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Applications of Spectral Analysis and 2D Modeling of Gravity Data for Depth to Basement Estimation in Parts of South Eastern Nigeria

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Abstract

This study interprets gravity data in parts of southeastern Nigeria using spectral analysis and 2D modeling. The study area is bounded by Latitudes 5ºN 30ˈ to 6ºN 30ˈ and Longitudes 7ºE 0ˈ to 8ºE 0ˈ. The Bouguer gravity data was obtained from the Nigerian Geological Survey Agency (NGSA) in Geosoft grid file format. The study uses the spectral analysis method and 2D modeling with GM SYS to estimate the average depth of the sedimentary strata and the basement from the Bouguer anomaly map. The data sets cover the southern part of the Anambra basin and the northern Niger Delta complex. Regional-residual separation was applied to the Bouguer gravity data through the polynomial fitting of the first degree. This gave rise to the residual and regional maps. Further filtering actions accentuated the subtlest anomalies peculiar to the study area. Spectral analysis results reveal two depth models: deep source (D1) and shallow source (D2). The deep source represents depths within the basement-related sources, while the Shallow source is associated with shallow-related gravity sources. D1 varies from 1.50 km to 4.02 km with an average value of 2.95 km, while D2 varies from 1.91 km to 0.514 km with an average value of 1.50 km. The thickest depth of the Modelled cross-section is at about 6845.62 m, which is within the tertiary recent sediment with clayey sands and shale extending beyond the study area. The average or actual sedimentary thickness of 2.95 km suggests that the area will be plausible for hydrocarbon exploration. The thickest sedimentary cover represents density variation in sedimentary rock of the basin, which occurs at the southern part of block 4 (Okigwe).

Keywords: *Bouguer anomaly; Regional; Residual; Sedimentary cover; Basement.*

1. Introduction

In geophysics, the gravity technique measures the earth's gravitational field variations to calculate the underlying density distribution [1]. To evaluate the physical and chemical characteristics of soil, rocks, and groundwater, geophysical techniques are mainly used to measure how these materials react to different electromagnetic (EM) radiation, such as visible light, gamma rays, radar, microwaves, radio waves, acoustic and seismic energy, and other potential fields like gravity and the earth's magnetic field [2].

The gravity method of surveys is mainly used for large-scale crustal study, where measurements of the earth`s gravitational field are used for mapping variations in subsurface densities [3-4], sedimentary sequence, basement topography, sedimentary basin alongside its structural mapping and the regional groundwater exploration.

The spectral method of analysis has been employed increasingly in recent years. In these methods, the characteristics of the observed anomalies are studied by first transforming the data from the space to the frequency domain and then analyzing their frequency characteristics [5].

This research uses ground survey gravity data covering some parts of Southeastern Nigeria using the Spectral Analysis Method to estimate the depth to the basement of gravity sources in the study area. Gravity data can be represented accurately by an analytic function using Fourier series. The method used in this study involves Fourier transformation of the digitized gravity spectrum. This work is predetermined to estimate the depth of the basement in the study area by implementing a geophysical method to interpret the ground survey gravity data covering the study area.

2. Location of study

The study area covers 1:250,000 of scale located in the Southeastern region of Nigeria, as shown in Fig. 1, occupying parts of Enugu, Ebonyi, Anambra, Abia, Imo, and Akwa Ibom State (Fig. 1). It comprises longitude E7º 0' to E8º 0' and latitude N5º 30' to N6º 30'.

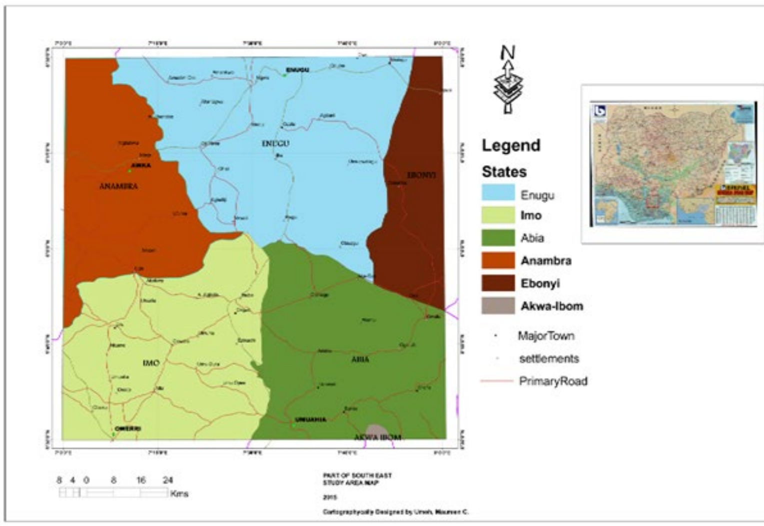

Fig 1. Map of study area.

2.1. Geology of study area

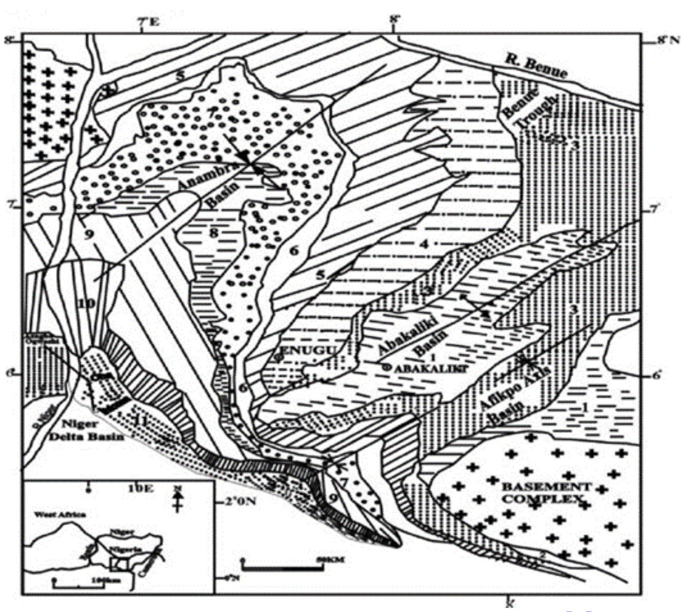

Fig 2. Geological map of southeastern Nigeria [7].

The study area is located within the southern part of the Anambra Basin and a portion of the Northern part of the Niger Delta Complex. Therefore, the primary exposed lithologies are Cretaceous sandstones, shale, and siltstones; Tertiary clay, sandstones, and shales (Fig 2).

According to [6], Eze-Aku Shale, Awgu Shale, Mamu Formation, Nsukka Formation, Imo Shale, Odukpani Formation, Ameki Formation, Aku River Group, Enugu/Nkporo Shale, Ogwashi Asaba Formation and Ajali Sandstone, are the first eleven formations. The geographic location of the Cretaceous to Tertiary periods north of the Niger Delta Basin is shown on this basic geological map of southeast Nigeria.

3. Materials and methods

3.1. Data acquisition

The digitized ground survey Bouguer anomaly data were obtained from the Nigerian Geological Survey Agency (NGSA). The survey was tied to the International Gravity Standardization Net 1971(IGSN`71).

3.2. Spectral analysis

The spectral analysis breaks down anomaly signals according to wavelength to determine the mean depth of the anomaly sources. The slope of the spectral diagram, which plots wavelength vs power spectral magnitude, may be used to determine the average depth of the anomaly sources. The estimate of the anomaly source depth for the gravity data can then be written as [8-9].

$$D=\frac{P(r2)-P(r1)}{4\pi(r2-r1)} \quad (1)$$

The equation stated above may be used to determine the power spectral P(r) value in the logarithmic form of the FFT magnitude result, where r is the matching wavelength, given that it is effectively a straight-line gradient. The power spectral density is a function of depth in the relation produced by the computation using equation (1) above, which may be expressed as an exponential equation based on depth h [9-12].

$$P = s^{-2ke} \quad (2)$$

where s is a constant proportional to the equivalent layer and k is the angular vector.

The average thicknesses of various segments of the sedimentary basin determined using radially averaged power spectrals were calculated by first dividing the gridded residual map of the entire study area into smaller square blocks of 16 blocks (each sheet is divided into four) with dimensions 25 km x 25 km and the average depth computed for each block.

Using the Magmap extension/interface of Geosoft, the grid for each block was Fast Fourier transformed, and radial average spectrum was run for each block; this produces a column for logs of spectral energy and the corresponding frequencies. The text file was saved in an Excel worksheet, and then the Excel worksheet was used to plot the graphs in the Matlab environment.

The log spectrum used in considering a line of these data to determine the depth to the top of a statistical ensemble of sources using the relationship

$$logE(k) = 4\pi hk \quad (3)$$

where h is the ground-unit depth and k is the wave number in cycles/ground-unit.

The gradient of each segment of the straight line was evaluated and converted to depth using equation 4.

$$H = \frac{-GRAD}{4\pi} \quad (4)$$

$where;\ H = expected\ depth\ and\ \pi = 3.142$

Two gradients corresponding to the linear segments were evacuated, with the steep gradient related to deeper sources and the low gradient related to the shallow sources. Values closer to the end of the plot were considered to be noise; hence, care was taken to avoid them. Usually, any typical energy spectrum for potential field (both gravity and magnetic) data will display three parts of the anomaly depth component namely – a deep source, a shallow source and a noise. But for this work, only the deep and shallow source components were determined.

3.3. Modelling with GM-SYS

The GM-SYS module of Geosoft Oasis Montaj software was employed in modeling selected traverses across the study area to determine the variation in the thicknesses of the sedimentary basin. The profiles were taken in directions orthogonal to the prominent trends/structures and also to cut close to locations of the gravity aureoles.

The residual grid map was analyzed qualitatively by comparing it with geological map of the study area; and lineaments that traversed the sedimentary basin area were thus delineated. The development of the models involved; Filtering the bouguer anomaly to obtain the residual anomaly, inversion of the residual anomaly with a constant density contrast to obtain a model of the basement, adjustment of the inversion parameters and of the basin sediment density to obtain a model for basement depths which satisfies the profiles taken across prominent anomalies within the study area. Three profiles were taken on the residual bouguer gravity map to produce the models for this study.

4. Results and discussion

4.1. Bouguer gravity anomaly

The bouguer gravity anomaly map in Fig 3 shows the four sheets that makes up the complete Bouguer anomaly map of the study area. Fig 4 shows positive and negative anomalies, the bouguer low on the two sides of the study area is a negative density contrast which could be due to high sedimentary fill or deep internal intrusion. Bouguer high (trending NE – SW) indicates high density body due to shallow basement or massive density body while the green and yellow colored areas have little or no density contrast.

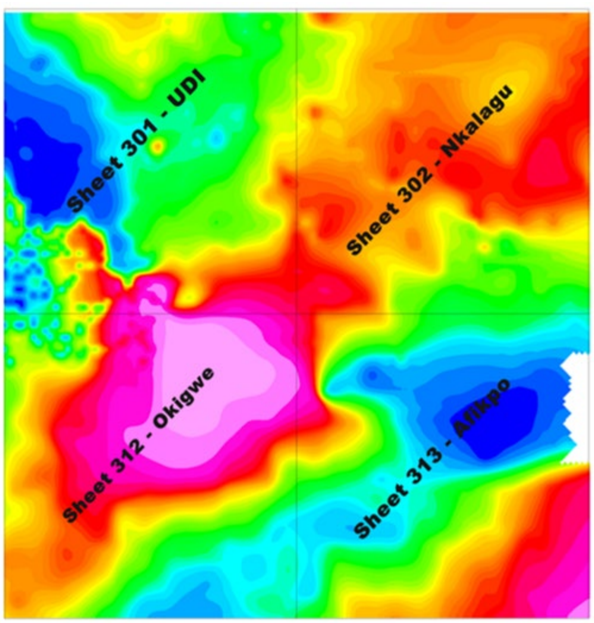

Fig 3. Map showing the four grids that make up the complete gravity bouguer anomaly map of the study area.

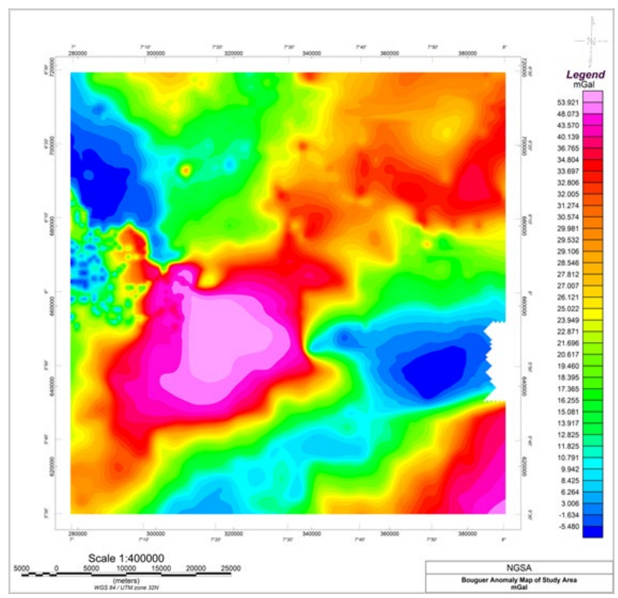

Fig 4. Bouguer gravity grid map of study area.

4.2. Regional-residual separation

Regional-residual separation was carried out on the original Bouguer gravity data (Fig 3), and this resulted in the generation of the regional (Fig 4) and residual maps (Fig 4). The regional gravity anomaly value (Fig 4) was subtracted from the gravity bouguer anomaly values from the original grid (Fig 3) to obtain the residual grid (Fig. 5).

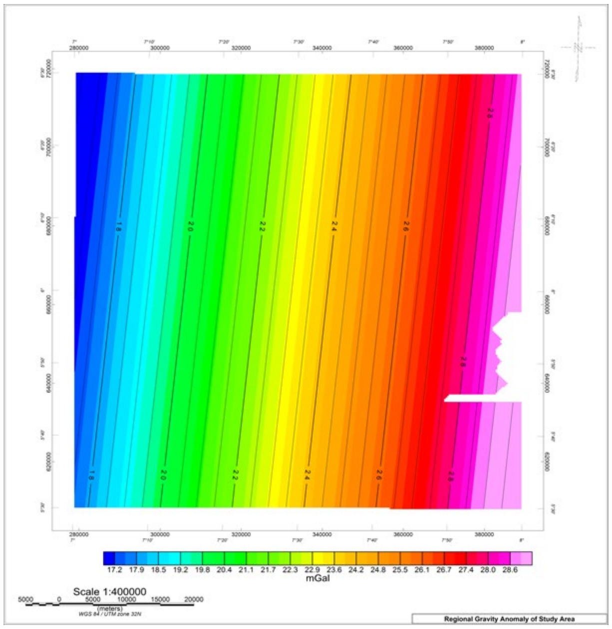

Fig 5. Regional Bouguer gravity map of study area.

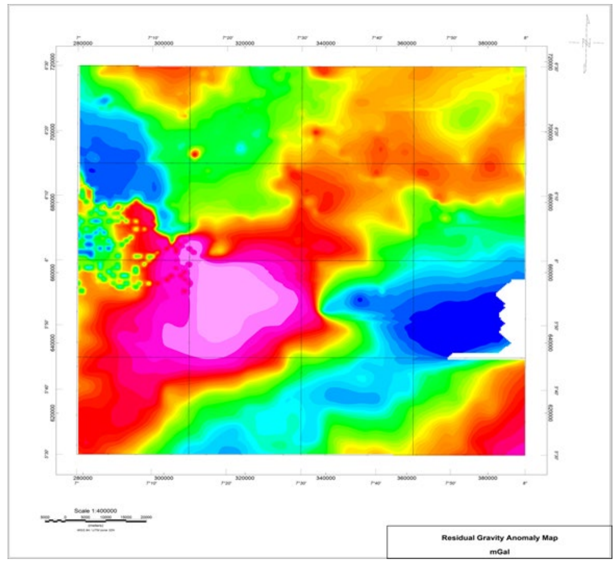

Fig 6. Residual gravity map of study area showing the division of the sixteen blocks used for the spectral plots.

4.3. Depth estimation using spectral analysis

Spectral analysis of the bouguer gravity data of the study area reveals two major anomaly source depths. Fig. 6 shows the division of the 16 blocks from the four sheets (Fig. 7) making up the study area, used for the spectral calculations. Depths to the gravity sources are calculated from the curve slopes of Figs. 7, 8, 9 and 10 respectively.

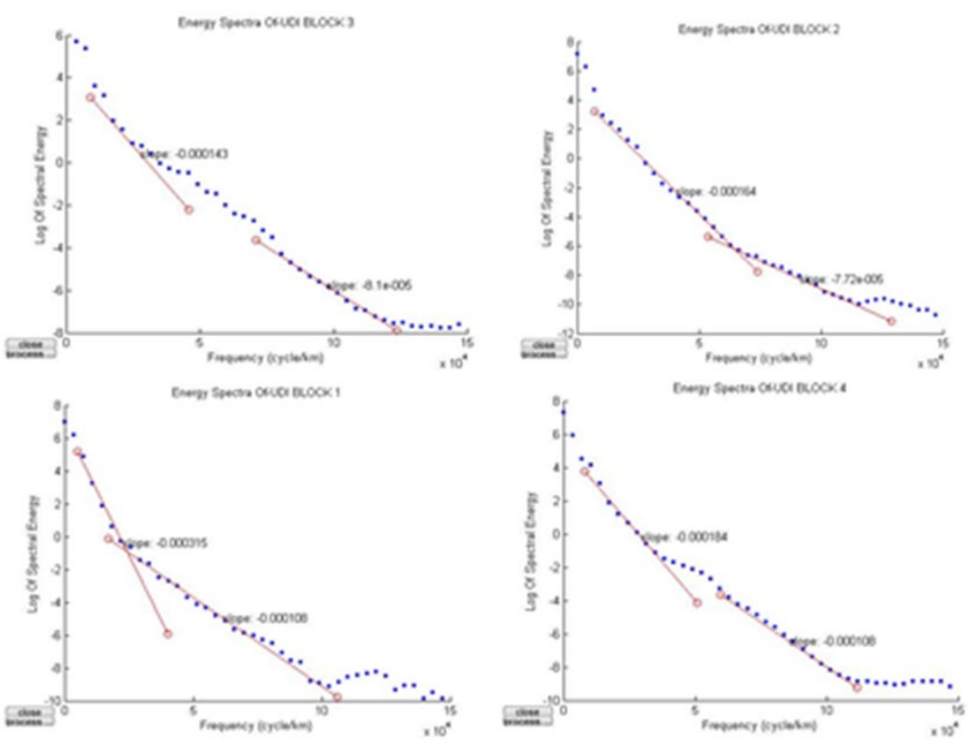

Fig 7. Spectral plot for sheet 1 (Udi).

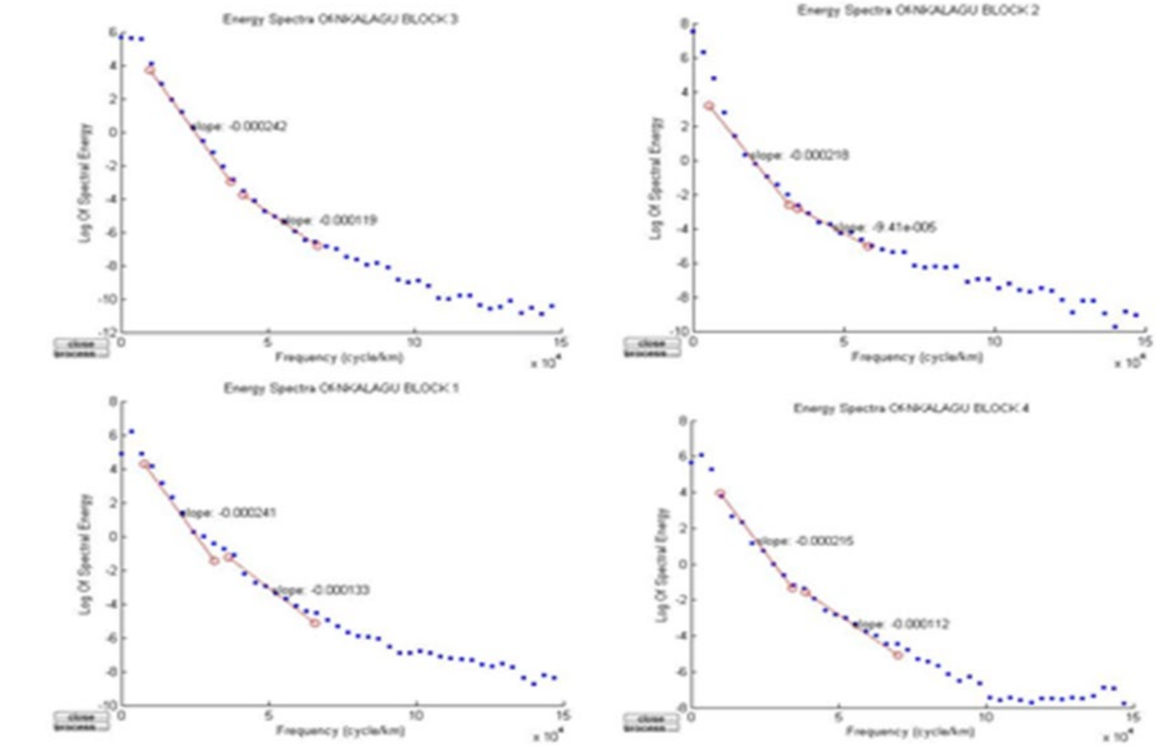

Fig 8. Spectral plot for Sheet 2 (Nkalagu).

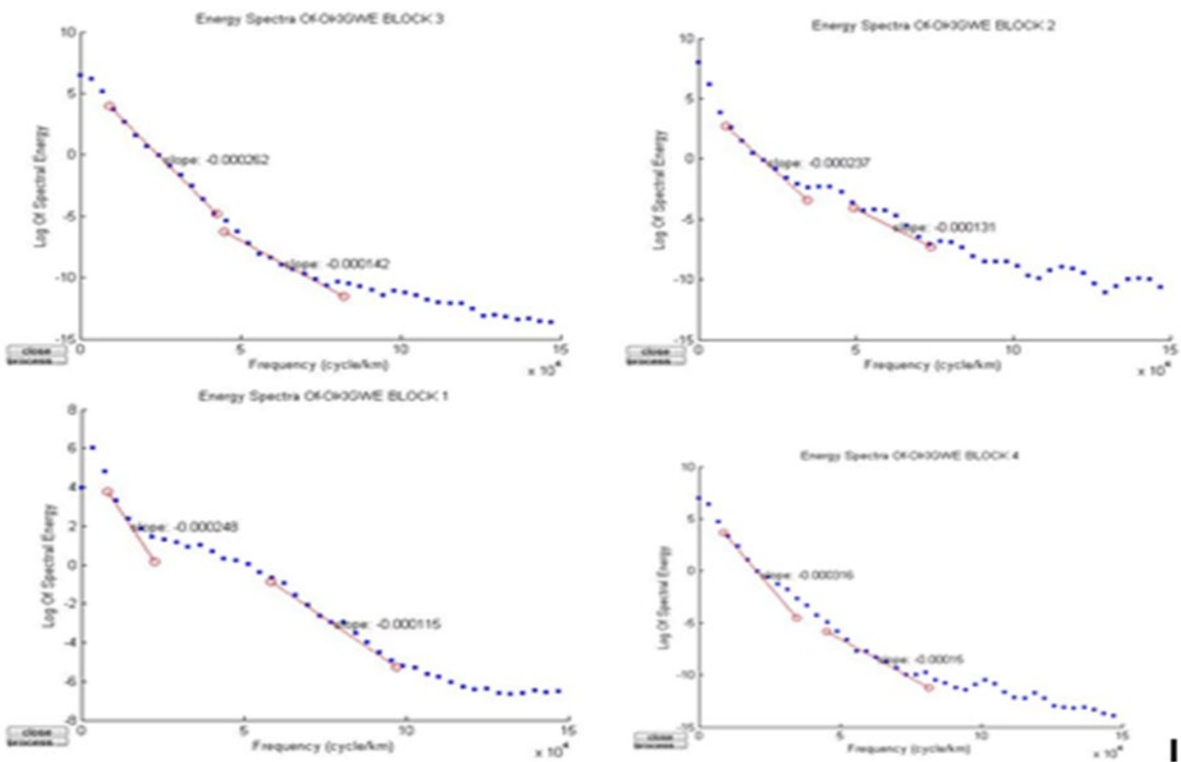

Fig 9. Spectral plot for Sheet 3 (Okigwe).

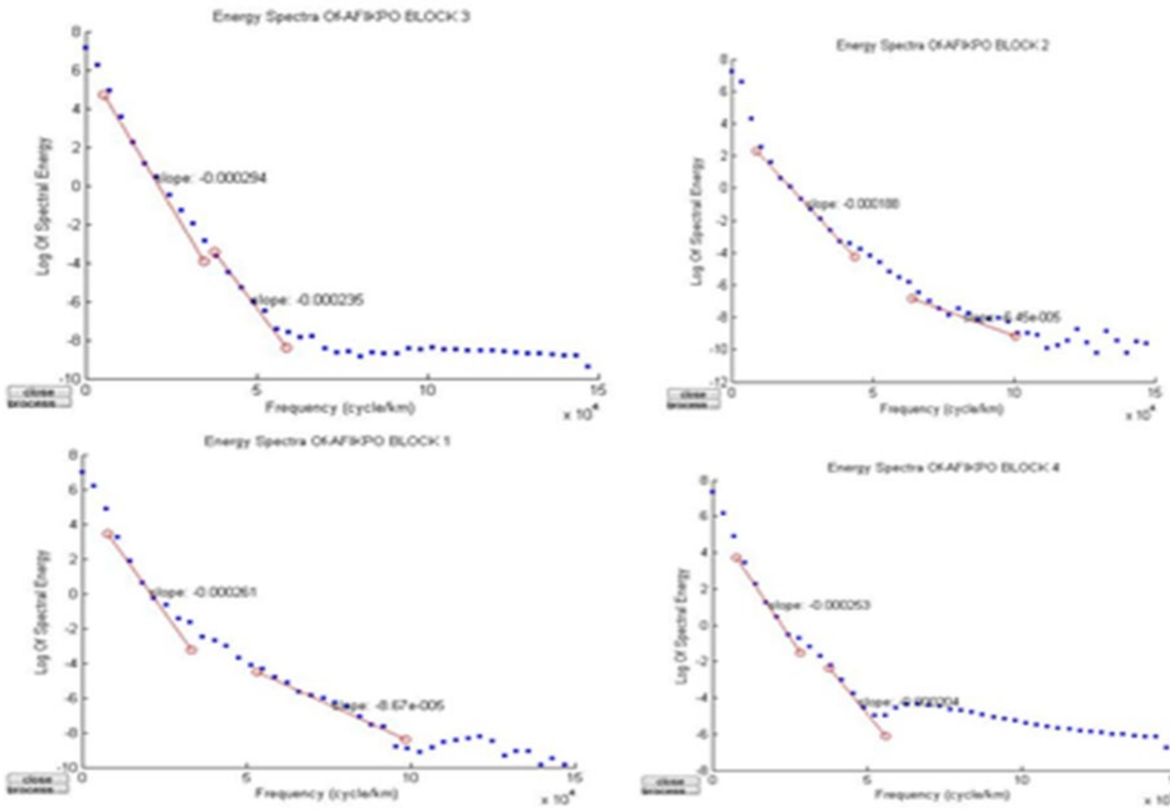

Fig 10. Spectral plot for Sheet 4 (Afikpo).

The survey was done through traverses in order to get the understanding of the causative bodies. The sought parameters of the source bodies were obtained using spectral analysis method, the spectral analysis reveals two major anomaly source D1 for deep source and D2 for shallow source. The sheets names in the bouguer map are; Udi, Nkalagu, Okigwe and Afikpo, the slope is a negative slope, D1 ranges between 1.50 to 4.02, while D2 ranges between 0.514 to 1.91. The thickest sedimentary cover occurs at the southern part (block 4) Okigwe. It represents density variation in the sedimentary rock of the basin. Matlab was used for the spectral plotting of the data obtained.

Table 1 shows the estimated depths to deep (D1) and shallow sources (D2). Average depth which produced gravity anomaly values of deep sources is 2.95 km while for the shallow source it is about 1.50 km.

The average of shallow depth referred to bedrock underlying the thin sediment in the eastern and western flanks while the average of deep source is related to deep seated bedrock underlying the thick sediment in the middle area. It is established that error in depth estimation increase with depth of source. The average of shallow depth referred to bedrock underlying the thin sediment in the eastern and western flanks while the average of deep source is related to deep seated bedrock underlying the thick sediment in the middle area. The depth (values) obtained here is lower than that obtained by source parameter imaging this is because the spectral method is not devoid of error due to the positions of the trend lines (gradients) on the spectral plots which is manually done. It is established that error in depth estimation increase with depth of source.

Table 1. Estimated depths from spectral analysis.

Sheet	Longitude	Latitude	Estimated depths (km)	
			D1	*D2*
Udi- Block 1	7.0 - 7.25	6.25 – 6.5	4.01	1.38
Block 2	7.25 - 7.5	6.25 – 6.5	2.09	0.98
Block 3	7.0 - 7.25	6.0 – 6.25	1.82	1.03
Block 4	7.25 - 7.5	6.0 – 6.25	2.34	1.37
Nkalagu - Block1	7.5- 7.75	6.25 – 6.5	3.07	1.69
Block 2	7.75- 8.0	6.25 – 6.5	2.78	1.20
Block 3	7.5 - 7.75	6.0 – 6.25	3.08	1.51
Block 4	7.75 - 8.0	6.0 – 6.25	2.74	1.42
Okigwe- Block 1	7.0 – 7.25	5.75 – 6.0	3.16	1.46
Block 2	7.25 – 7.5	5.75 – 6.0	3.02	1.03
Block 3	7.0 – 7.25	5.5 – 5.75	3.34	1.81
Block 4	7.25 – 7.5	5.5 – 5.75	4.02	1.91
Afikpo- Block 1	7.5 – 7.75	5.75 – 6.0	3.32	1.104
Block 2	7.75 – 8.0	5.75 – 6.0	1.50	0.514
Block 3	7.5 – 7.75	5.5 – 5.75	3.74	2.99
Block 4	7.75 – 8.0	5.5 – 5.75	3.22	2.59
Average depth =		2.95 1.50		

4.4. Development of Model using GM – SYS interface

Technique used in any survey depends on the structures intended to model and also the purpose of the study. From the residual bouguer gravity anomaly map (Fig 5) of the study area three major anomaly profiles were modeled. The profiles (Fig 11) are labeled P1, P2 and P3. The dotted lines indicate the observed gravity value while the solid straight lines represent the model-calculated anomaly value. The distance cover for profile 1 (Fig 12) is 55195.92 m, profile 2 (Fig 13) is 94774.29 m and profile 3 (Fig 14) is 68780.56 m. Figure 12 shows profile 1 and profile 3 cut across the centers of the two major residual gravity lows. Profile 2 cut across the major high and a low.

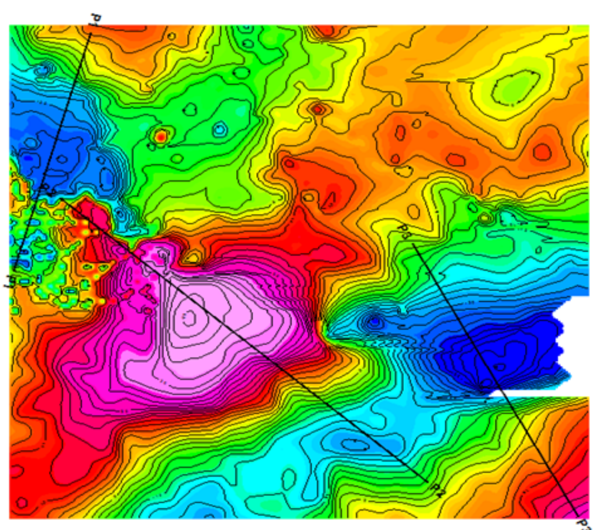

Fig 11. Residual Bouguer anomaly showing profile lines (P1, P2 and P3).

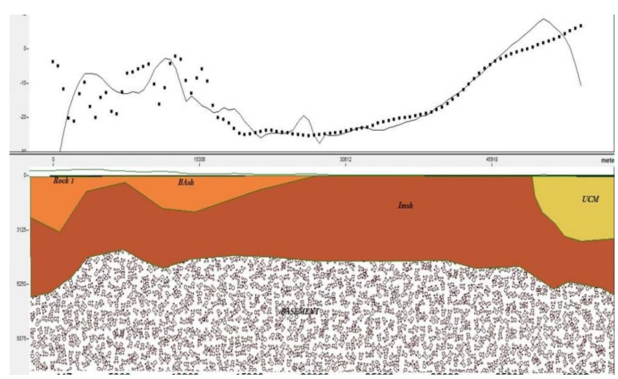

Fig 12. Modelled cross-section (profile line 1, P1) showing anomaly due to lithological changes and sedimentary section, about 6845.62m thick.

Fig 13 with the thickest depth at about 6845.62 m is within the tertiary recent sediment with clayey sands and shale extends beyond the study area. This is in agreement with the

geologic setting of the area that the sediment becomes thicker towards the southern part of Nigeria.
Fig 14 showing profile 2 taken across the major gravity high has the lowest depth of the three profiles taken. It has an excellent fit with root mean square error of about 2.39.

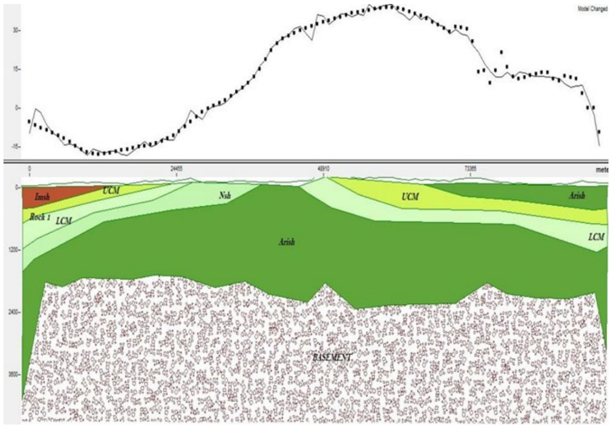

Fig 13. Modelling of residual gravity anomaly along profile line 2 (P2). The subsurface gravity model shows the structure in basin about 4050m thick.

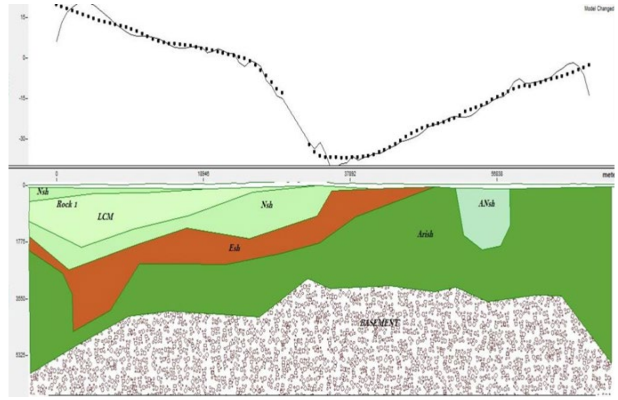

Fig 14. Modeling of residual gravity anomaly along profile line 3 (P3). The subsurface gravity model shows the structure in basin with maximum thickness of about 5517m.

The resulting Bouguer anomaly profiles depict high and low Bouguer alternating. The high Bouguer surface geology is consistent with the findings of [13-14]. It indicates a folded basement surface ridge or an intrusion behind a thin sedimentary layer at the basement sediments contact border. This demonstrates that a ground gravity response is present in most deposits and related intrusions. The low gravity indicates a significant sediment fill, consistent with the [14] results.

Typically, the rock type/minerals in the study area have densities between 1.19 and 2.55 (g/m^3) from Table 2. Gravity survey not only reflects the shape of major lithologies, but also a correspondence of the tectonic lineaments and regional fault systems. Therefore, gravity surveying is also useful for searching for intrusive bodies and major faults. Majority of the lineaments trending NE-SW direction and sedimentary thickness from the results of this work increases southwards. These trends agree with those described by [15-19] that, there are major NE-SW lineaments in the lower Benue Trough and other sedimentary basins in Nigeria. Its origin is linked to the Cretaceous opening of the South Atlantic Ocean. Faults, ridges, shear zones, intrusive and volcanic areas are among the identified structures. These structures are particularly common in the southern Benue Trough and tend to run northeast-southwest. Some of these structures may serve as hydrocarbon traps and migration channels, with intrusives providing heat for source rock maturation [20].

Table 2. Densities of rocks and minerals in study area.

S/No.	Rock type/minerals	Average density (g/m^3)
1.	Sand	2.0
2.	Shale	2.4
3.	Limestone	2.55
4.	Sandstone	2.35
5.	Coal	1.3
6.	Siltstone	2.0
7.	Clay	2.21
8.	Lignite	1.19
9.	Mudstone	1.65

5. Conclusion

The study area has a mean sedimentary thickness of 2.95 km to 1.50 km. The average basement depth values estimated from spectral analysis and the abundance of intrusive shows that the area may not be viable for hydrocarbon exploration as the shallow basement depth is not conducive for hydrocarbon generation and accumulation. The complex network of fractures and lineaments with dominant trends of NE – SW, then NW – SE, N – S, and E – W directions.

This research area shows that the gravitational basement surface may be represented by the deep anomalous source, which has an average depth of 2.95 km. In contrast, the shallow source may be defined by the other depth, which has an average depth of 1.50 km. The likelihood of hydrocarbon accumulation is extremely low based on the area's projected sedimentary thickness, many intrusive bodies, and the deformational history of the sedimentary rock sequences under examination.

Acknowledgement

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