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Full Length Research

Estimation of sedimentary thickness using spectral depth analysis approach: A case study of Sokoto Basin of northwestern Nigeria

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ABSTRACT: Spectral depth analysis using high resolution aeromagnetic data was carried out to evaluate the sedimentary thickness of northeastern part of Sokoto Basin, Nigeria. The study area is situated between longitude 5^0 00′00″E to $6^0$00′00″E and latitude12^{0}30′00″N to 13^{0}30′N. Covering four (4) sheets namely; sheet 11 (Rabah), sheet 12 (Isah), sheet 30 (Dange) and sheet 31 (Mafara). Spectral depth analysis and source parameter imaging (SPI) were carried out on the composite map of the area to estimate depth variation to basement and infer areas of probable hydrocarbon maturation prospects. The result of the spectral studies indicates an increase in sedimentation northeastern part, with several depressions on the basement rock. Two prominent magnetic layers of depths, deeper depth (Z_1) and shallow depth (Z_2) varying from 0.91 to 2.09 km and 0.35 to 0.73 km were observed with averages 1.6025 and 0.549 km respectively. Source Parameter Imaging (SPI) depth result ranges from 0.239 km (shallow magnetic bodies) to 1.912 km (deep lying magnetic bodies). These blocks where higher sedimentary thicknesses are observed in the study area such as blocks G (2.02 km), K (2.20 km) L (2.09 km) and P (1.91 km) are probable sites for prospect of hydrocarbon maturation in the study area.

Keywords: Basement depth, composite map, hydrocarbon maturation, sedimentary thickness, spectral analysis.

INTRODUCTION

Geophysical investigations and interpretation methods have played very significant roles in the development of the world economy. This is as a result of the improvements in terms of their instrumentations, and also the modern ways of interpretation techniques (Keary et al., 2004). Nigeria, like other countries in the world adopts the use of geophysics for mineral exploration and similar activities. The Geological Survey of Nigeria (GSN), now Nigerian Geological Survey Agency (NGSA) was given the responsibility for the airborne magnetic surveying of the country and the publication of the airborne geophysical map series.

Geophysical investigations of this type are extended to provide geologic information which will perhaps stimulate and also assist in a mineral exploration programs in the country.

Most of economic minerals (hydrocarbon) and ground-water lie concealed beneath the earth surface, thus hidden from direct view (Corell and Grauch 1985). The presence and magnitude of these resources can only be ascertained by geophysical investigations of the subsurface structures in the area. Reynolds (1990) pointed out that If the area under investigation has no previous geological information and the primary aim of the study is to search for hydrocarbon maturation sites, the first question that must be answered, is whether the sedimentary basin is large enough and thick enough to justify any further investigations.

Hydrocarbon and sedimentary basins

Petroleum is usually formed from organic matter, which was deposited in a marine environment and remained buried under anoxic conditions for 100 to 400 million years. Over the years, layers of silt, sand and other sediments settled over the buried organic matter. The increase of pressure and temperature by these layers slowly transformed the organic matter into hydrocarbons. The first stage is the formation of kerogen between temperatures of 60 to 120^{0}C, as the pressure and temperature in the source rock is further increased, kerogen converts to petroleum (Reynolds, 1990). The fundamental criteria for assessing a sedimentary basin for possible hydrocarbon maturation according to Keary (2004), Obaje (2004) and Sharma (1989) includes, among others;

1. Paleo-temperatures or ancient Paleo-temperatures are responsible for generation of hydrocarbon from organic matter.
2. The presence of a source rock with adequate organic materials of various types determines whether oil or gas will be sourced in the process of hydrocarbon generation.
3. Reservoir rock that ensures hydrocarbon generated is accommodated in pore spaces that exist between the grains in the subsurface.
4. Seals that are without pore spaces to ensures that hydrocarbon generated in the reservoir rocks are kept in place and prevented from migrating to the surface and subsequent loss.
5. The trap to ensures that oil sealed in place does not migrate and be lost.

The minimum average thickness of sediment required to achieve a threshold temperature for commencement of hydrocarbon formation is 2.3 km (Wright et al., 1985). It is therefore logical and fundamentally necessary in a recoinnansce survey to prospect for hydrocarbon potential maturation sites; the sedimentary thickness must be ascertained as a prerequisite for further investigations.

Location of the study area

The study area lies between longitude 5^{0}00′00″E to 6^{0}00′00″E and latitude12^{0}00′00″ N to 13^{0}30′N covering four sheets: sheet 11 (Rabah), sheet 12 (Isah), sheet 30 (Dange) and sheet 31 (Mafara) located in the north-eastern part of Sokoto Basin. The area lies in the Late Paleocene Deposits called the Sokoto group made up of the Dange, Kalambiana and Gamba formations. Figures 1a and 1b are the geology maps of Nigeria and that of the study area respectively.

Sokoto Basin is one of the sedimentary basins in Nigeria; several researches were conducted in the basin to investigate its hydrocarbon potentials. Some of the results such as that of Sambo (1994), Bonde et al. (2014), Ofor and Udensi (2014), Ofoha et al. (2016), Stephen and Iduma (2018), Labbo and Ugodulunwa (2007) and Bonde et al. (2014b), all pointed out that in some sections, the basin is thick enough for possible hydrocarbon maturation and the thickness of the sediments generally increases northwards toward the border with Niger republic where petroleum has been discovered. Therefore, the objective of the research work is to investigate locations where sufficient sedimentary thickness exists in the study area that could be possible hydrocarbon maturation sites.

MATERIALS AND METHODS

Four digitized aeromagnetic maps (sheets 11, 12, 30 and 31) representing Rabah, Isa, Dange, and Mafara respectively to be used for this research was obtained from Nigeria Geological Survey Agency (NGSA) and were assembled to obtain one block, referred to as northeastern part of Sokoto Basin in this work. Total Magnetic Intensity Map (TMI) of the area was produced using Oasis Montaj version 7.2. In the production of the TMI, the single map of the study area obtained was gridded and the grid was then saved into database (Microsoft excel) and new coordinates were projected to change the current coordinates of the grid from x and y in meters (m) to latitude and longitude in degree. The data base was again re-gridded and transported into Oasis montaj software to produce the TMI map of the study area.

Magnetic data observed in geophysical surveys comprises of the sum of all magnetic fields produced by all underground sources. The composite map produced using such data, therefore contains two important disturbances, which are different in order of sizes and generally super-imposed. The large features generally show up as trends, which continue smoothly over a considerable distance. These trends are known as regional trends. Super-imposed on the regional field, but frequently camouflaged by these, are the smaller, local disturbances which are secondary in size but primary in importance. These are the residual anomalies. They may provide direct evidence of the existence of the reservoir type structures or mineral ore bodies. The residual magnetic field of the study area was produced by subtracting the regional field from the total magnetic field using the Polynomial fitting method. A computer programed, Oasis Montaj software version 7.2 was used to derive the residual magnetic values by subtracting values of regional field from the total magnetic field values to produce the residual magnetic map and the regional map.

For the purpose of estimating the depth to magnetic sources within the study area, spectral analysis method and source parameter imaging technique were employed.

Spectral analysis

The residual map of the study area obtained was divided into sixteen (16) sub-blocks of overlapping section for the spectral depth analysis to be carried out in order to obtain

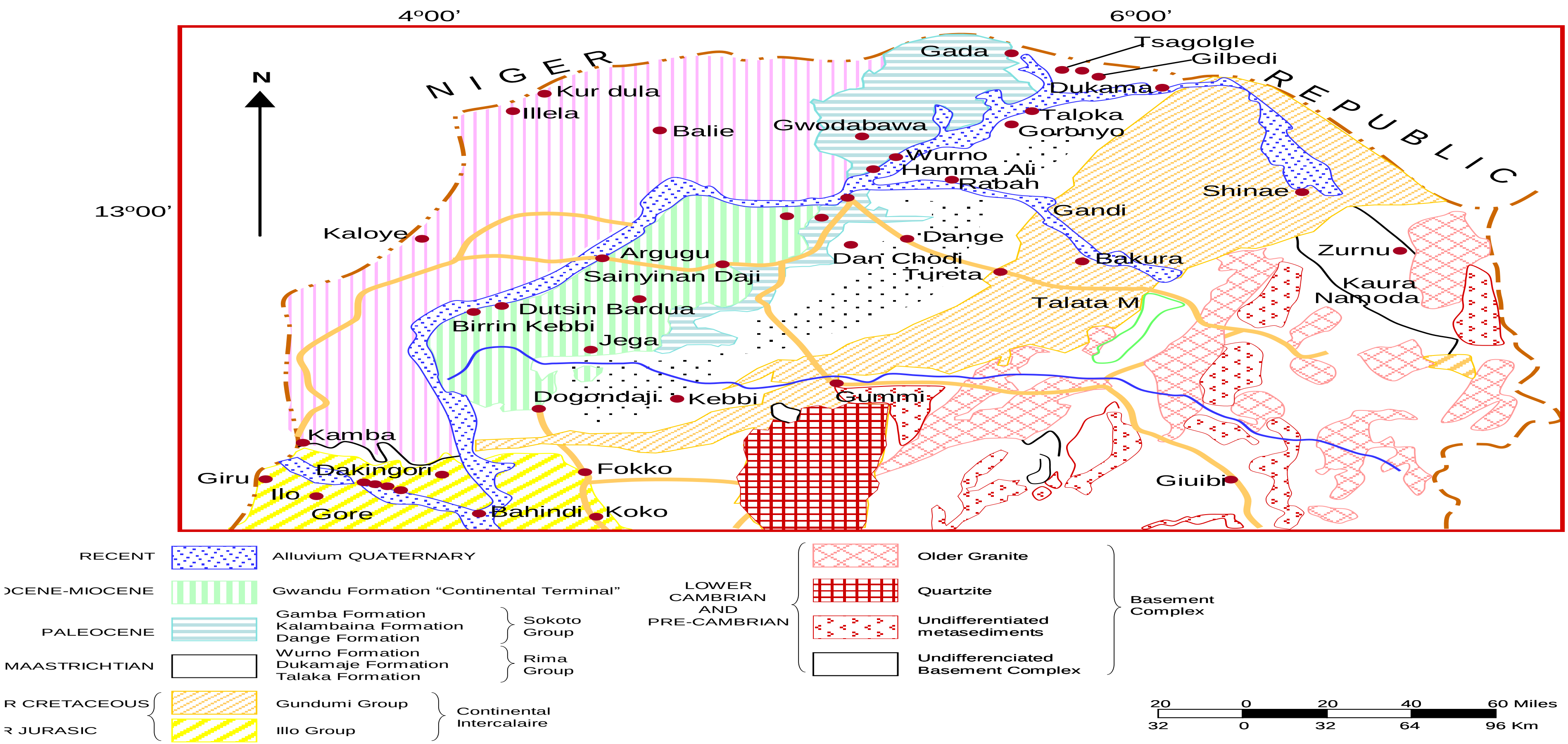

Figure 1a. The Geology Map of Sokoto Basin (Etu-Efotor,1998).

the basement depth of the study area. The analysis was done in four stages to produce the spectral cells. In the first step, the map was divided into 3 by 3 equal spectral cells producing nine blocks that is block A to I, in the second step the map was divided into 2 by 2 equal spectral cells producing blocks J to M, in step three, the map was divided into 2 which produced blocks N and O, and in the last step the whole map was considered producing block P, that gives a total of 16 spectral cells. 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) against frequency in circle per meter. For each block, two linear segments could be identified which implies that there are two magnetic source layers in the study area. The gradient of the deep and shallow line segments were first evaluated and the deep and

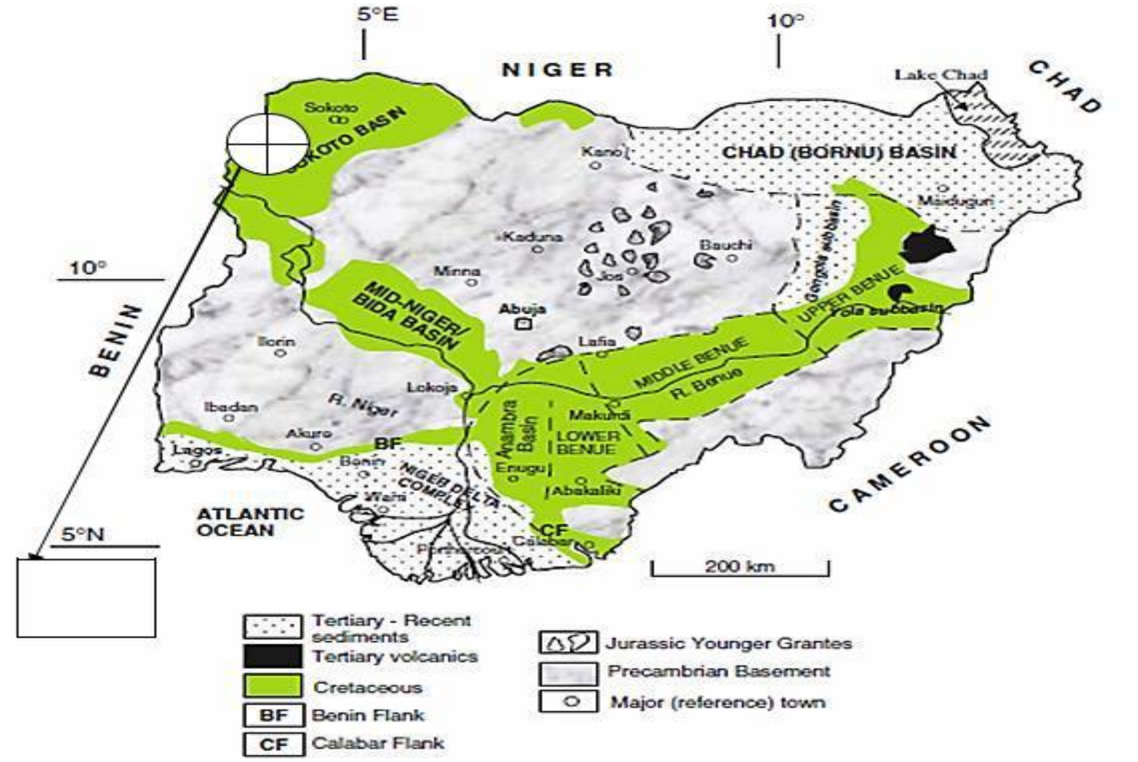

Figure 1b. Geological map of Nigeria showing study area (Ofoha et al., 2016).

shallow depth were calculated using equations 4 and 5 respectively.

Spectral analysis of aeromagnetic data over an area would differentiate and characterize region of sedimentary thickness from those of shallow basement and also to determine the depth to the magnetic sources. The result could be used to suggest whether or not the study area has potential for oil/gas (hydrocarbon) concentration.

The application of spectral analysis to the interpretation of potential field data is a method that can be used to determine the basement depth, and is now sufficiently well established (Spector and Grant, 1970).

The spectral method has an advantage over other geophysical methods involves in the determination of basement depth because it has the ability to filter all the noise away from the data, information is not lost during the process, and in many cases, operations are easier to perform in the transform domain (Telford et al., 1990).

In this work, the characteristic of the residual magnetic field was analyzed using statistical spectral methods. The spectral analysis of the residual field data was used to determine the basement depth of the study area. The Fourier transforms of the potential field due to a prismatic body was used to estimate the depth this transformation has a broad spectrum whose peak location is a function of the depth to the top and bottom surface and whose amplitude is determined by its magnetization.

For a bottomless prism, the spectrum peak at the zero wave number according to the expression:

$$F(\omega) = e^{-h\omega} \qquad (1)$$

Where ω is the angular wave number in radian/ground and h is the depth to the top of the prism. For a prism with top and bottom surface, the spectrum is:

$$F(\omega) = e^{-h_t\omega} - e^{-h_b\omega} \qquad (2)$$

Where h_t is depth to the top and h_b is the depths to the bottom.

As the prism bottom moves closer to the observation point at surface, the peak moves to a higher wave number. The effect of increasing the depth is to shift the peak to a lower wave number (Spector and Grant, 1970).

Because of these characteristics, there is no way to separate the effect of deep sources from shallow sources of the same type by using wave number filters. The sources can only be separated if the deep sources have greater amplitude or if the shallow sources have less depth extent (Salako and Udensi, 2013). When considering a line that is long enough to include many sources, the log spectrum of this data was used to obtain the depth to the top of statistical ensembles of sources using the expression:

$$\log E(k) = 4\pi \mathrm{hk} \qquad (3)$$

Where h is the depth in ground and k is the wave number in cycles/ground. The depth of an ensemble of sources can be determined by measuring the slope of the energy (power) spectrum and dividing by 4π.

Computer software was used to generate the energy frequency plots and the slopes. From the slopes of the plot, the first and the second magnetic sources depth was respectively estimated using the expression:

$$Z_1 = \frac{-m_1}{4\pi} \qquad (4)$$

$$Z_2 = \frac{-m_2}{4\pi} \qquad (5)$$

Where m_1 and m_2 are slopes of the first and second segments of the plots, and Z_1 and Z_2 are first and second depths respectively.

Source parameter imaging

This study adopted the use of Source Parameter Imaging (SPI) technique to quantitatively determine the depth to basement or the thickness of the sediments in addition to spectral analysis employed. The Source Parameter Imaging (SPI) technique 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). 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. One merit of the SPI technique over spectral depth analysis is that the depth can be visualized in a raster format and the true thickness determined for each anomaly and the depth parameter determined is independent of an assumed model (Bello et al., 2017). The SPI used in this work estimates the depth from the local wave number of the analytical signal. The analytical signal A (x, z) is defined by Nabighian (1972) as:

$$A\,(x, z) = \frac{\partial m}{\partial x}(x, z) - j\,\frac{\partial m}{\partial z}(x, z) \qquad (6)$$

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:

$$\frac{\partial m}{\partial x}(x, z) <=> -\frac{\partial m}{\partial z}(x, z) \qquad (7)$$

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

$$K_1 = \frac{\partial}{\partial x}\tan^{-1}\left[\frac{\frac{\partial m}{\partial z}}{\frac{\partial m}{\partial x}}\right] \qquad (8)$$

RESULTS AND DISCUSSION

Total magnetic map of the study area

The total magnetic map of the study area is shown in Figure 2; the map can be divided into three main sections though minor depressions exist scattered all over the area. The low magnetic intensity value represented by dark green – blue color is found all around most areas in the map but concentrated toward the northeast part ranging between -23.9 - 57.0 nT, the western part of the map is dominated by high magnetic intensity values (pink – red color) with values varying between 82.3-103.3 nT, the two sections are separated by a zone characterized by medium magnetic intensity (62.4 – 76.6 nT) values area depicted by yellow- orange color with concentration toward southwestern part of the map.

Spectral

The result of the spectral depth estimates (Z_1 and Z_2) for the sixteen blocks are given in Table 1. The study area is having an average of 1.6025 km depth with a highest depth at block L (longitude 5.25^0 and latitude 12.75^0), and lowest depth at block I (longitude 5.83^0 and latitude 12.66^0).

Source parameter imaging

The SPI grid imaging map (Figure 3) shows varied colours displaying different magnetic susceptibilities contrast within the studied area. The red-pink colour generally indicates areas occupied by shallow magnetic bodies, while the blue-green colour depicts areas of deep lying magnetic bodies. The SPI depth result ranges from -0.239

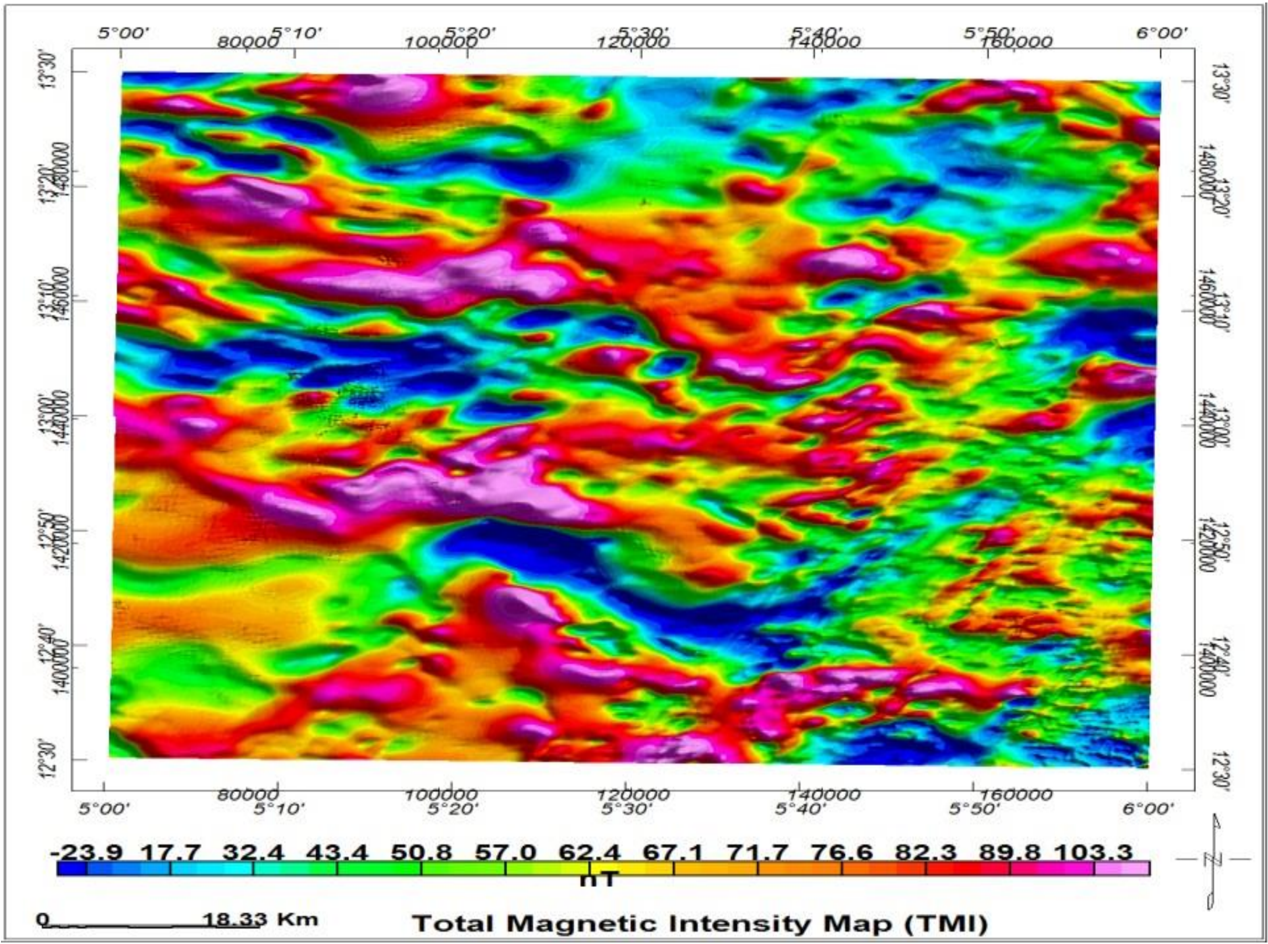

Figure 2. Total magnetic intensity map (TMI) of the study area spectral analysis.

km (shallow magnetic bodies) to -1.912 km (deep lying magnetic bodies). The negative values on the legend depict the depths of buried magnetic bodies, which may be deep seated basement rocks or near surface intrusive. This result also shows that the northern part through the central part have the highest sedimentary thickness around Isa, Rabah through Dange areas, with a shallow thickness in the southern part, generally the shallow thickness area trends SE-NW direction originated around Mafara area. This result is in total agreement with the result obtained using spectral analysis.

Contour of the basement depth

The contour of basement depth (Z_1) of the study area is as shown in Figure 4. The depth contours depict a number of basement depressions over the entire study area. Depths to magnetic basement range from 0.91 km in the southern part to 2.09 km at the northeastern bordering with Niger republic. A closer observation indicates a general increase in thickness from the southern part to northern part, more especially the northeastern part bordering with Niger republic. This general trend in sedimentation implies that the area is thickest at the northern part.

The TMI map shows that the area categorized by three magnetic intensity values, these are the high, medium and low magnetic intensities. The high magnetic intensity values, which dominate the western part of the sedimentary basin, are caused probably by near surface igneous rocks of high values of magnetic susceptibilities. The low amplitudes are most likely due to sedimentary rocks and other non-magnetic sources. In general, high magnetic values arise from igneous and crystalline basement rocks, whereas low magnetic values are usually from sedimentary rocks or altered basement rocks. The sedimentary thickness of the northeastern part of Sokoto Basin in general, appears to increases from south to north. This collaborates well with earlier findings of the trends of structures in the Sokoto Basin of northwestern Nigeria from the interpretation of aeromagnetic anomalies conducted by Ishaku (2000), spectral depth analysis of Sokoto Basin conducted by Bonde et al. (2014a) and determination of heat flow in the Sokoto Basin Nigeria using spectral analysis of aeromagnetic data conducted by Ofor and Udensi (2014).

Table 1. shows variation of depth in the study area.

Block	Longitude (Deg.)	Latitude (Deg.)	Deeper Depth Z_1 (Km)	Shallow Depth Z_2 (Km)
A	5.26	13.33	1.62	0.66
B	5.49	13.33	1.50	0.44
C	5.83	13.33	1.6	0.67
D	5.16	12.99	1.56	0.60
E	5.49	12.99	1.27	0.40
F	5.83	12.99	1.46	0.73
G	5.16	12.66	2.02	0.73
H	5.49	12.66	1.26	0.54
I	5.83	12.66	0.91	0.35
J	5.25	13.25	1.54	0.35
K	5.75	13.25	2.02	0.57
L	5.25	12.75	2.09	0.61
M	5.75	12.75	1.15	0.39
N	5.25	13.00	1.86	0.56
O	5.75	13.00	1.87	0.53
P	5.50	13.00	1.91	0.66

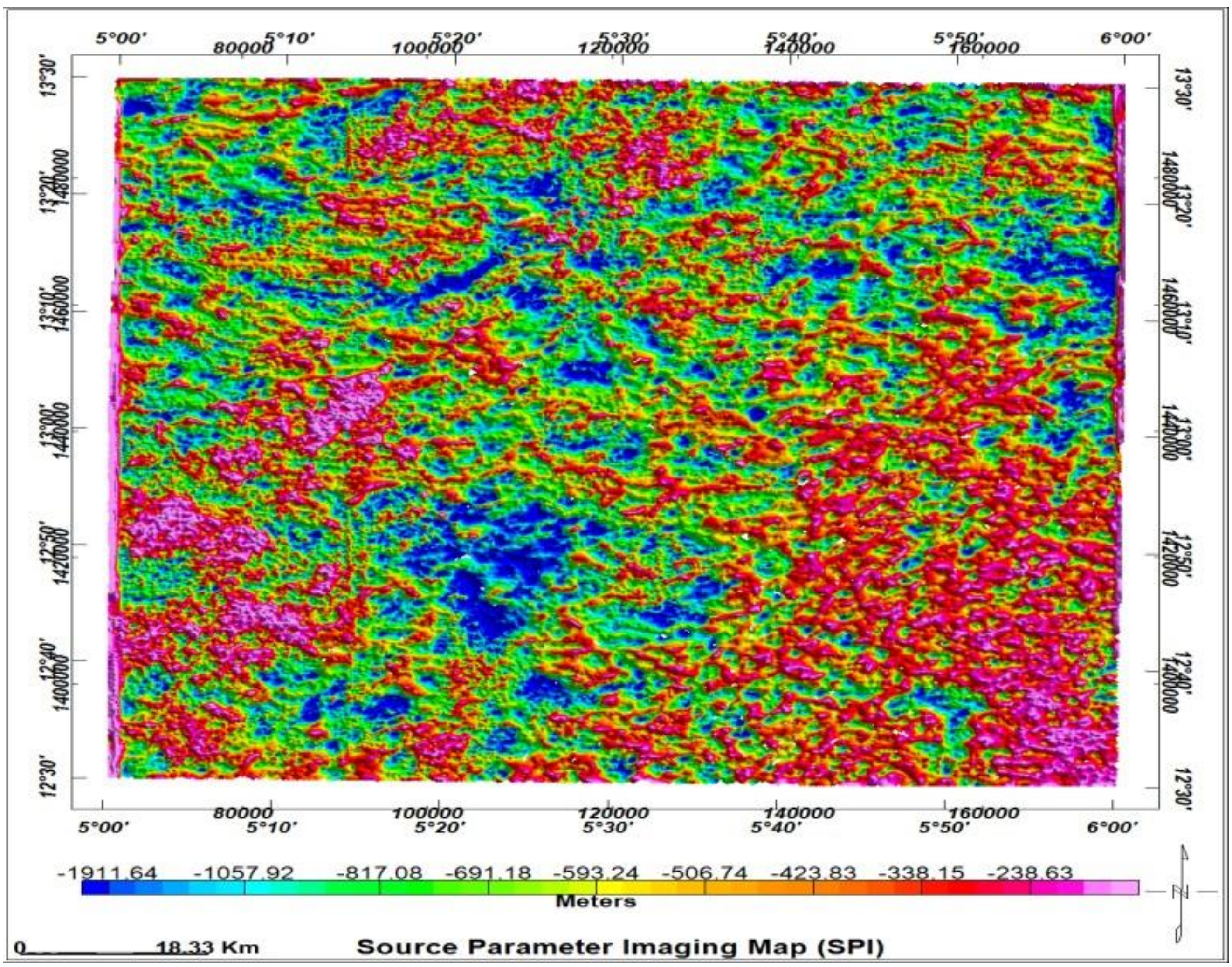

Figure 3. Source parameter imaging map.

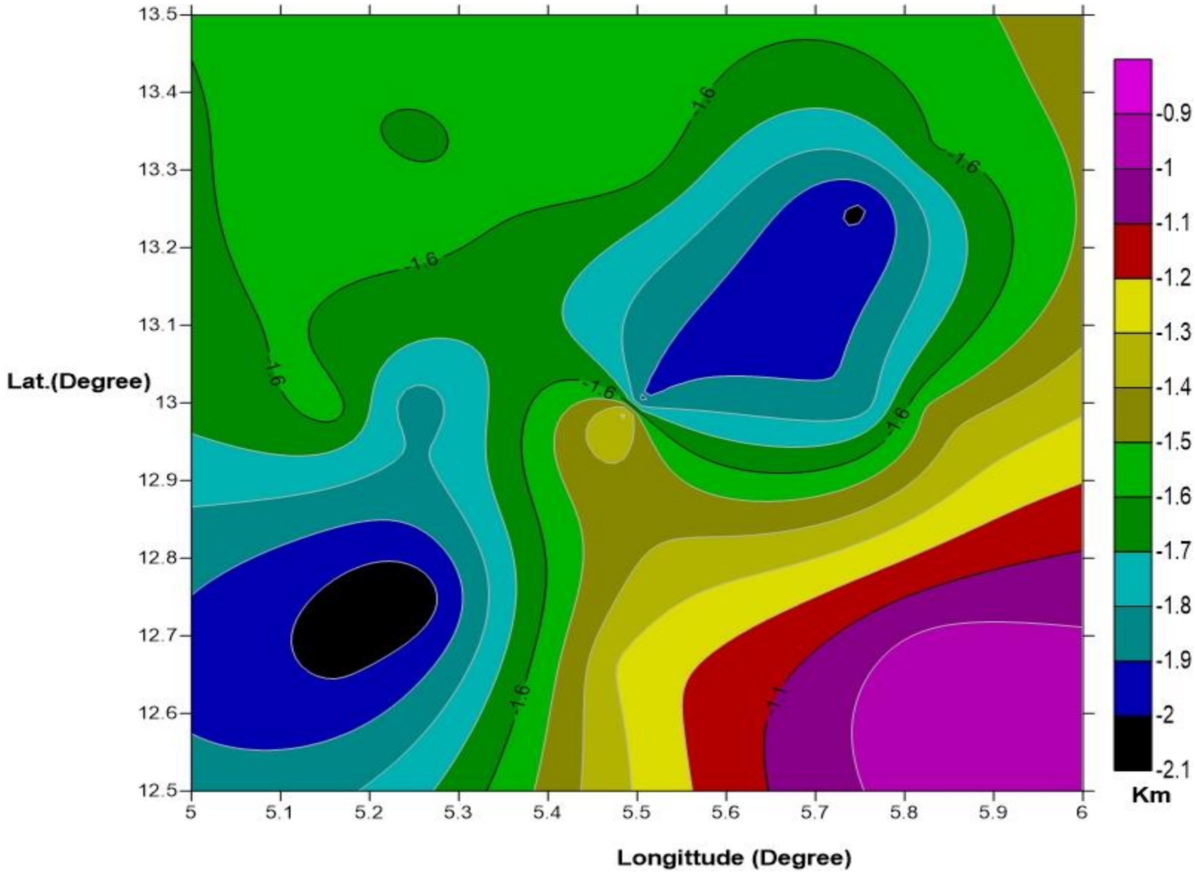

Figure 4. Depth contour map of the study area.

Summary

The total magnetic intensity map of the area revealed that the sedimentary thickness of the northeastern part of Sokoto Basin in general, appears to increases from south to north. The result of the spectral analysis over 16 overlapping blocks covering the study area suggests the existence of two main source depths, the shallow source depth ranging from 0.35 to 0.73 km with an average of 0.549 km and the deeper source depth varies from 0.91 to 2.09 km with an average value of 1.6025 km. These deeper sources are represented by low frequency component of the spectrum which reflect the depth to the magnetic basement. The SPI result shows that the northern part through the central part have the highest sedimentary thickness around Isa, Rabah through Dange areas, with a shallow thickness in the southern part.

Conclusion

Hydrocarbon presence and its potential is usually enhanced by the thickness of the sediment of the basin and also the kind of geological structures existing within the basement that form traps for oils and gas. The result revealed two major magnetic horizons under the area; the shallow magnetic sources represented by high frequency segment of the spectrum Z_1, while the deeper magnetic sources are represented by low frequency segment of the spectrum Z_2. The highest sedimentary thickness obtained in the area with spectral analysis is 2.4 km. This highest sedimentary thickness of 2.4 km was found at the Northeastern part of the study area was also confirmed by the result of SPI conducted on the area. This area of high sedimentary thickness should be the target for further exploration. Exploration of the Nigerian inland basins are worth given a push. Hydrocarbons if discovered and harnessed will increase the country’s reserve and boost productivity. All these will have economic and strategic benefits for the country.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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