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Spectral analysis and source parameter imaging of aeromagnetic data of Lafia and Akiri Areas, Middle Benue Trough, Nigeria

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This study aimed to estimate the depth of magnetic source bodies in Lafia and Akiri areas which fall within the middle Benue trough, Nigeria. Aeromagnetic data were used and spectral analysis and source parameter imaging were used for the quantitative interpretation of the data. The total magnetic intensity (TMI) contour map obtained from gridding of the data ranging from -39.5 to 100.0 nT was separated into regional and residual contour maps; it was done by polynomial fitting to produce the residual aeromagnetic intensity contour map. The residual intensity varies from -78.9 to 55.0 nT while the regional intensity varies from -39.18 to 39.84 nT. Depth results obtained from spectral analysis revealed two depth sources: the shallower magnetic source bodies and the deeper magnetic source bodies. The depth of shallower magnetic sources ranges from 0.557 to 1.261 km, with an average depth value of 0.899 km, whereas the depth of deeper magnetic sources varies from 2.419 to 5.732 km with an average depth value of 4.105 km. The SPI depth result ranges from -0.5638 km (shallow magnetic bodies) to 5.8381 km (deep lying magnetic bodies). The two methods showed depth estimation within the same range. The sedimentary thickness obtained from the different methods indicates the possibility of hydrocarbon accumulation if other conditions for hydrocarbon generation are satisfied.

Key words: Magnetic source bodies, depth estimation, spectral analysis, SPI, Lafia and Akiri areas, aeromagnetic data.

INTRODUCTION

The mineral resources and hydrocarbon (oil and gas) which man skilfully extracts from the bowels of the earth has led to industrial development of many countries in the world Nigeria inclusive. Civilization on earth would not have been meaningful without it. The search for these mineral resources and hydrocarbon (oil and gas) has been a major business challenge in Nigeria since the pre-colonial era and the 1960s, respectively. The bedrock of Nigeria's economy has been the solid mineral and currently the lucrative oil sector due to its high profitability. Over 80 percent of the country's revenue comes from export and domestic sales of the oil and gas upon which approximately over 170 million growing population depends on (Kamba and Ahmed, 2017). As

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the hydrocarbon potential of the prolific Niger Delta becomes depleted or in the near future may be exhausted due to continuous exploitation, attention needs to be shifted to other sedimentary basins. However, once hydrocarbon is confirmed in the area efforts and more money will be sunk into the area with the hope of finding oil in the near feature.

One way of harnessing these is by magnetic exploration. Magnetic exploration is carried out on land, at sea and in the air. For areas of appreciable extent, surveys usually are done with the airborne magnetometer (Telford et al., 1990). Airborne magnetic surveying is extremely attractive for reconnaissance because of low cost per kilometer and high speed. The speed not only reduces the cost, but also decreases the effects of time variations of the magnetic field. Aeromagnetic survey involves fixing of magnetic field measuring device to an aircraft and using it to fly over the area of interest at a particular height and at a particular spacing called line spacing. The aircraft flies in a grid-like pattern and the height and line spacing determining the resolution of the data. As the aircraft is flown across the area, the magnetometer measures the variations in the earth magnetic field due to the temporal effects of the constantly varying solar wind and spatial variations in the Earth's magnetic field. These variations are used for the production of the aeromagnetic map of the area. This map shows the magnetic anomalies originating from the materials within the earth subsurface.

Magnetic anomaly maps generally reflect variations in the Earth's magnetic field resulting from the underlying rocks' magnetic properties (for example magnetic susceptibilities) (Anudu, 2014). Though most rock-forming minerals have negligible to very low magnetic susceptibility and therefore are essentially non-magnetic; certain types of rocks contain enough magnetic minerals (especially magnetite), therefore generate recognisable magnetic anomalies. Sedimentary rocks generally have the lowest magnetic susceptibility, whereas metamorphic and basic igneous rocks have the highest magnetic susceptibilities (Dobrin and Savit, 1988; Telford et al., 1998; Kearey et al., 2002). Magnetic anomalies are caused by magnetic minerals contained in rocks; such anomalies are usually associated with underlying basement (igneous and/or metamorphic) rocks or by igneous bodies within sedimentary successions such as intrusive plugs, dykes, sills, lava flows and volcanic rocks (Gunn, 1997), as well as due to cultural iron contamination and antigenic alterations in sedimentary rocks possibly caused by hydrocarbon migration (Costanzo-Alvarez et al., 2000; Aldana et al., 2003).

Several studies have been carried out on the Benue Trough of Nigeria including the middle Benue trough. The formation was first recognized by Shell-BP geologist. The mines development of Nigeria also carried out a preliminary survey of Lead-Zinc in 1948 and 1949 using student geologist from United Kingdom. In this study, various depths to magnetic sources would be determined using Spectral analysis and Source Parameter Imaging for Lafia and Akiri both in the Middle Benue Trough basement terrain. The Spectral analysis and Source Parameter Imaging (SPI) of aeromagnetic fields over this area would differentiate and characterize regions of sedimentary thickening from those of uplifted or shallow basement. The results could be used to suggest whether or not the study area has the potential for oil/gas and mineral deposits concentration.

Location and geology of the survey area

Geographically, the study area (Figure 1a) is located in the Middle Benue Trough Nigeria within Latitude 8.0°N to 8.5°N and Longitude 8.5°E to 9.5°E. The geology of the study area consists of basement complex dominated by three rock types, older granites, younger granites and volcanoes and sheets of basalts. The older granites date to the late Cambrian and Ordovician, the younger granites were emplaced dating to the Jurassic. The Middle Benue Trough (MBT) extends Northeast ward approximately as far as line joining Bashar and Mutum Biyu. This boundary marks the Southern limit of the Gombe and Keri-Keri Formation, while the older sediments of the Upper Benue Trough undergo lateral facies change in this area. The middle Benue trough is divided into six formations: the Asu River Group, Awe Formation, Keana Formation, Ezeaku Formation, Awgu Formation and finally the youngest which is the Lafia Formation (Figure 1b). The lithological units of MBT show that the Cretaceous stratigraphy of this geographic division of the Benue Trough comprises the oldest rocks belonging to the Asu River Group: a mixture of shale and siltstones of marine origin, and lava-flows, dykes and silts.

This group, which is believed to be about 3000 m thick, lies uncomfortably on an older basement complex. The basement complex, which crops along the fringes of the study area, consists of granulitic gneisses, migmatites, older granites, younger granites, porphyries and rhyolites. Rock units belonging to the Asu River Group outcrop along the axis of the Keana anticline to the east of the town of Keana (Offodile, 1976). The Asu River Group is overlain by the transitional beds of the Awe Formation. This consists of flaggy, whitish, medium to coarse-grained sandstones, interbedded with carbonaceous shales or clays from which brine springs issue continuously (Ford, 1981; Offodile, 1984). The Awe Formation marks the beginning of the regressive phase of the Albian Sea and is overlain by continental fluviatile sands of the Keana Formation. The Ezeaku Formation comprises essentially of calcareous shale, micaceous fine to medium grained friable sandstones, and occasional beds of limestone.

The Agwu Formation consists mainly of black shale,

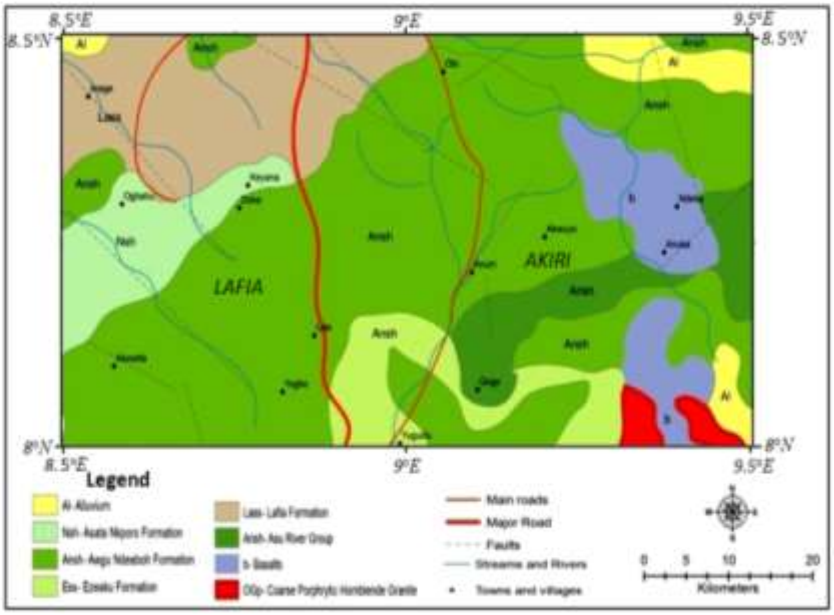


Figure 1a. Geological map of the study area.

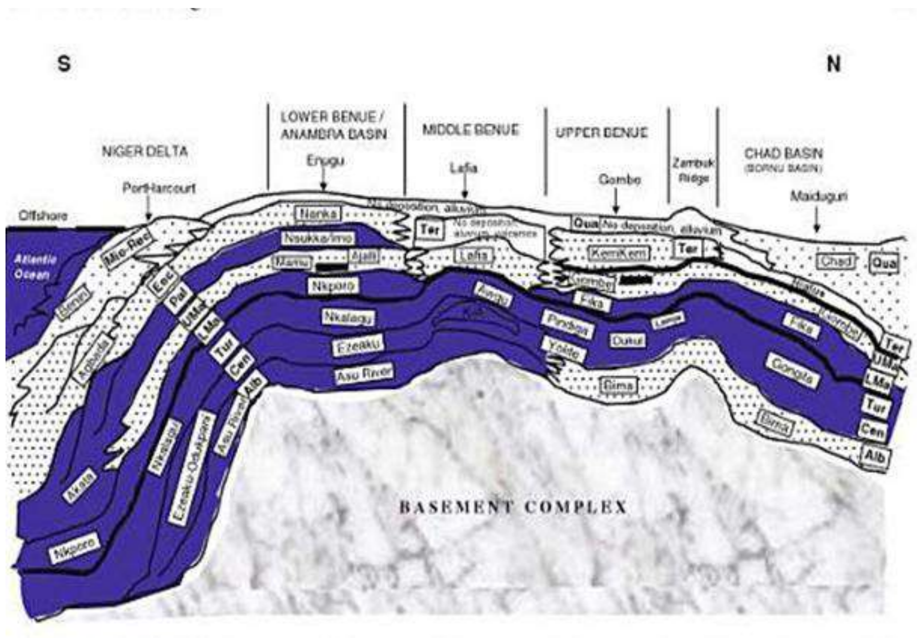


Figure 1b. Stratigraphic succession in the Benue trough (Obaje, 2004).

sandstones and local coal seams. The Lafia Formation is the youngest formation reported in the MBT and consists of coarse-grained ferruginous sandstones, red loose sand, flaggy mudstones and clays (Offodile, 1976).

MATERIALS AND METHODS

The materials used in this study include two sheets of aeromagnetic data of Lafia and Akiri. Software applications used include Oasis Montaj, Microsoft excel and Surfer32. The high resolution aeromagnetic data of Lafia and Akiri were obtained from the Nigerian Geological Survey Agency (NGSA). The aeromagnetic data were obtained using a 3 x Scintrex CS2 cesium vapour magnetometer. Fugro Airborne Surveys carried out the airborne geophysical work in 2009. The survey was flown at 80 m elevation along flight lines spaced 500 m apart. The flight line direction was 135 while the tie line direction was 225. The geomagnetic gradient was removed from the data using International Geomagnetic

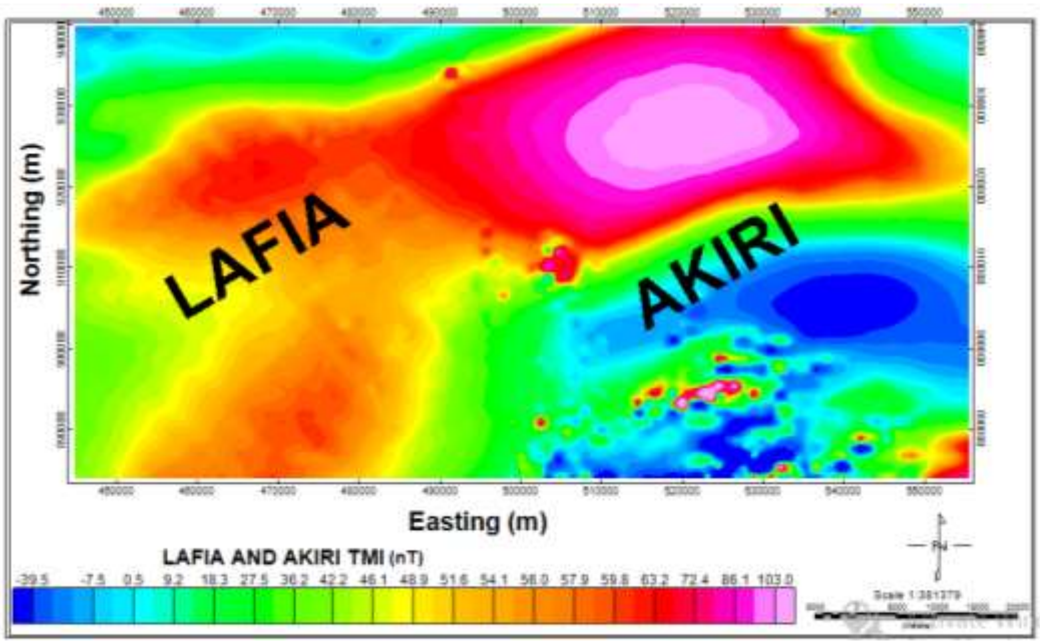


Figure 2. Total magnetic intensity (TMI) map of the study area.

Reference Field (IGRF).

Data processing

The two digitized sheets of Lafia and Akiri were first merged into a single sheet which formed the study area. The data were gridded in order to produce the total magnetic intensity (TMI) map of the study area (Figure 2). A grid size of 200 was used in order to avoid over or under sampling based on the sampling distance of the two data. The first step in processing the data was the polynomial fitting in order to remove the regional anomalies (Figure 5) from the total magnetic intensity, to obtain the residual anomaly (Figure 6). The first order polynomial fitting was applied on our data. Other processing techniques applied include the first vertical derivative, second vertical derivative and horizontal derivative (Biswas et al., 2017).

Two methods of interpretation were employed in this study: qualitative and quantitative. Qualitative interpretation involves the extraction of geologic information from maps and grids. The extracted residual anomaly was used for qualitative interpretation based on visual inspection of the data. Qualitative interpretation of aeromagnetic data has been done by many researchers including Vacquier et al. (1951) and Sharma (1976).

The qualitative interpretation of a magnetic anomaly map begins with a visual inspection of the shapes and trends of the major anomalies, delineation of the structural trends, closer examination of the characteristic features of each individual anomaly etc (Nwosu, 2014). These features majorly dwell on the relative locations and amplitudes of the positive contour parts of the anomaly (magnetic highs) and negative contour parts of the anomaly (magnetic lows) Sharma, 1976. The qualitative interpretation carried out in this work dwells on the production and interpretation of the composite anomaly map of the area, the regional map, the residual map and the lineament map of the study area. Quantitative interpretation was carried out by employing spectral analysis and source parameter imaging (SPI). These two methods were used to estimate depths of anomalous bodies.

Spectral analysis

Spectral analysis is the process of calculating and interpreting the spectrum of the potential field data. The spectral depth method is based on the principle that a magnetic field measured at the surface can be considered as an integral of magnetic signature from all depths. The Discrete Fourier Transform is the mathematical tool for spectral analysis and applied to regularly spaced data such as the aeromagnetic data. The application of the power spectrum method to potential field data was proposed by Bhattacharrya (1966); and the determination of the anomalous body depth was given by Spector and Grant (1970). It is based on the principle that a magnetic field measured at the surface can be considered the integrals of magnetic signatures from all depths. The power spectrum (obtained through Fourier Transform) of the surface field can be used to identify average depths of source ensembles. In its complex form, the two dimensional Fourier transform pair (Bhattacharyya, 1966) may be written as;

$$G(u,v) = \iint_{-\infty}^{\infty} g(x,y) e^{i(u_x - v_y)} d_x d_y \qquad (1)$$

$$G(x,y) = \frac{1}{4\pi^2} \iint_{-\infty}^{\infty} g(u,v) e^{i(u_x - v_y)} d_u d_v \qquad (2)$$

where u and v are the angular frequencies in x and y directions respectively. G(u,v) when broken up into its real and imaginary parts, it is given as;

$$G(u,v = P(u,v) + iQ(u,v) \qquad (3)$$

Then the energy spectrum is given by,

$$E(u,v) = [G(u,v)]^2 = (P^2 + Q^2) \qquad (4)$$

Expression for the energy spectrum in polar form (Spector and Grant, 1970) follows that if

$r^2 = (u^2 + v^2)$ and $\theta = arc\ tan\left(\frac{u}{v}\right)$

The energy spectrum E (r, θ) could be given by:

$$\left(E(r,\theta)\right) = 4\pi^2 M^2 {R_G}^2 (e^{-2hr})((1-e^{-tr})^2)\left(S^2(r,\theta)\right)\left({R_P}^2(\theta)\right) \quad (5)$$

Where, ⟨*E*(*r, θ*)⟩ indicates the expected value, $r^2 = (u^2 + v^2)$ is the magnitude of the frequency vector and $\theta = arc\ tan\left(\frac{u}{v}\right)$ is the direction of the frequency vector. *M* is magnitude of the moment/unit depth, h is the depth to top of the prism, t is the thickness to top of the prism, *S* is the factor for the horizontal size of the prism, R_P is the factor for the magnetization of the prism and R_G is the factor for geomagnetic field direction.

The ensemble average depth h, enters only into the factor

$$\{e^{-2hr}\} = \frac{e^{2hr}\sinh(2r\Delta h)}{4r\Delta t} \quad (6)$$

The energy spectrum will then consist of two parts; the first spectrum which relates to the deeper source is relatively strong at the low frequencies and decays rapidly. The second spectrum which varies from the shallower ensembles of sources dominates the high frequency end of the spectrum. In general case, the radial spectrum may be conveniently approximated by straight line segments, the slopes of which relate to depths of the possible layers (Spector and Grant, 1970; Hahn et al., 1976). Thus the average depth to magnetic sources is computed from the gradient as (Hinze et al., 2013):

$$h(f) = \frac{M}{4\pi} = M \times 0.08 \text{ cycles / unit distance} \quad (7)$$

$$h(f) = \frac{M}{2} = M \times 0.5 \text{ radians / unit distance} \quad (8)$$

Where, $M = \frac{Log\ E}{f}$ is the gradient and $E(f) = e^{-2hf}$ is the energy spectrum and Log E is the variation of the logarithm of the power spectrum in the interval of frequency.

Source parameter imaging (SPI)

The Source Parameter Imaging (SPI) function is a method for calculating the depth of potential field sources. Thurston and Smith (1997) defined Source Parameter Imaging as a profile or grid-based method used for estimating potential field source depths, and for some source geometries the dip and susceptibility and density contrast. The Source Parameter Imaging (SPI) function is also a quick, easy, and powerful method for calculating the depth of magnetic sources (Kamba and Ahmed, 2017). Its accuracy has been shown to be +/- 20% in tests on real data sets with drill whole control. This accuracy is similar to that of Euler deconvolution; however SPI has the advantage of producing a more complete set of coherent solution points and it is easier to use. A stated goal of the SPI method (Thurston and Smith, 1997) is that the resulting images can be easily interpreted by someone who is an expert in the local geology. This method utilizes the relationship between source depth and the local wave number (*k*) of the observed field, which can be calculated for any point within a grid of data through horizontal and vertical gradients. At peaks in the local wave number grid, the source depth is equal to $\frac{n}{k}$, where n depends on the assumed source geometry (analogous to the structural index in Euler deconvolution); for example n = 1 for a contact, n = 2 for a dyke. Peaks in the wave number grid are identified using a peak tracking algorithm (Blakely and Simpson, 1986) and valid depth estimates isolated. The Source Parameter Imaging method (Thurston and Smith, 1997) used in this work estimates the depth from the local wave number of the analytical signal. The analytical signal A_1 (x, z) is defined by Nabighian (1972) as:

$$A_1(x,z) = \frac{\partial M}{\partial x}(x,z) - j\frac{\partial M}{\partial z}(x,z) \quad (9)$$

Where, M (x, z) is the magnitude of the anomalous potential field, j is the imaginary number, x and z are Cartesian coordinates for the vertical direction and horizontal direction, respectively. The result from the work done by Nabighian (1972) shows that the vertical and horizontal derivatives which comprise the real and imaginary parts of the 2D analytical signal are related as:

$$\frac{\partial M}{\partial x}(x,z) \Longleftrightarrow -\frac{\partial M}{\partial z}(x,z) \quad (10)$$

Where, <=> denotes a Hilbert transformation pair. Thurston and Smith (1997) gave the definition of the local wave number K, to be:

$$K_1 = \frac{\partial}{\partial x} tan^{-1}\left[\frac{\frac{\partial M}{\partial z}}{\frac{\partial M}{\partial x}}\right] \quad (11)$$

RESULTS

The qualitative interpretation of aeromagnetic data was first done by producing the total magnetic intensity map (Figure 2) using oasis montaj software. The TMI of the study area ranges from -39.5 nT (minimum) to 103.0 nT (maximum); this indicates that the study area is characterized with low and high magnetic signature, and this variation in the intensity could be due to the differences in magnetic susceptibility or depth.

First vertical derivative (FVD) and Second vertical derivative (SVD) (Figures 3 and 4) enhanced shallow sources by suppressing deeper ones and gave a better resolution to closely spaced sources. The regional field ranging from 39.18 to 39.84 nT (Figure 5) was removed from the total magnetic intensity map to obtain the residual map (Figure 6) with a first order polynomial fitting.

The 2D residual map of the study area revealed that the magnetic field intensity ranges from -78.9nT (minimum) to 55.0nT (maximum). This indicates that the study area is characterized with low (blue colour) and high (pink colour) magnetic signature.

The spectral determination of layers of magnetization depths was based on the following procedures; division into spectral cells, generation of radial energy spectrum, plots of log energy values versus frequency, estimation of the depth to magnetic sources and magnetic basement surface plot. To have a close investigation of the magnetic anomalies in the area, the residual blocks of the

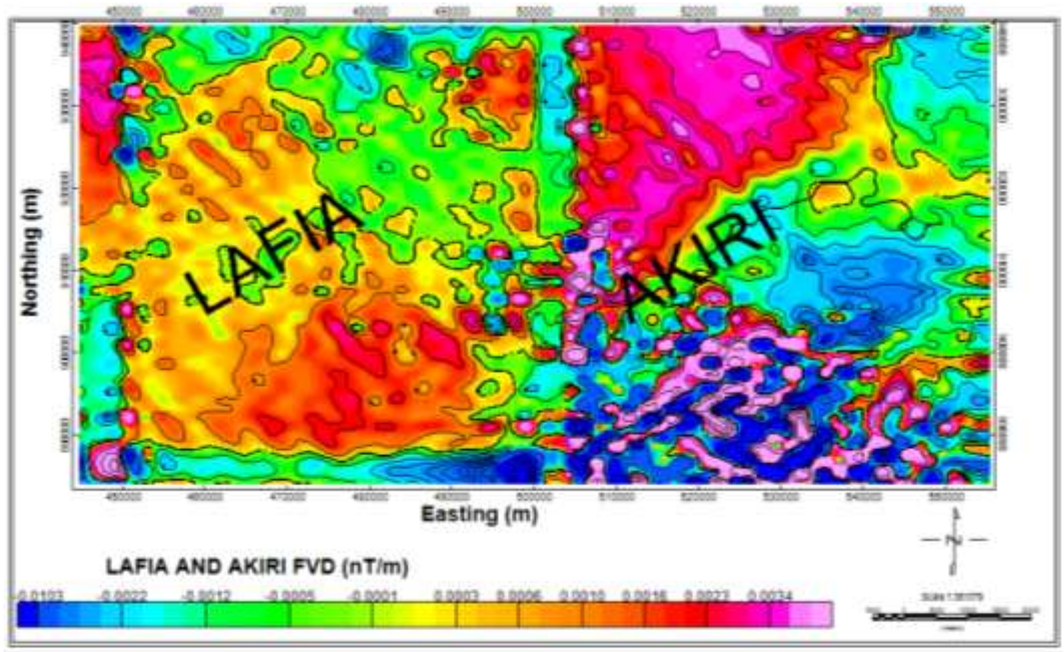


Figure 3. FVD map of the study area.

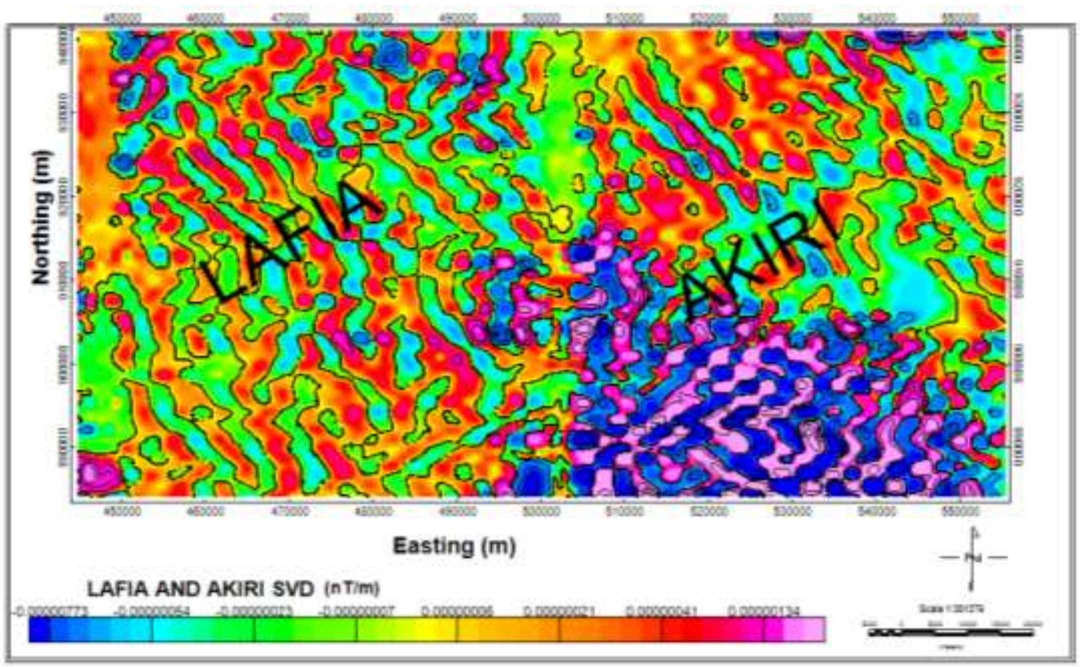


Figure 4. SVD map of the study area.

study area was divided into 18 spectral cells; each block is 18.33 by 18.33km. Microsoft (MS) excel program employing the Fast Fourier Transform (FFT) technique was used to transform the magnetic data into the radial energy spectrum for each block. The average radial energy spectrum was calculated and displayed in a logarithm figure of energy versus frequency. Graphs of radial average energy spectrum were plotted in MS Excel using Excel chart wizard as Log of Energy (FFT magnitude) versus Frequency in cycle per meter. The graphs for the 18 spectral blocks are shown in Figure 8. For each block, two linear segments could be identified

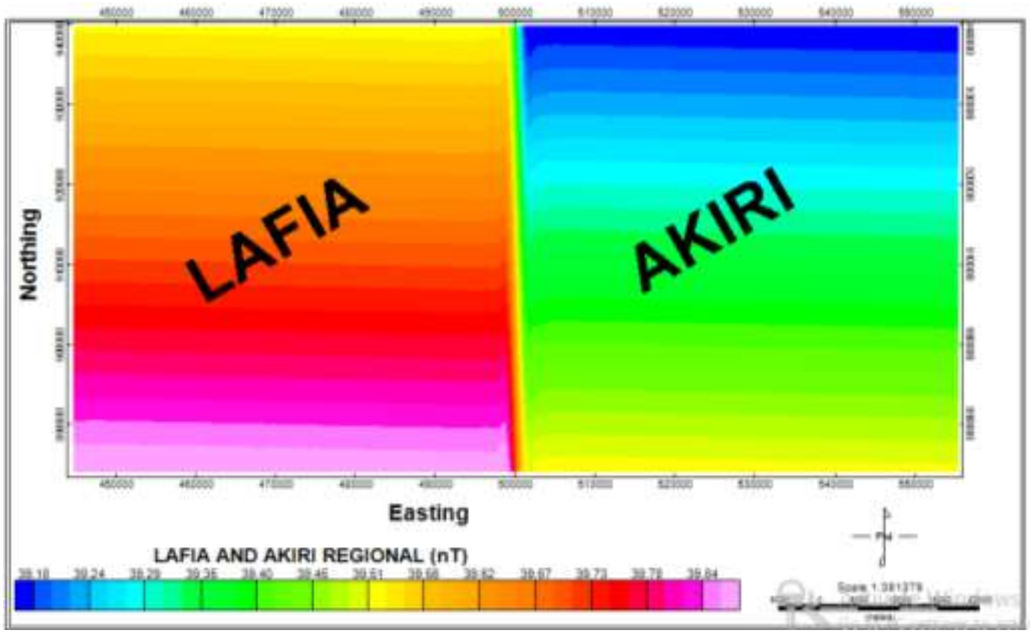


Figure 5. Regional magnetic intensity (TMI) map of the study area.

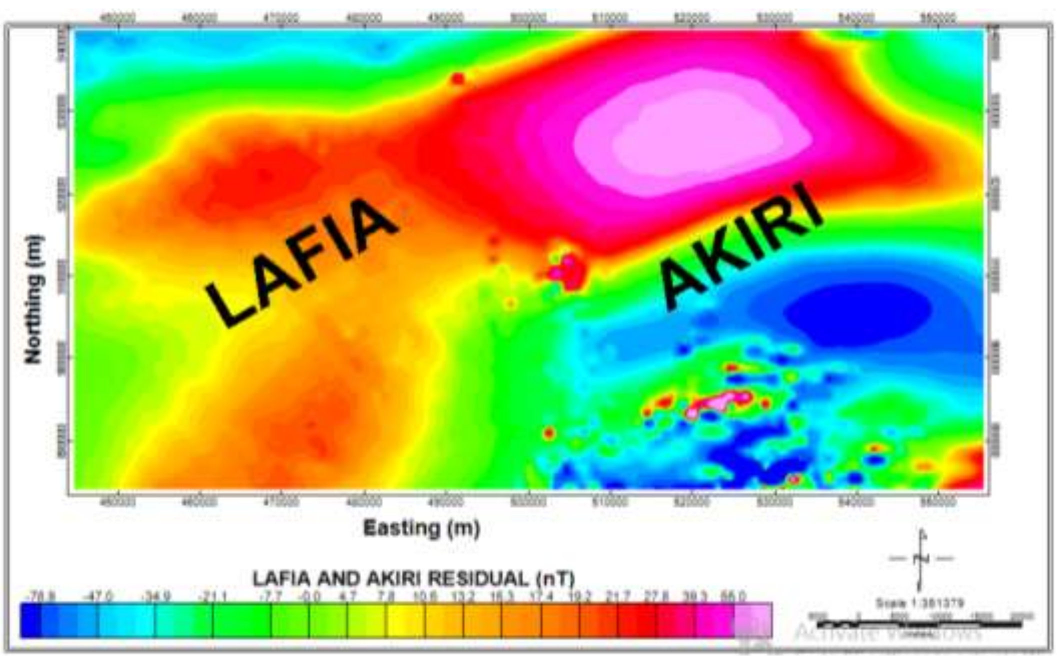


Figure 6. The residual magnetic intensity (TMI) map of the study area.

which implies that there are two magnetic source layers in the study area. The gradient of the deep (red colour) and shallow (black colour) line segments were first evaluated and the deep and shallow depth were calculated using equation 7. The coordinates and the two depth estimates (D_1 and D_2) for each of the 18 spectral blocks are given in Table 1.

From the computed values (Table 1), the deep magnetic basement depth (Figure 9) and shallow magnetic basement depth (Figure 10) were plotted and contoured using surfer 32 software.

The computed deep depth to basement was used to construct the three dimension (3D) basement topography map of the study area (Figure 11). The topographic map generated using Surfer 32 software shows the undulating nature of the basement surface with thickest sediments at

Table 1. Depth estimates of the first and second magnetic layers for the 18 spectral blocks and their coordinates.

S/N	Spectral blocks	co-ordinates (m)		depth source value (km)	
	Sections	X(Easting)	Y(Northing)	DEEP(D_1)	SHALLOW(D_2)
1	1	453725	893165.8	3.571	0.661
2	2	472092	893165.8	4.233	0.763
3	3	490459	893165.8	3.628	0.857
4	4	508826	893165.8	4.286	0.882
5	5	527193	893165.8	4.586	0.887
6	6	545560	893165.8	3.968	0.794
7	7	453725	911602.8	2.419	0.970
8	8	472092	911602.8	3.685	0.909
9	9	490459	911602.8	3.075	1.052
10	10	508826	911602.8	3.855	0.766
11	11	527193	911602.8	4.233	0.827
12	12	545560	911602.8	4.257	1.167
13	13	453725	930039.8	4.113	0.557
14	14	472092	930039.8	4.034	1.080
15	15	490459	930039.8	4.431	0.794
16	16	508826	930039.8	4.335	0.921
17	17	527193	930039.8	5.411	1.035
18	18	545560	930039.8	5.732	1.261
Average depth				4.103	0.899

the Akiri area and an elevation with shallowest sediments at Lafia area.

The SPI grid image and SPI legend are shown in Figure 12. The generated SPI grid image and SPI legend show varied colours displaying different magnetic susceptibilities contrast within the studied area, and could also portray the undulations in the basement surface. The negative values on the legend depict the depths. The pink colour generally indicates areas occupied by shallower sediment or near surface lying magnetic bodies, while the blue colour depicts areas of thicker sediments or deep lying magnetic bodies. The SPI depth result ranges from -0.564 km (shallow magnetic bodies) to -5.838 km (deep lying magnetic bodies). These are clearly portrayed in 3-D view in Figure 13 which is in different tilt positions.

DISCUSSION

The TMI map (Figure 2) shows that the TMI anomaly values vary from -39.5 to 103.0 nT, while the residual values (Figure 6) are from –78.9 to 55.0 nT. Areas of low and high TMI values are revealed by the colour legend bar. The high amplitude anomalies were observed in the southwest and northeast parts of the study area, while the low amplitude anomalies were seen in the south eastern part of the area. The Akiri area is dominated by bodies with high magnetic intensity in the northern part while the central part of Akiri is marked by low magnetic intensity which trends eastward. The southern part is dominated by patches of low intensity anomalies with intermingling of few high intensity anomalies. The Lafia area is dominated with high intensity anomalies which trend WE in the north and SN in the southern part (Figure 2). The regional field ranges from 39.18 to 39.84 nT. The removal of the regional anomaly (Figure 5) from the TMI gave a better resolution of the TMI map (Figure 6). The regional field ranges from 39.18 to 39.84 nT (Figure 7). The results from the spectral analysis (Table 1) show that the depth of the shallower magnetic sources vary from 0.557 to 1.261 km, with an average depth value of 0.899 km, whereas the depth of the deep magnetic sources vary from 2.419 to 5.732 km, with an average depth value of 4.103 km. Figures 10 and 11 which are contour maps of deep and shallow magnetic sources, respectively, were produced in colour aggregate as indicated by the legend. Locations with blue colour correspond to the deeper depth areas, while the places with purple colour depict lowest depth to magnetic source bodies. The Akiri area has the highest sedimentary thickness which occurred in the northern part while the southern part has a relatively high thickness compared to Lafia area with the lowest thickness (Figures 9, 10 and 11). The SPI grid image and legend colours are shown in Figure 12. The negative values on the legend depict the depths of buried magnetic bodies, which may be deep seated basement rocks or near surface intrusive. The pink colour generally indicates areas occupied by shallow magnetic bodies, while the blue colour depicts areas of deep lying

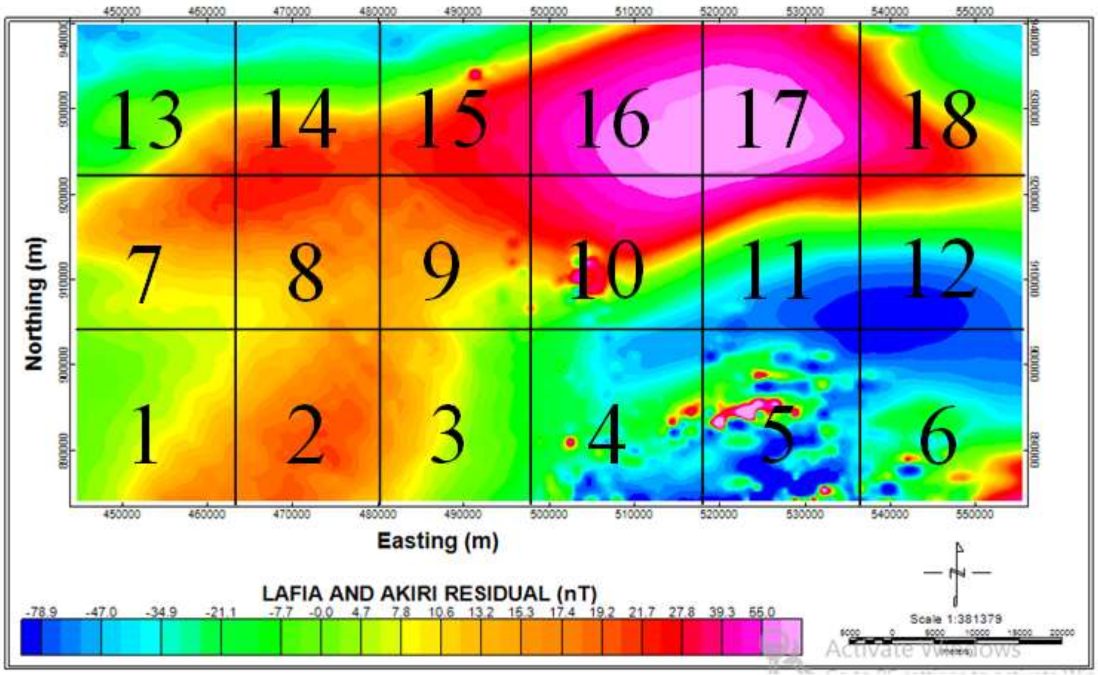
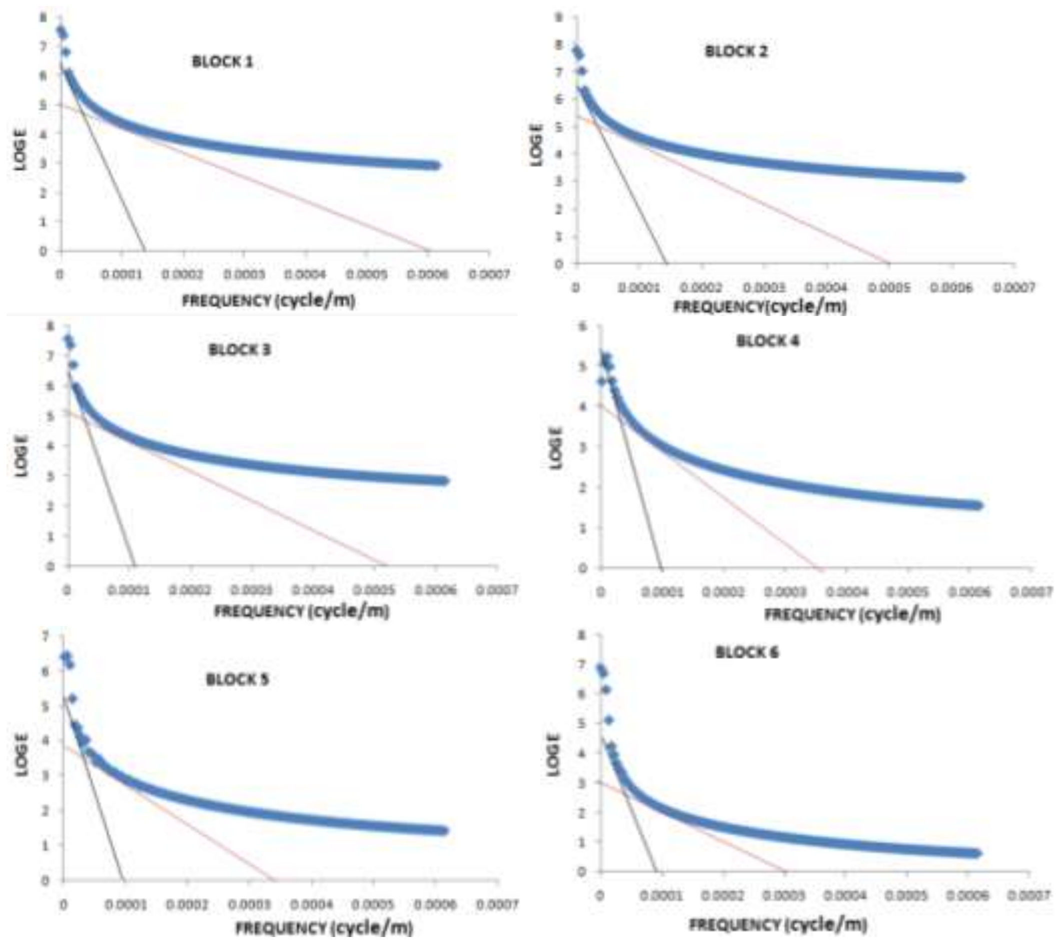
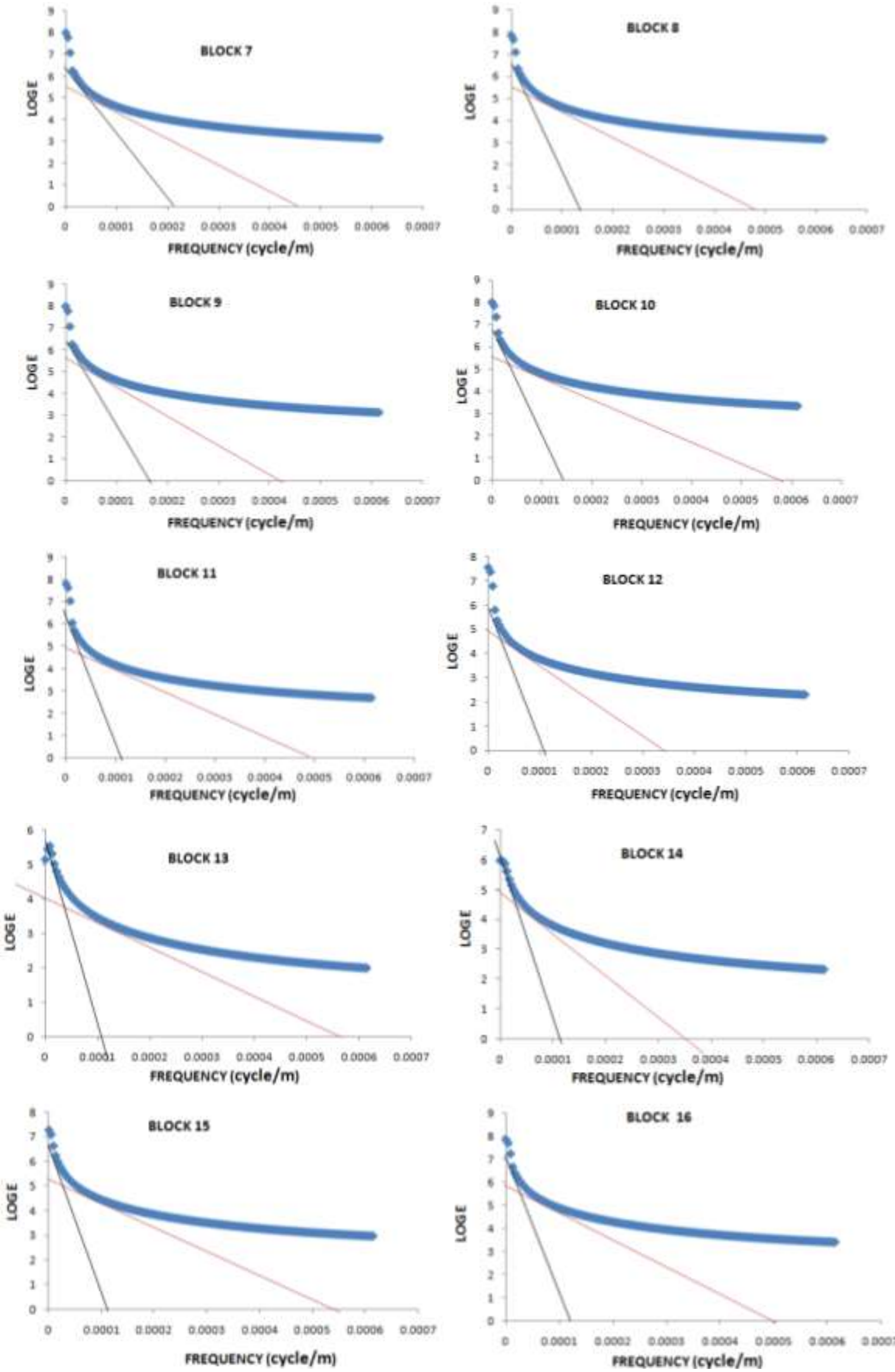


Figure 7. Division into 18 spectral blocks for estimation of the depth to basement.

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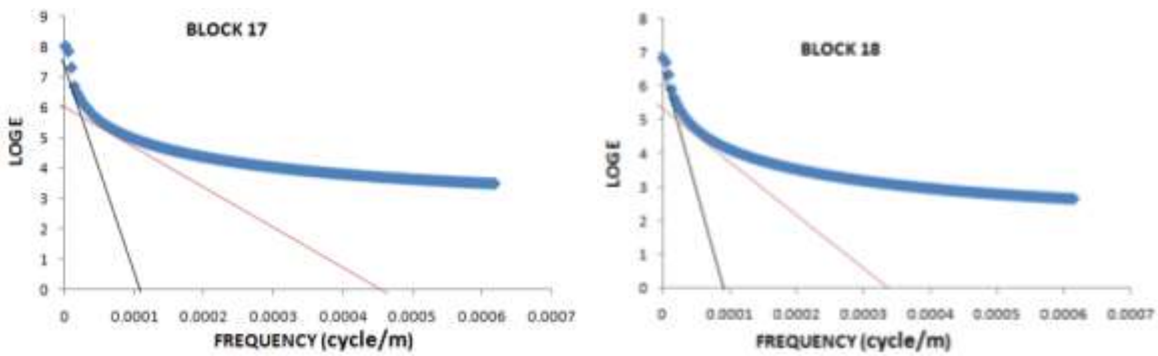

Figure 8. Spectral plots of logarithm of Energy against Frequency (cycle per meter).

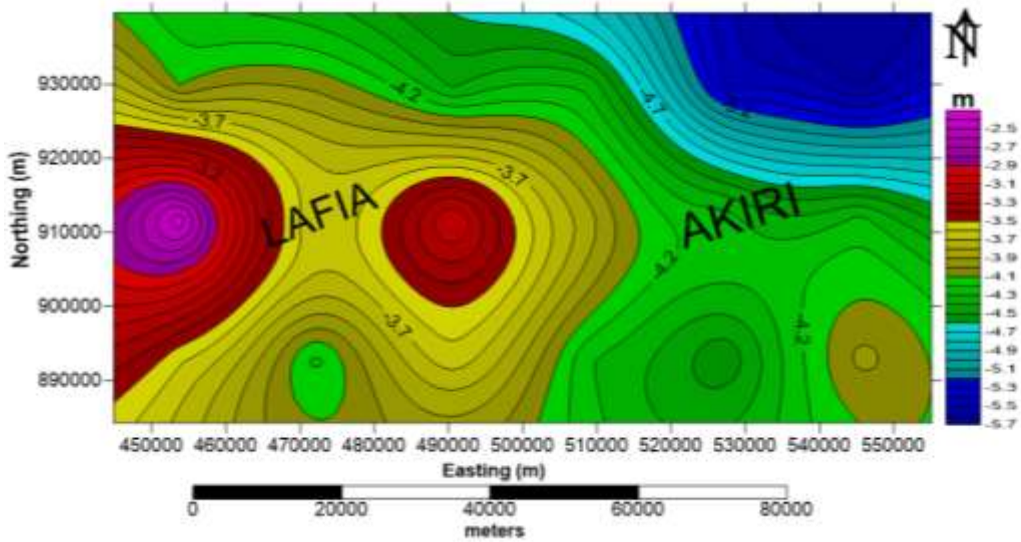

Figure 9. Deep depth to basement map.

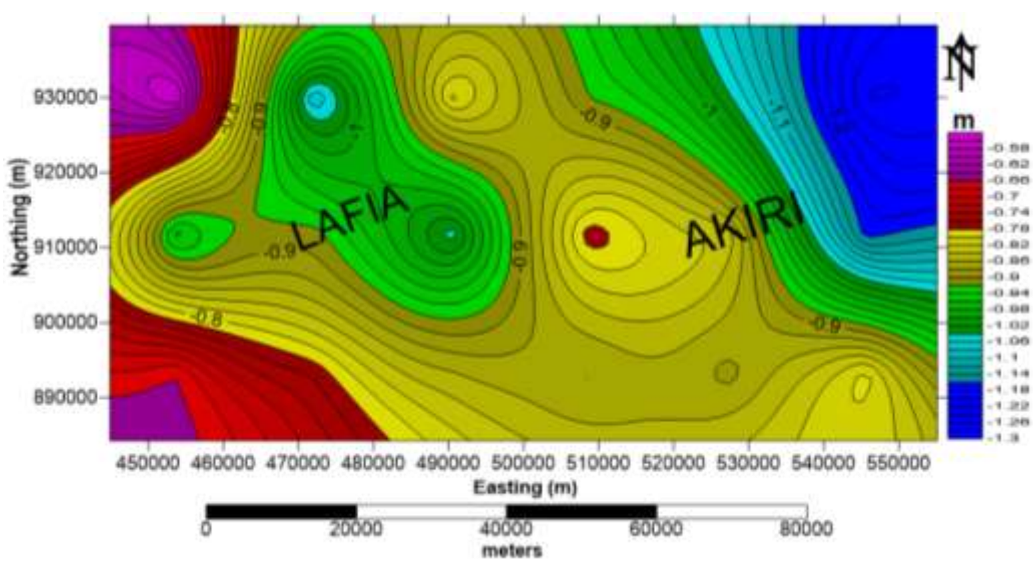

Figure 10. Shallow depth to basement map.

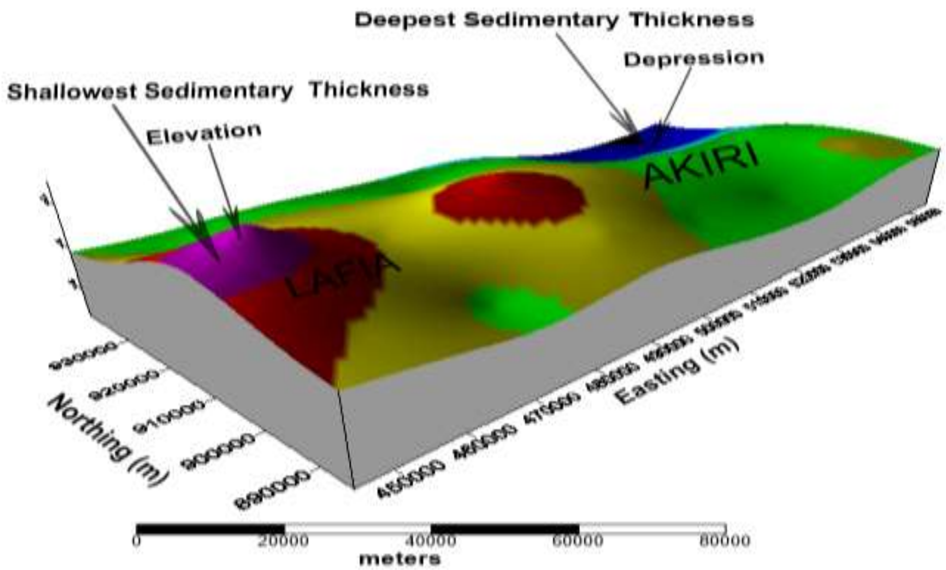

Figure 11. 3D map of the study area showing magnetic basement topography.

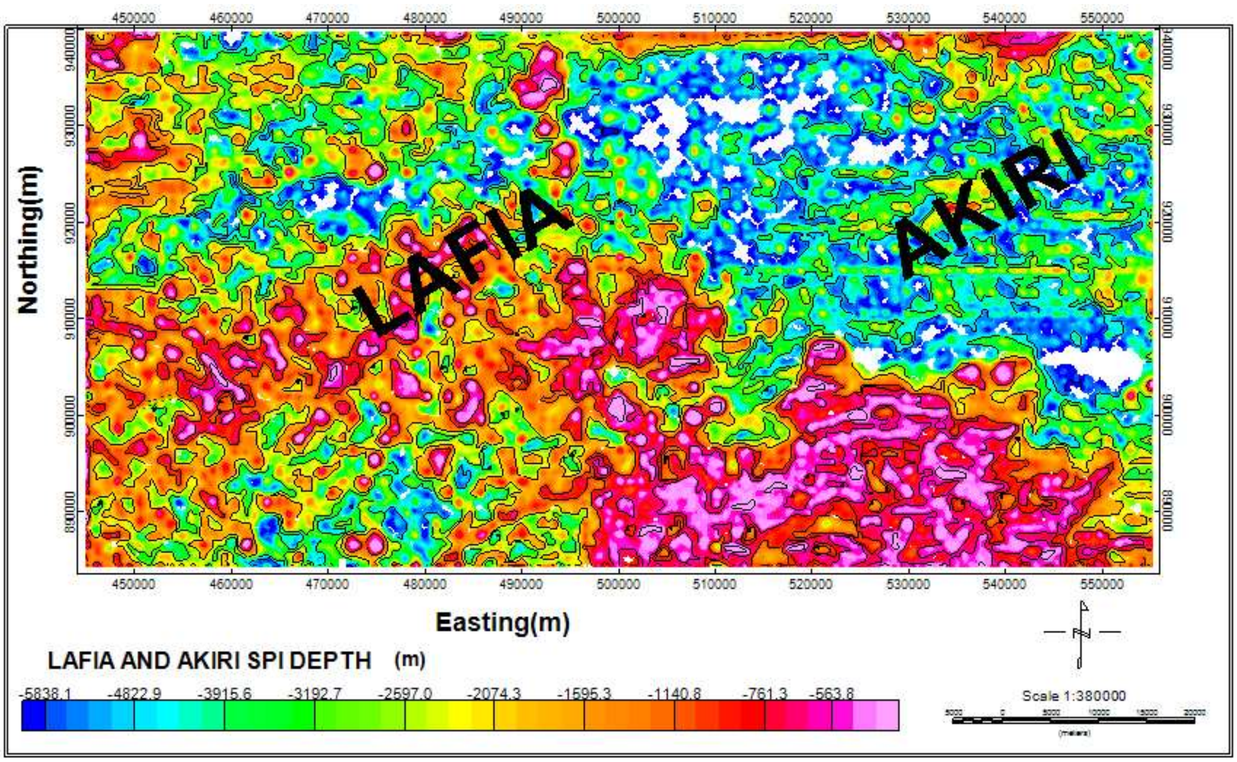

Figure 12. Source parameter image (SPI) map of the study area.

magnetic bodies. The SPI depths result ranges from 0.564 (shallow magnetic bodies) to 5.838 km (deep lying magnetic bodies). This result also shows that the northern part of Akiri has the highest sedimentary thickness with a shallow thickness in the southern part, while Lafia area showed moderate thickness generally with the shallow thickness area trending SW-NE direction. These depths are found to be within the range of depths predicted by earlier researchers (Ofoegbu, 1984; Nwosu, 2014). The sedimentary thickness obtained from the different methods indicated the possibility of hydrocarbon accumulation (Wright et al., 1985; Nwosu, 2014).

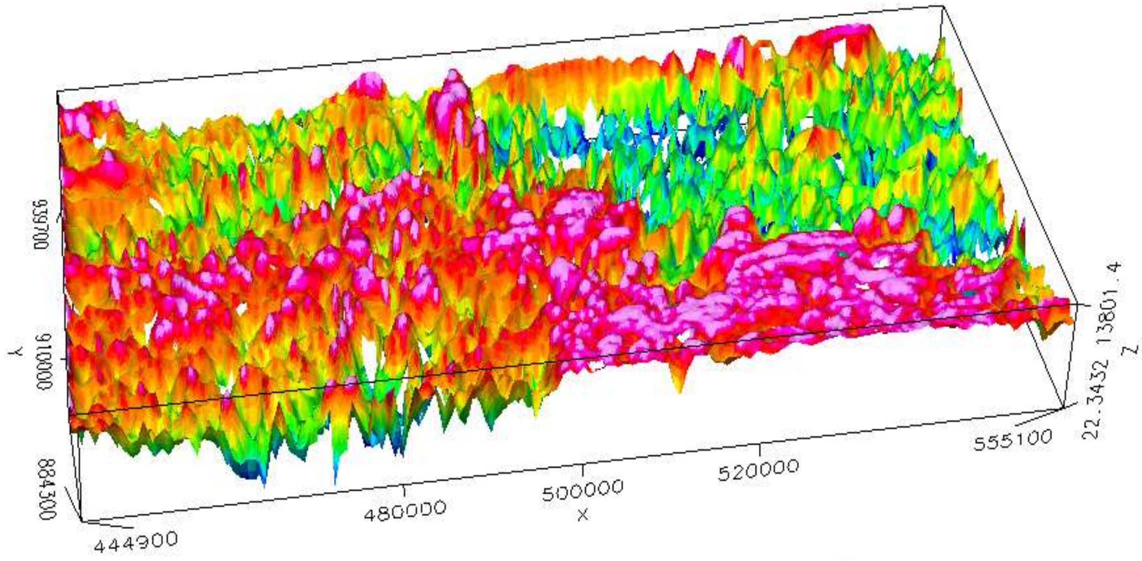

Figure 13. The 3-D SPI view of the study area.

Conclusion

The interpretation of the aeromagnetic data of Lafia and Akiri areas was done qualitatively and quantitatively using spectral analysis and Source parameter imaging. The depth of shallower magnetic sources ranges from 0.557 to 1.261 km with an average depth value of 0.899 km, whereas the depth of deeper magnetic sources vary from 2.419 to 5.732 km with an average depth value of 4.105 km. The SPI depth result ranges from 0.5638 km (shallow magnetic bodies) to 5.8381 km (deep lying magnetic bodies). The two methods showed depth estimation within the same range. The sedimentary thickness obtained from the different methods indicates the possibility of hydrocarbon accumulation. If this study area is quantitatively interpreted using any other method to determine the thickness of this magnetic basement, it is very likely that this thickness may be greater than 2.4 km depth, hence the area may be favourable for hydrocarbon accumulation if other conditions are made. Wright et al. (1985) reported that when all other conditions for hydrocarbon accumulation are favourable, and the average temperature gradient of $1^{o}C$ for 30 m obtainable in oil rich Niger Delta is applicable, then the minimum thickness of the sediment required to achieve the threshold temperature of $115^{o}C$ for the commencement of oil formation from marine organic remains would be 2.3 km deep. Previous studies have confirmed that the geology of the Benue Trough offers promises to prospective investors and researchers in general. The quantitative calculations done in this trough using old data from researchers like Nwachukwu (1985), Ahmed (1991), Osazuwa et al. (1981) and Onyewuchi et al. (2012) have all revealed two magnetic source layers and have shown the thickness of the magnetic basement of this area to be more than 2.3 km depth. The result obtained was able to satisfy the objectives of this work, which includes the determination of depth of anomalous bodies.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interest.

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