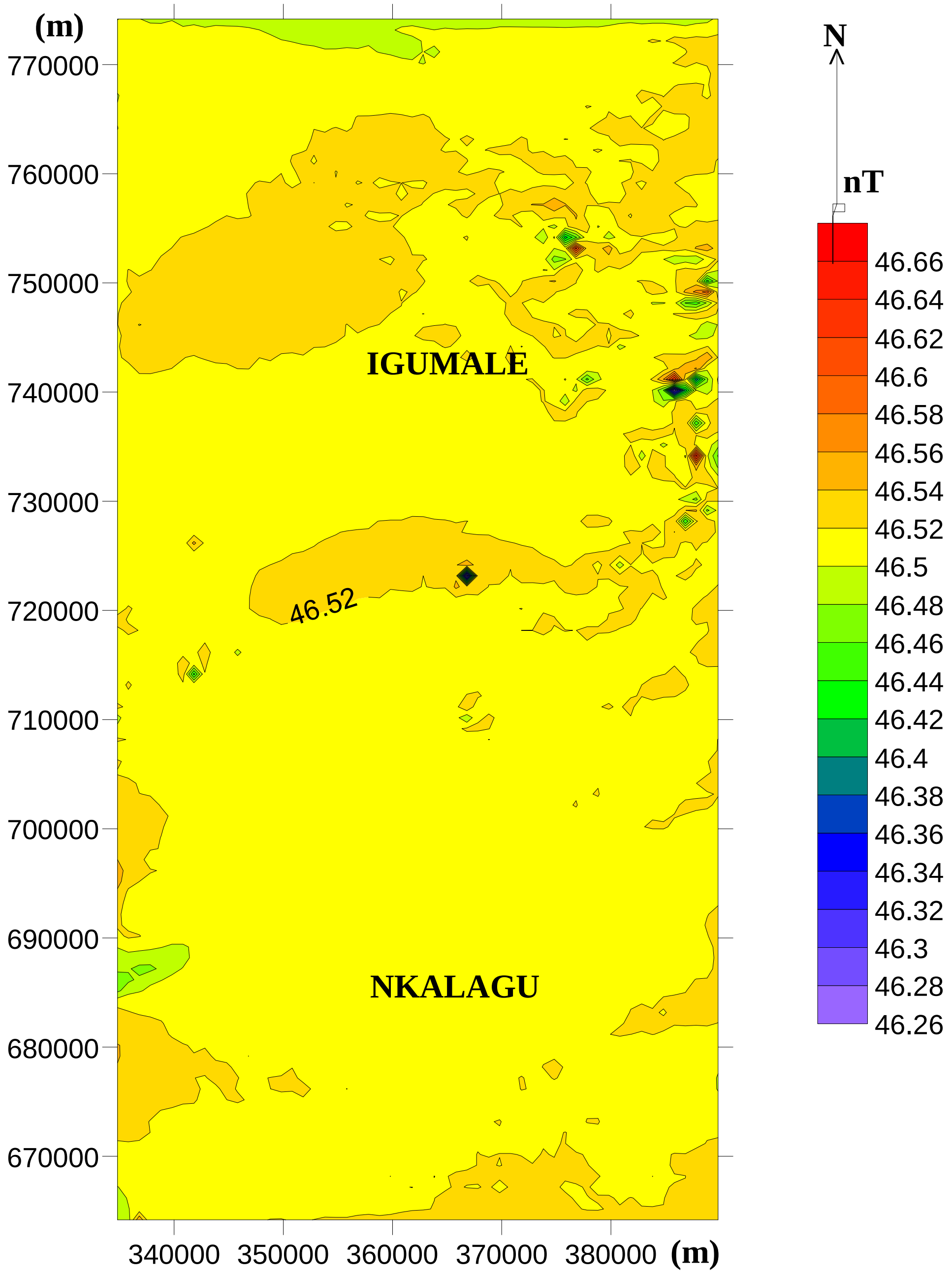

Figure 5. Vertical derivative anomaly map of the study area.

node together with the values at its eight nearest neighbours to give a new value at the centre point. The smoothing operator was moved repeatedly row-by-row over the whole grid to produce new gridded values. The problems of aliasing effect and Gibb's phenomenon which are normally encountered in the course of performing spectral analysis were taken care of by the use of small sampling intervals to reduce frequencies greater than Nyquist frequency.

RESULTS

The spectral plots of logarithmic energy against frequency for the six representative cells of the profiles are shown in Figures 8 to 13. Two-depth models have been estimated for all the cells and these values are summarized in Table 1. The slope is given by the equation:

$$S = \frac{\Delta LogE}{\Delta F} = \frac{LogE_2 - LogE_1}{F_2 - F_1}$$

While the depth to slope relationship is given by $D = -S/4\pi$ when frequency is in cycle/km (Bonde et al., 2014).

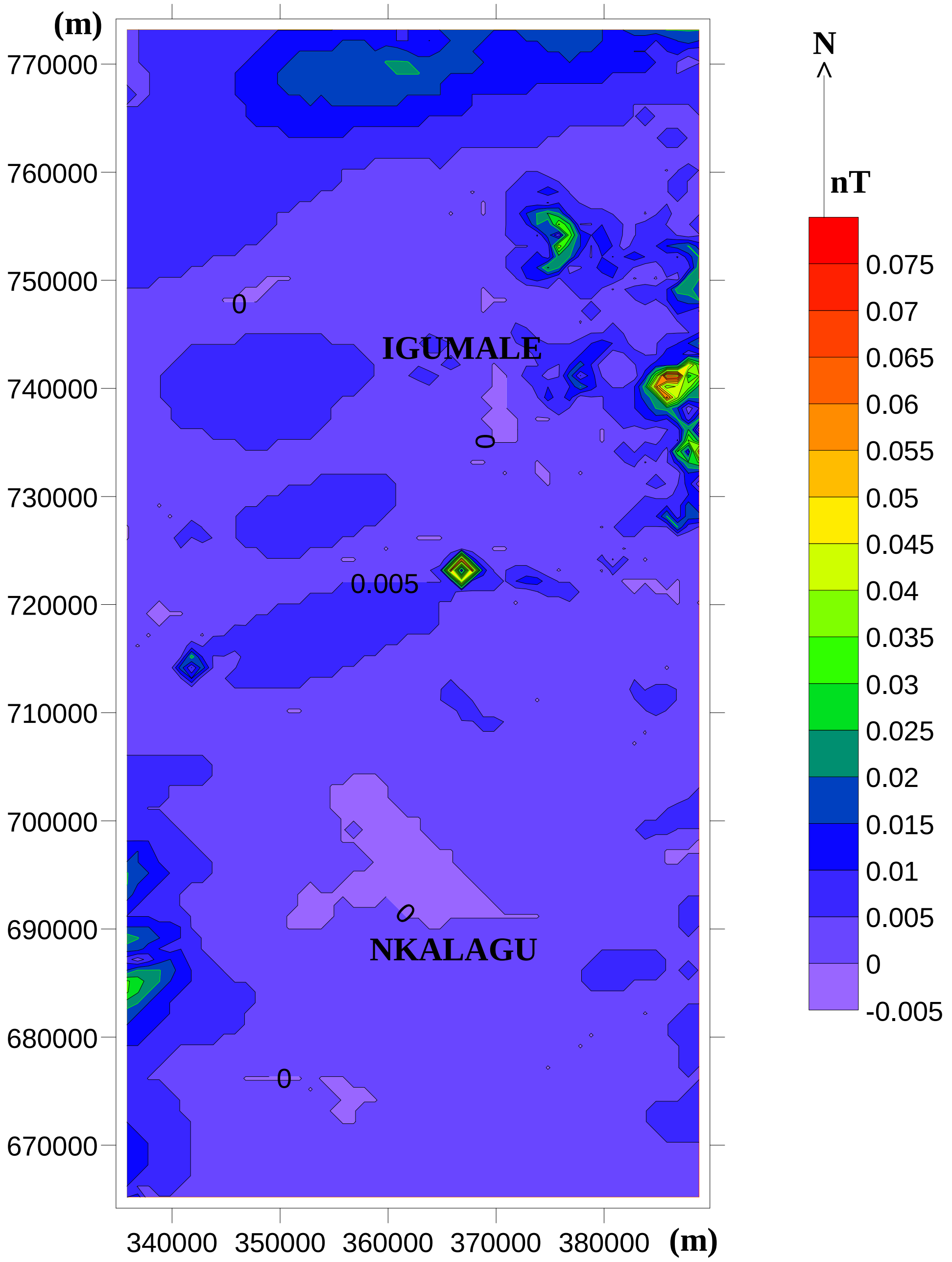

Figure 6. Horizontal derivative anomaly map of the study area.

DISCUSSION

A visual inspection (subjective) of the total magnetic intensity (TMI) and residual maps show that the contour lines of the central and southern parts are widely spaced, suggesting that the depths to magnetic basement in these areas are relatively high. At the northern part of the maps, the contour lines are more closely together, suggesting that the depth to basement is shallow at this part. Also, there are spikes at the northeastern part which shares a geologic boundary with Ejekwe (very similar to Abakaliki, geologically) indicating the presence of magnetic mineral rocks or intrusive bodies within the sedimentary cover. So it is possible that the existence of intrusive bodies within the Abakaliki anticlinorium of the Benue Trough (Ofoegbu and Onuoha, 1991; Ugwu and Ezema, 2012; Abdulahi et al., 2014) extends to Igumale. The distribution of high magnetic intensities from just above the central part toward the southern part of the study area suggests the existence of deep penetrating fractures within the area while the low magnetic intensity indicated by closures and the linear sub parallel

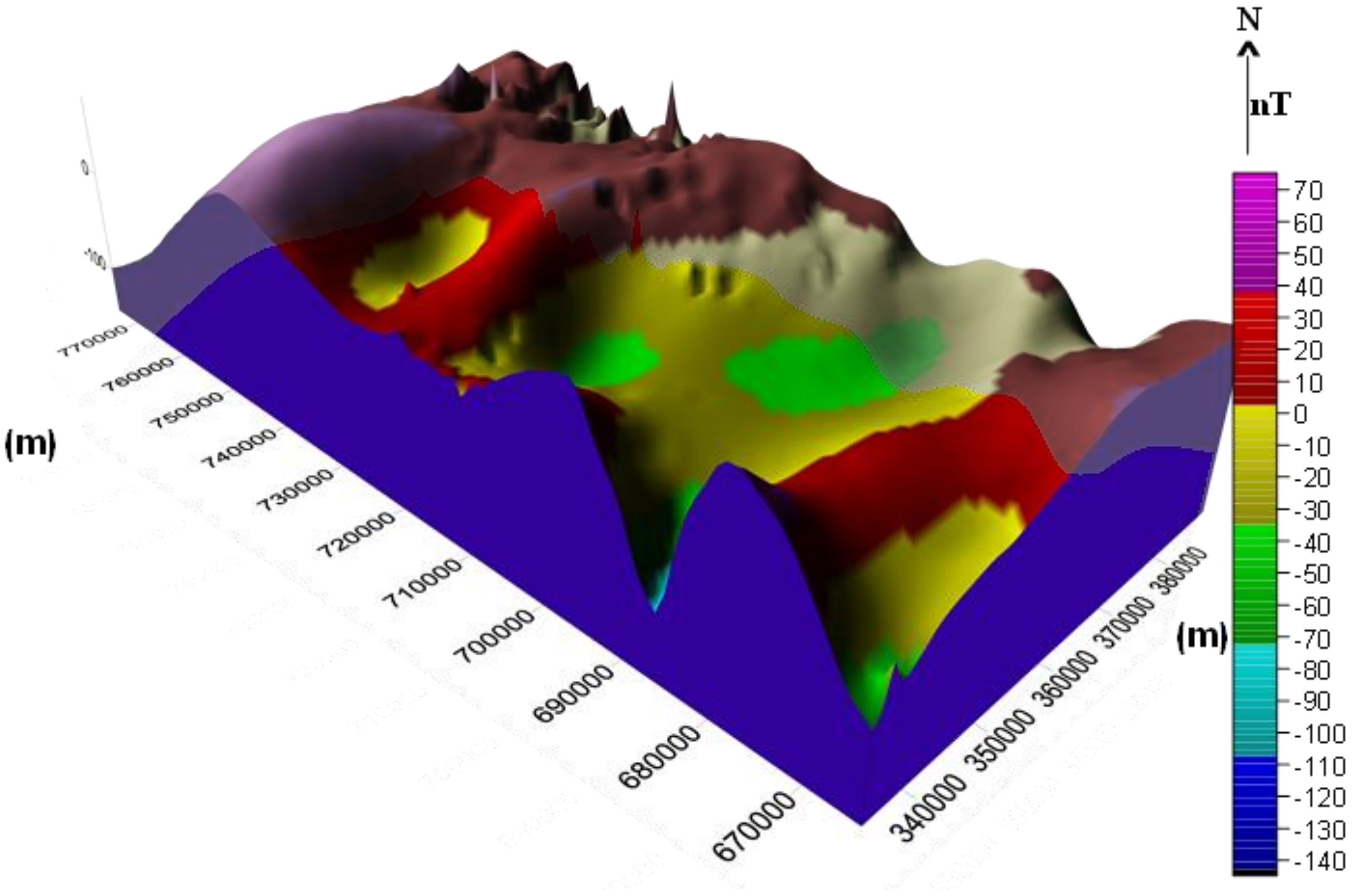

Figure 7. 3-D surface anomaly map of the study area showing the basement topograghy.

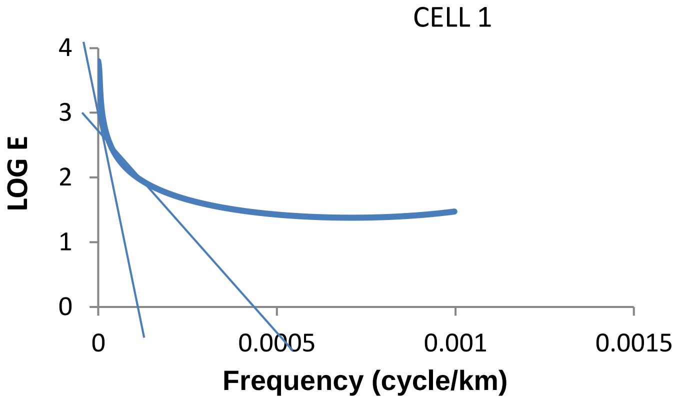

Figure 8. Cell 1 of Profile One.

orientations of the contours at the uppermost northern part of the map suggest a shallow geologic structure. Structural trends within the study area as shown by delineation in the residual map are mainly NE-SW and NW-SE directions which agree with the fault orientation within the Benue Trough, with the NE-SW trends being dominant.

The 3-D surface map of the study area (Figure 7) shows high basement, relief indicating folded and undulating topography, which can be interpreted as part

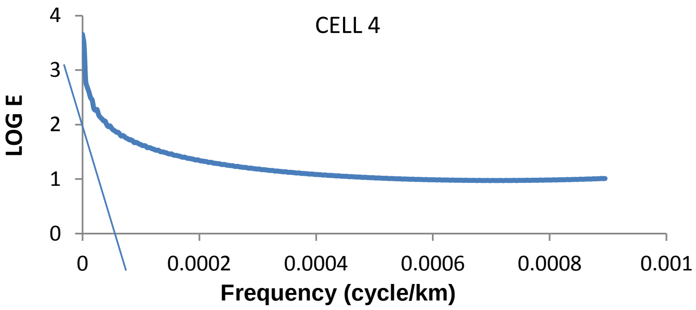

Figure 9. Cell 5 of Profile Two.

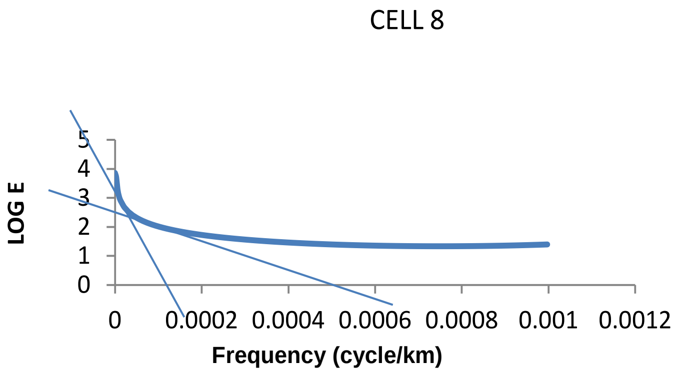

Figure 10. Cell 8 of Profile Three.

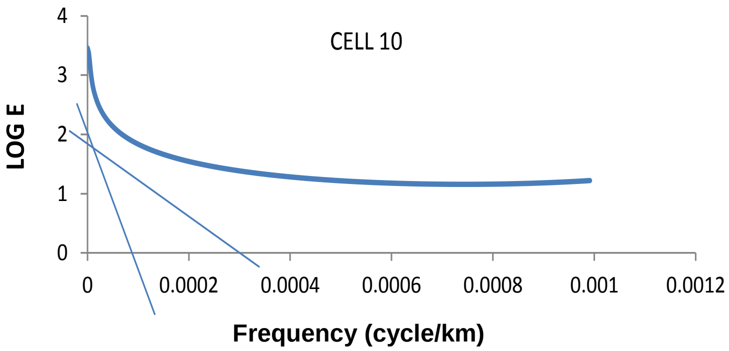

Figure 11. Cell 10 of Profile Four.

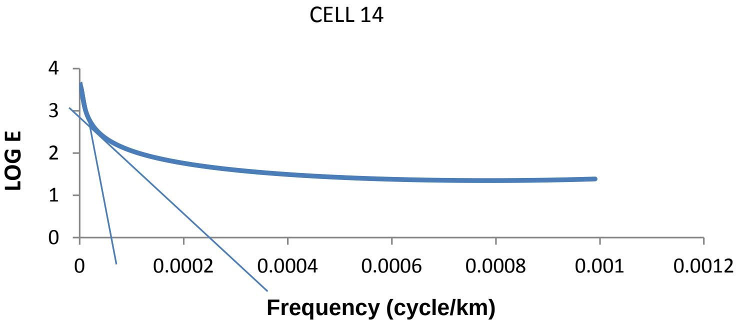

Figure 12. Cell 14 of Profile Five.

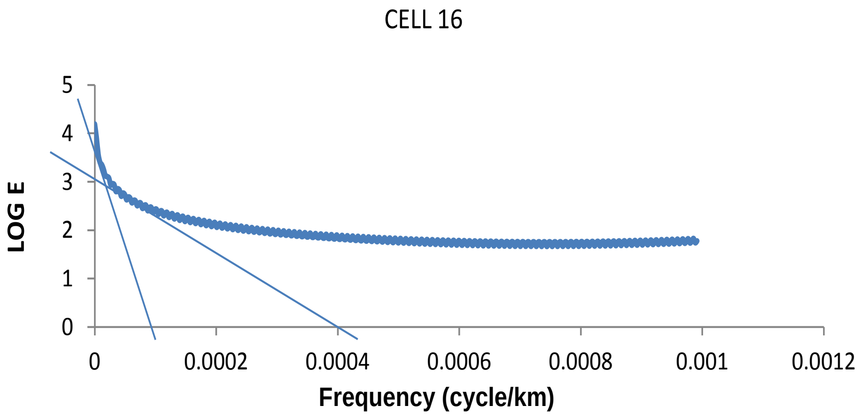

Figure 13. Cell 16 of Profile Six.

Table 1. Summary of the estimates of spectral depths to the magnetic basement in the study area.

Cell 16	**Cell 17**	**Cell 18**	**Profile 6**
D1 = 2.67 km	D1 = 4.97 km	D1 = 3.98 km	Average D1 = 3.87 km
D2 = 0.46 km	D2 = 0.94 km	D2 = 0.50 km	Average D2 = 0.63 km
Cell 13	**Cell 14**	**Cell 15**	**Profile 5**
D1 = 2.39 km	D1 = 4.77 km	D1 = 3.98 km	Average D1 = 3.71 km
D2 = 0.48 km	D2 = 0.35 km	D2 = 0.45 km	Average D2 = 0.43 km
Cell 10	**Cell 11**	**Cell 12**	**Profile 4**
D1 = 4.30 km	D1 = 2.99 km	D1 = 2.98 km	Average D1 = 3.42 km
D2 = 0.40 km	D2 = 0.46 km	D2 = 0. 82 km	Average D2 = 0.56 km
Cell 7	**Cell 8**	**Cell 9**	**Profile 3**
D1 = 2.15 km	D1 4.64 km	D1 = 3.28 km	Average D1 = 3.36 km
D2 = 0=0.42 km	D2 = 0.66 km	D2 = 0.59 km	Average D2 = 0.56 km
Cell 4	**Cell 5**	**Cell 6**	**Profile 2**
D1 = 3.71 km	D1 = 3.58 km	D1 = 5.25 km	Average D1 = 4.18 km
D2 = 0.53 km	D2 = 0.64 km	D2 = 0.82 km	Average D2 = 0.66 km
Cell 1	**Cell 2**	**Cell 3**	**Profile 1**
D1 = 4.38 km	D1 = 3.56 km	D1 = 4.00 km	Average D1 = 3.98 km
D2 = 0.80 km	D2 = 0.66 km	D2 = 0.99 km	Average D2 = 0.82m

of the Abakaliki folded belt. The results of the vertical derivative anomaly maps indicate the lithologic boundaries between different formations underlying the area. The horizontal derivative map shows the possibility of faults or local fractured zones passing through the north central and central part of the study area.

Results of the spectral analysis of the aeromagnetic data over the study area indicated a two-depth source model. The shallow depth model is between 0.35 and 0.99 km which probably indicates the presence of intrusive bodies. The deep source lies at a depth that varies between 2.15 and 5.25 km. These deep sources represented by the first segment of the spectrum in all the cells of the six profiles reflect the Precambrian basement of the study area. Profile two shows the thickest sedimentary cover in the Nkalagu area (cells 4, 5 and 6 of Table 1). This result closely agrees with the results from other aeromagnetic works which had indicated depth (sedimentary thickness) of 1.5 to 4 km in Nkalagu (Nur et al., 1994; Obi et al., 2010). The range of the average profile depths implies a nearly evenly distributed sedimentary thickness within the study area and ranges between 3.5 and 4.2 km.

Conclusion

Quantitative interpretation of the aeromagnetic data over Nkalagu and Igumale areas of the Lower Benue Trough has been successfully carried out using spectral analysis to determine depth to the magnetic basement. Structural interpretation of the residual anomaly map was also used to delineate the basement morphology, relief, and the structural features associated with the basin and their trends. The results of the study have shown that the area is characterized with an average sedimentary thickness of 3.75 km for the deep source model. From economic point of view, the results indicate possible mineralization within Igumale area due to presence of a few intrusive bodies within the area. The results also show very high possibility for hydrocarbon occurrence due to the existence of folded basement, faults/fractures capable of trapping hydrocarbons. The occurrence of reasonable Cretaceous sedimentary thickness in the area supports the hydrocarbon potential of the area.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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