IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG)
e-ISSN: 2321–0990, p-ISSN: 2321–0982.Volume 9, Issue 6 Ser. II (Nov. – Dec. 2021), PP 45-55
www.iosrjournals.org

Interpretation of High-Resolution Aerogravity Data over Parts of Lower Benue Trough of Nigeria for Hydrocarbon Potential Evaluation

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Abstract
Airborne gravity data over parts of the Lower Benue Trough of Nigeria were analyzed and interpreted to determine the basement depth of the source to gravity anomaly over the area. The study area lies within latitude 7.0^0 to 8.0^0 North and longitude $7.0^0$to 8.5^0 East in the Lower Benue Trough of Nigeria. The data were interpreted by source parameter imaging (SPI) and spectral depth analysis techniques. The basement depth obtained from SPI method ranges from -0.79 to -6.57 km while the basement depth from the spectral analysis shows the deep source varying from 1.91 to 6.50 km and the shallow source varying from 0.83 to 1.89 km. The depth to basement of the deep source is deepest around Oturkpo area but shallowest around Agana area. The maximum depths obtained from the two methods agree with each other and show thick sediments that are sufficient for hydrocarbon accumulation in the study area.

***Key words**: Lower Benue Trough, Source Parameter Imaging; Spectral Analysis; Sedimentary Thickness; Hydrocarbon Accumulation.*

Date of Submission: 15-12-2021 Date of Acceptance: 31-12-2021

I. Introduction

Geophysical survey is a scientific method of measuring the physical properties of the earth subsurface with appropriate instruments. It includes interpretation of the measurements to obtain useful information on the structure and composition of the concealed zones for both scientific and economic reasons. Gravity method is one of the geophysical techniques most widely employed for exploration work. Gravity exploration gives geoscientists an indirect way to "view" beneath the earth's surface by obtaining the physical properties of rocks. It measures variations in the earth's gravitational field caused by differences in the density of sub-surface rocks. The airborne survey is carried out by a spacecraft satellite or by using a gravimeter aboard or towed behind an aircraft. This provides an effective way for surveying a very large area quickly for regional exploration.

The study area for this research falls within the Lower Benue Trough of Nigeria. The Lower Benue Trough of Nigeria is one of those basins reported to have high hydrocarbon potential, besides other economic mineral deposits[1,2,3,4]. Most of geophysical works carried out in the basin employed airborne magnetic data hence the need for gravity data investigation to enrich the geophysical understanding and the economic importance of this part of the Lower Benue Trough.

Geology of the Study Area

The study area is located in the Lower Benue Trough of Nigeria (Figure1) within latitude 7.0^0 to 8.0^0 North and longitude 7.0^0 to 8.5^0 East with an area of approximately $18{,}150\ km^2$. The geology of the Benue Trough of Nigeria is now well documented[5,6,7,8,9,10]. The depositional history of the Benue Trough is characterized by phases of marine regression and transgression[10].

The lower Benue trough is underlain by a thick sedimentary sequence deposited during the Cretaceous[10]. The stratigraphic succession in the basin has been discussed by several authors[7,9,10,11,12]. The Cretaceous sediment is made up of Albian shales, subordinate siltstones of the Asu River Group and volcanic and pyroclastic materials which form elongated conical hills in the cores of the anticlinal structures[4,9]. The Asu River Group comprises of bluish black shales with minor sandstone unit. The shales are typically fractured and weathered to needle shaped bodies at the surface. Sandstone horizons are minor in the extreme south but tend to increase northwards[10].This is the oldest sediment overlying Precambrian basement complex[11]. Deposited on top of these Asu River Group sediments in the area were the Upper Cretaceous sediments, comprising mostly the Ezeaku shales[4,7] which consist of thick flaky calcareous and non-calcareous shales, sandy or shelly limestones, and calcareous sandstones. It has the Amaseri, Makurdi and Tobi sanstones as major sandstone facies[7,9]. The

Awgu shale which was deposited in the Santonian stage consists of marine fossilferous grey-blue shales associated with subordinate limestones and calcareous sandstones. The Awgu shales are overlain by Nkporo shales (Campanian) which also consist of blue or dark grey marine shale in the southern part of the sedimentary basin with occasional thin beds of sandy shale and sandstone in south-west part of Benue valley[7]. Figure 2 is the stratigraphic succession in the Lower Benue Trough[7].

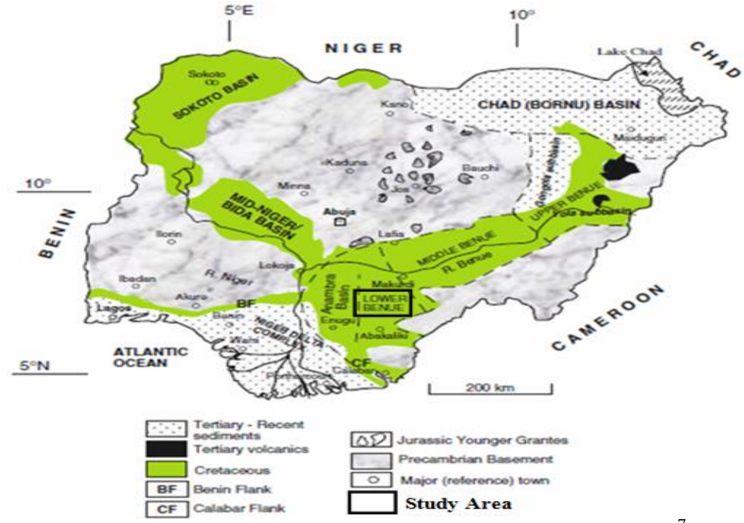

Figure 1.Geological map of Nigeria showing the study area[7].

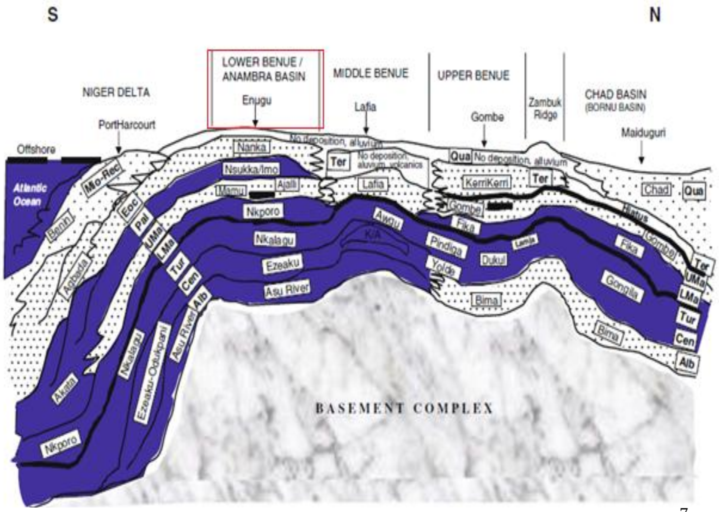

Figure 2. Stratigraphic succession in the Lower Benue Trough[7].

II. Materials and Methods

Source of Data

The high resolution airborne gravity data of Dekina (sheet 248), Soko (sheet 249), Agana (sheet 250), Angba (sheet 268), Ankpa (sheet 269) and Oturkpo (sheet 270) for this study were obtained from Nigerian Geological Survey Agency (NGSA). The data were acquired in 2008 by Fugro Airborne Surveys Limited. The data were obtained in XYZ format; X and Y are distances in meters measured along East and North direction respectively, while Z is the total Bouguer gravity anomaly measured in miligal.

Data Analysis:

The six sheets of the airborne gravity data were merged together to form a composite data sheet of 18,150 km^2 which forms the study area. The merged data were imported into Oasis Montaj 8.4 software for analysis and interpretation. The regional anomaly was separated from the residual anomaly by applying the first order polynomial fitting using least squares method.

Spectral Analysis

The spectral analysis uses discrete Fourier transform which is applied to regularly spaced data such as the airborne gravity data to calculate the spectrum of the potential field. The application of the power spectrum method to potential field data was proposed by[13] and the determination of the anomalous body depth was given by[14]. The technique is based on the principle that the gravity field measured at the surface can be considered the integral of gravity signatures from all depths. The power spectrum of the surface field can be used to identify average depths of source ensembles. In its complex form, the two dimensional Fourier transform pair[13] may be written as;

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

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

where u and v are the angular frequencies in x and y directions respectively. G(u, v) when split into its real and imaginary parts becomes:

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

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[14] follows that if

$$r^2 = (u^2 + v^2) \text{ and } \theta = \arctan\left({}^{u}/_{v}\right) \qquad 5$$

then the energy spectrum E(r,θ) can be given as:

$$\langle E(r,\theta)\rangle = 4\pi^2 M^2 R_G^2 (e^{-2hr})((1 - e^{-tr})^2)\big(S^2(r,\theta)\big)(R_P^2(\theta)) \qquad 6$$

where$\langle E(r,\theta)\rangle$ indicates the expected value, $r^2 = (u^2 + v^2)$ is the magnitude of the frequency vector, M is the 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 gravitational force on the prism and R_G is the factor for the gravitational field direction. The term $\exp(-2hr)$ is the dominant factor in the power spectrum; where h is the depth and r is the frequency.

To begin the spectral analysis, the residual Bouguer anomaly map was divided into twenty four (24) overlapping equal spectral blocks. Each profile covers a square area of 27.5 km by 27.5 km. Fast Fourier Transform (FFT) technique was used in Microsoft (MS) Excel program to transform the gravity data into frequency and radial energy spectrum for each block. The average radial energy spectrum was calculated and displayed in logarithm of energy versus frequency. Graphs of radial average energy spectrum were plotted in MS Excel as Log of Energy (FFT magnitude) against Frequency in cycles/m. The gradient of each of the line segments was first evaluated and the depths of the source ensembles (h_1 and h_2) subsequently calculated using the equations of[14]:

$$m = -\frac{\Delta \log E}{\Delta f} \qquad 7$$

The average depth to gravity sources is computed from the gradient m as[15]:

$$h(f) = \frac{m}{4\pi} = m \times 0.08 \text{ cycles/m distance} \qquad 8$$

$$\therefore h_1 = \frac{m_1}{4\pi} \qquad 9$$

$$h_2 = \frac{m_2}{4\pi} \qquad 10$$

where m_1 is the slope of the first fitting straight line and m_2 is the slope of the second fitting straight line.

From the computed values, the gravity basement depths were plotted and contoured using Surfer 32 software. The computed source to basement depths (h_1 and h_2) were used to construct the 3D basement topographic map of the study area.

Source Parameter Imaging

The Source parameter imaging technique is an extension of the use of complex analytical signal to estimate potential field depths[16]. The 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 via horizontal and vertical gradients[16]. The depth is displayed as an image. The relationship between depth (h) and the peak value K_{max} of the local wave number K over the step source is expressed as[16,17]:

$$Depth, h = \frac{1}{K_{max}} \qquad 11$$

$$\text{where } K_{max} = \sqrt{\left(\frac{\partial Tilt}{\partial z}\right)^2 + \left(\frac{\partial Tilt}{\partial y}\right)^2} \qquad 12$$

$$Tilt = \arctan\left[\frac{\left(\frac{\partial T}{\partial z}\right)}{\sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2}}\right] \qquad 13$$

III. RESULT

Figure 3 is the total Bouguer gravity anomaly map of the study area while Figure 4 is the residual gravity anomaly map of the study area after the regional-residual separation. The Bouguer anomaly of the study area varies from -29.4 mgal to 14.5 mgal (Figure 3) while the residual Bouguer map varies from -23.2 mgal to 13.8 mgal (Figure 4). The colour bar identifies areas (Dekina and Ankpa) with gravity high (red and pink) which correspond to regions with high density contrast beneath the surface. Intermediate gravity values (green and yellow) were identified around Angba and Oturkpo areas while gravity lows (blue colour) that correspond to regions of low density contrast were identified around Soko and Agana areas. The areas with high density contrast could be associated with igneous and metamorphic rocks and rock bearing minerals while areas with low density contrast could be associated with sediment deposits in the area. Figure 5 shows the twenty four spectral blocks of the study area while eight representative spectral profiles are as shown in Figure 6. The coordinates and the two depth estimates (h_1 and h_2) for each of the twenty four spectral blocks are as given in Table 1. The deep source (h_1) varies from 1.918 to 6.508 km with an average of 4.481 km, whereas the shallow source (h_2) varies from 0.830 to 1.888 km with an average of 1.287 km. The deep source to basement is shallowest (pink colour) around Agana area (Figure 7) but deepest (blue colour) around Oturkpo area while the shallow source to basement is shallowest (purple colour) at the western and northeastern part of the study area but deepest (blue colour) at the southern part of the study area (Figure 8). The topographic map generated using Surfer 32 software (Figure 9) shows the undulating nature of the basement surface with thickest sediments around Oturkpo area and shallowest sediments around Agana area.

The depth estimates from the SPI method with the colour bar are as shown in Figure 10. The negative values on the legend depict the depths of buried gravity bodies which may be as a result of deep seated basement rocks or near surface intrusions. The pink colour generally indicates areas with shallow gravity bodies, while the blue colour depicts areas with deep lying gravity bodies. The SPI depth estimates range from -7.97 km (shallow gravity bodies) to -6.58 km (deep lying gravity bodies). These values agree closely with those obtained from the spectral depth analysis of the same data in this work. The depths from source parameter imaging and spectral analysis also agree closely with those of some previous researchers in Lower Benue Trough[3,17,18,19,20,21].

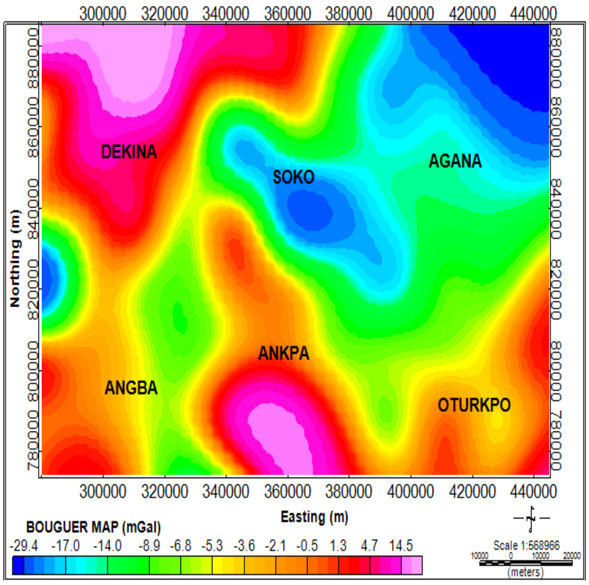

Figure 3.Total Bouguer gravity anomaly map of the study area.

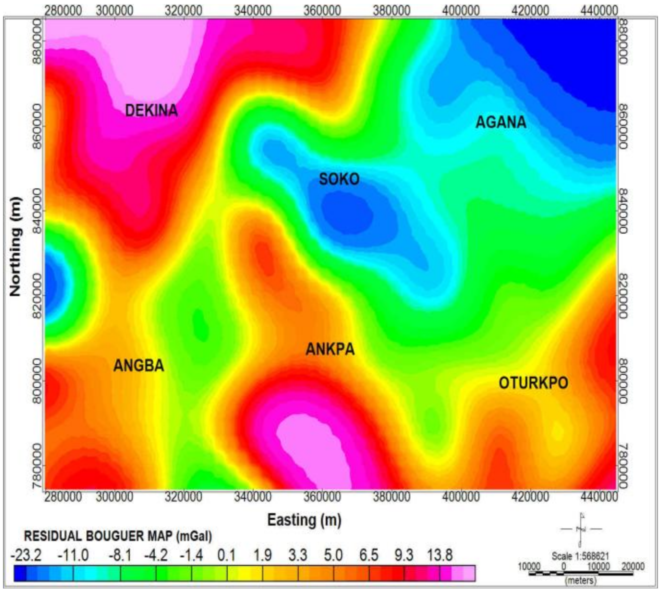

Figure 4. Residual Bouguer gravity anomaly map of the study area.

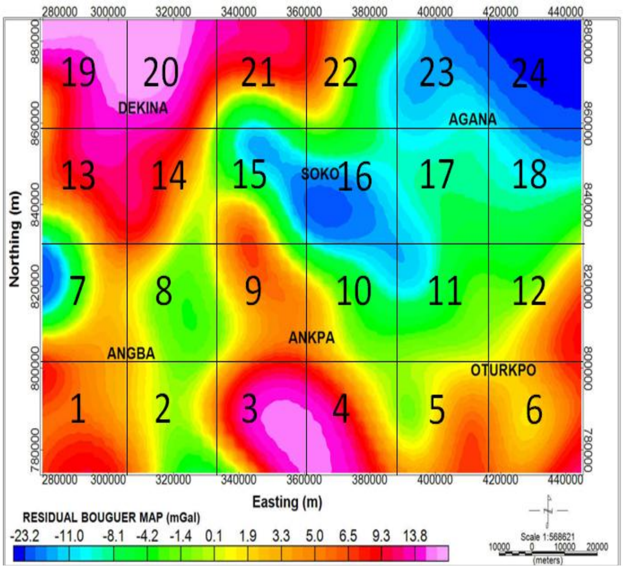

Figure 5. Spectral blocks of the study area.

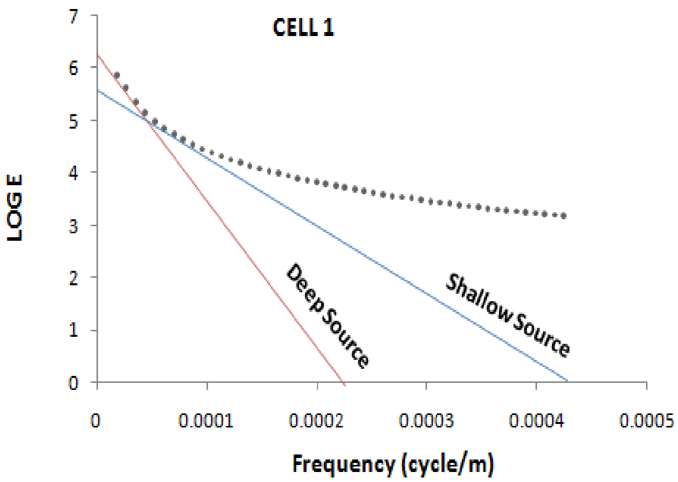

Figure 6a. Spectral plot of logarithm of Energy against Frequency.

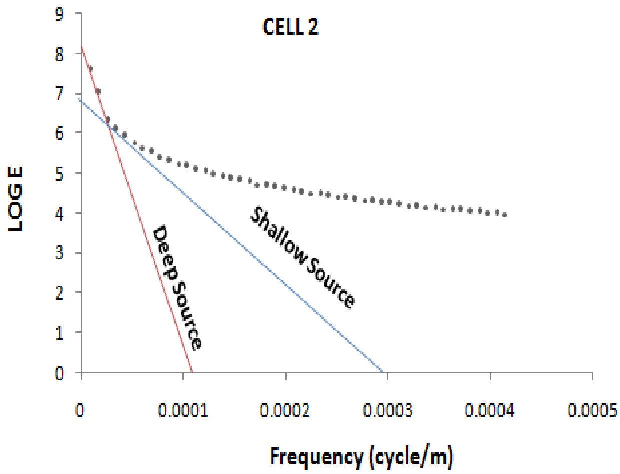

Figure 6b. Spectral plot of logarithm of Energy against Frequency.

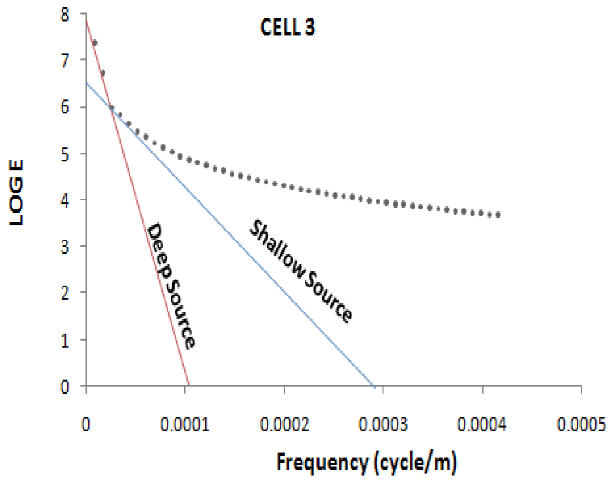

Figure 6c. Spectral plot of logarithm of Energy against Frequency.

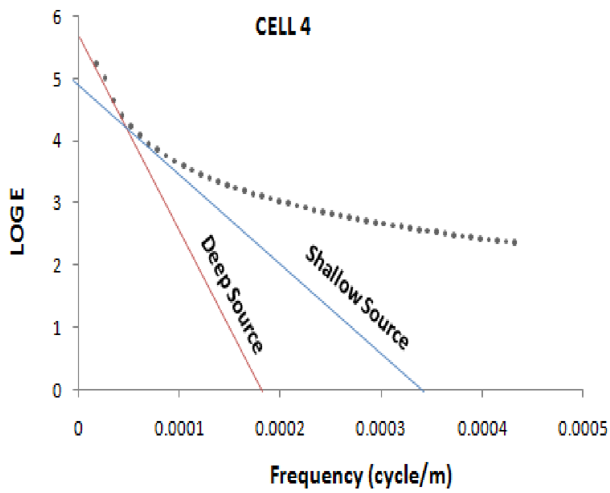

Figure 6d. Spectral plot of logarithm of Energy against Frequency.

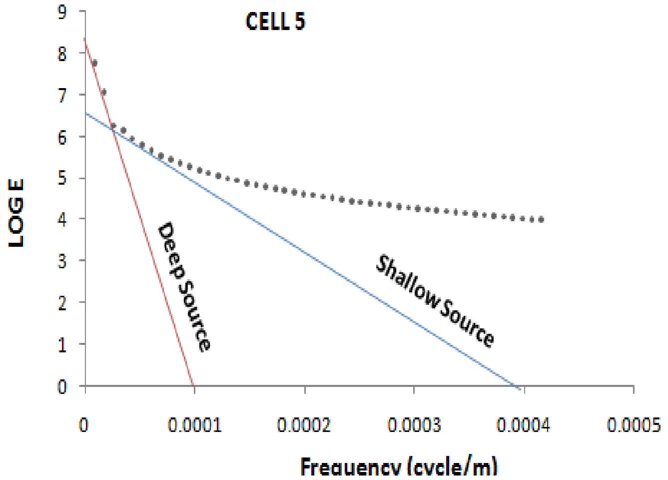

Figure 6e. Spectral plots of logarithm of Energy against Frequency.

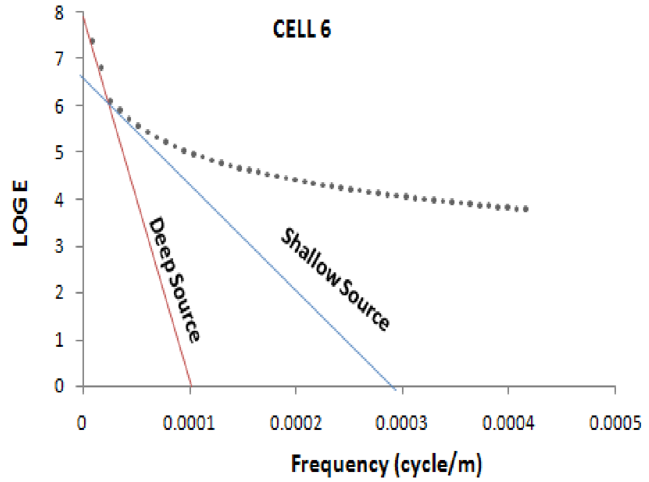

Figure 6f. Spectral plot of logarithm of Energy against Frequency.

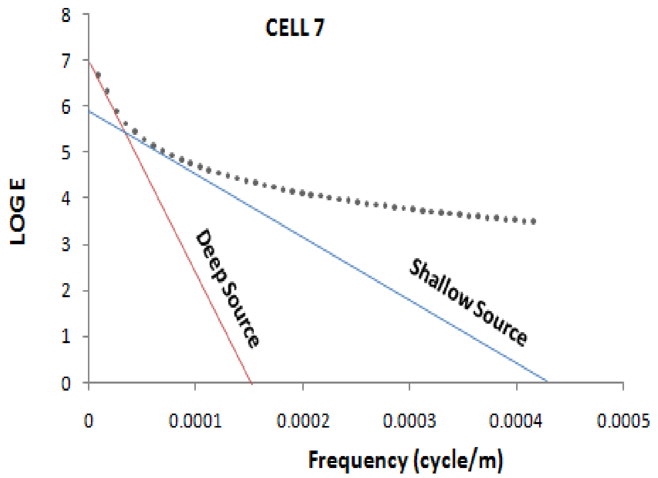

Figure 6g. Spectral plot of logarithm of Energy against Frequency.

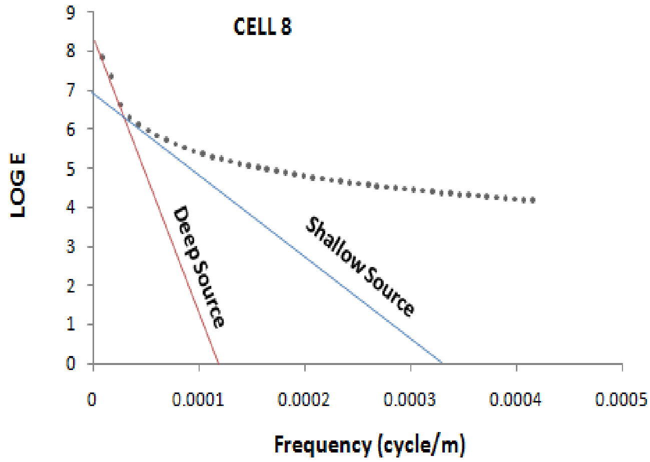

Figure 6h. Spectral plot of logarithm of Energy against Frequency.

Table 1: Summary of estimates of depth to basement of the spectral blocks of the area.

S/N	SPECTRAL BLOCKS	CO-ORDINATES (m)		DEPTH SOURCE VALUE (km)	
	SECTIONS	X (Easting)	Y (Northing)	DEEP (h1)	SHALLOW (h2)
1	1	293345.38	788406.19	2.139	0.992
2	2	320794.25	788406.19	5.357	1.888
3	3	348243.12	788406.19	5.628	1.779
4	4	375691.99	788406.19	2.661	1.144
5	5	403140.86	788406.19	6.508	1.378
6	6	430589.73	788406.19	6.270	1.834
7	7	293345.38	816047.38	3.704	1.071
8	8	320794.25	816047.38	5.423	1.634
9	9	348243.12	816047.38	3.968	1.287
10	10	375691.99	816047.38	2.632	0.992
11	11	403140.86	816047.38	4.535	1.255
12	12	430589.73	816047.38	4.649	1.502
13	13	293345.38	843688.57	2.165	0.861
14	14	320794.25	843688.57	5.225	1.373
15	15	348243.12	843688.57	5.886	1.587
16	16	375691.99	843688.57	5.772	1.416
17	17	403140.86	843688.57	4.906	1.066
18	18	430589.73	843688.57	2.661	0.830
19	19	293345.38	871329.76	5.291	1.172
20	20	320794.25	871329.76	4.884	1.172
21	21	348243.12	871329.76	4.195	1.118
22	22	375691.99	871329.76	6.111	1.354
23	23	403140.86	871329.76	5.067	1.237
24	24	430589.73	871329.76	1.918	0.938
AVERAGE DEPTH				4.481	1.287

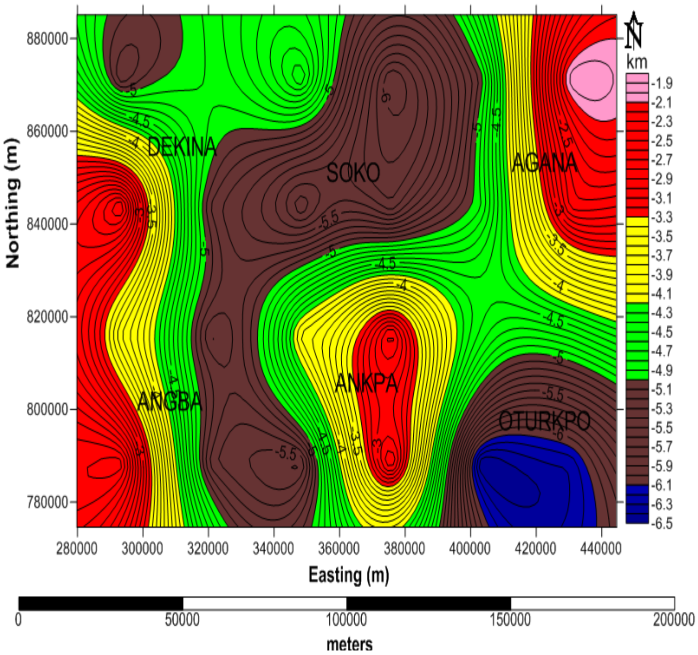

Figure 7. Deep depth to basement map of the study area (contour interval 0.1km).

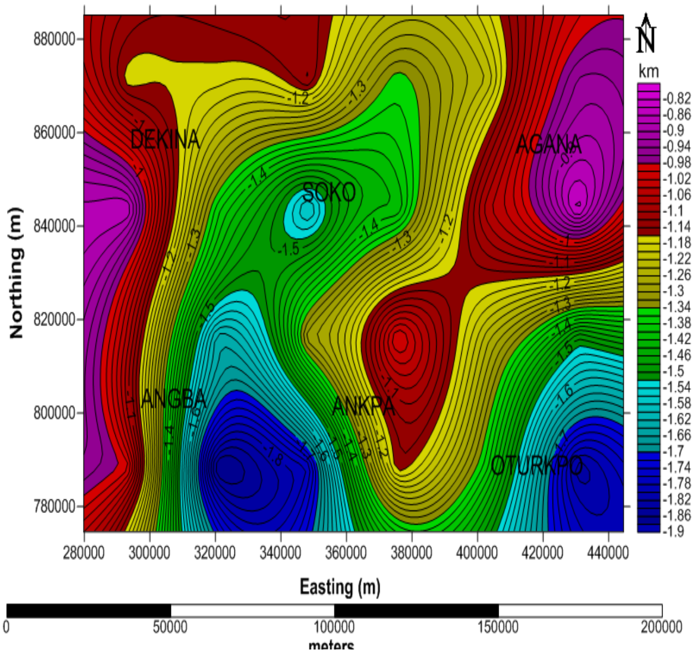

Figure 8. Shallow depth to basement map of the study area (contour interval 0.02km).

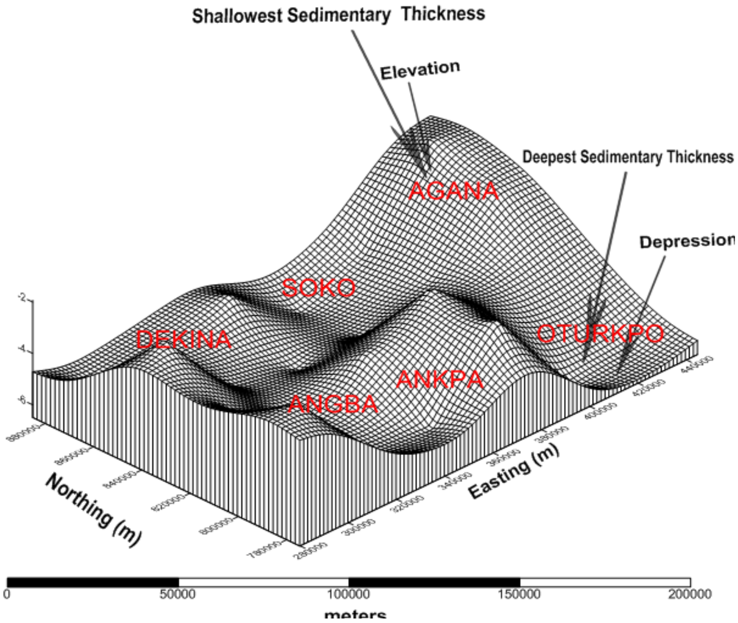

Figure 9. 3D gravity basement map of the study area.

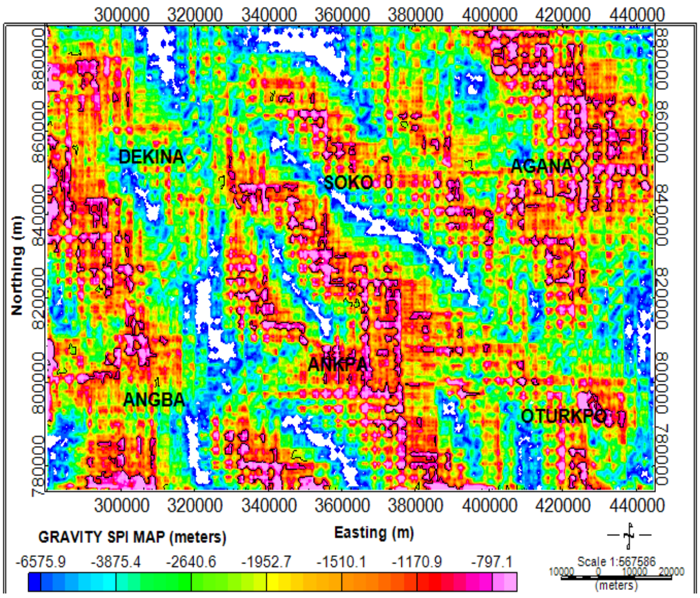

Figure 10. 2D SPI depth map of the study area.

IV. Discussion

The Bouguer anomaly of the study area varies from -29.4 mgal to 14.5 mgal while the residual anomaly of the study area varies from -23.2 mgal to 13.8 mgal. The Bouguer gravity anomaly map identified regions of gravity high (which correspond to regions with high density contrast) and regions of gravity low (which correspond to regions of low density contrast). The residual field map showed local features which tend to be obscured by the regional anomalies. The basement depths obtained from SPI (-0.79 to -6.57 Km) and spectral analysis (1.91 to 6.50 Km) are in close agreement. The deep depth to basement from the spectral analysis is shallowest (pink colour) around Agana area but deepest (blue colour) around Oturkpo area. These depths are found to be within the range of depths obtained by earlier researchers that worked in Lower Benue Trough[3,17,19]. The results from the two interpretation methods revealed basement depths sufficient for hydrocarbon accumulation.

V. Conclusion

This work has utilized the spectral depth analysis and source parameter imaging techniques to analyze and interpret the aerogravity data over Dekina, Soko, Agana, Angba, Ankpa and Oturkpo areas of the Lower

Benue Trough of Nigeria. The result from spectral analysis shows depth range of 1.91 to 6.50 km for deep source to basement while the estimated depths from SPI depth analysis ranges from -0.79 to -6.57 km. The maximum depths obtained from the two methods show thick sediments that are sufficient for hydrocarbon accumulation in the study area, if other conditions such as thermal maturity of the source rock and petrographic characteristics are favourable.

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