The Use of Aerogravity Data Interpretation to Determine the Variations of Crustal Thickness in Northwestern Parts of Niger Delta, Nigeria

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ABSTRACT

Two methods have been employed to determine the variation of Crustal thickness in the Northwestern parts of Niger Delta. The first was the Empirical relations which revealed an average Crustal thickness ranging from 34.97 to 44.5km to reflect lateral variations across the area. The contour map of the average empirical relations shows higher crustal depth (40.5km – 45.5km) in the South and decreases at 0.5km interval to relatively lower values (31.5km-37.5km) in the Northern part. Spectrum analysis further resolved multiple subsurface layers, revealing Basement depth value from 3.07 to 5.18km, Conrad discontinuities range within 7.95-11.85km, and Mohorovicic depth that varies between 25.48 and 43.79km. Bouguer anomalies recorded range from -37.9 to -4.3mGal with Northern values between -22.7 and – 4.3mGal, and Southern values -37.9 to -22.7mGal, reflecting variations in sediment loading and crustal configuration.

KEYWORDS
Empirical relation, Mohorovicic, Bouguer anomaly, Spectral analysis

I. INTRODUCTION

The need to obtain detailed information about the subsurface and its composition, for economic purposes in any part of Nigeria, has long captured the interest and attention of the Nigerian government. The Niger Delta is characterized by complex geological formations and significant hydrocarbon reserves, making the investigation of its crustal structure particularly important for both academic and economic reasons [7]. Aero gravity data from North-western part of Niger Delta have been interpreted to determine Crustal structures and depth variations in this study area. Two methods were used to achieve this: Empirical relations using [2], [13] and [14] and Spectral Analysis. Bouygues gravity anomaly map produced also indicated the variations of crustal thickness based on the sign (negative or positive) of the values. Based on the geologic setting and rock parameters, one can use gravity data can be used in various ways for different exploration problems [4], [9] and [8].

II. LITERATURE REVIEW

Gravity prospecting involves measurements of variation in the gravitational field of the Earth, with the aim of locating local masses of greater or lesser density than the surrounding formations. Observations can be made at the Earth’s surface or above the surface although underground surveys also are carried out occasionally [12]. Variations in gravitational field result from density lateral variations of subsurface rocks within the portion where the measurement is observed [10]. Gravity anomaly is oscillating quantities that express degree of separation of actual gravity field of the earth from its normal field [6].

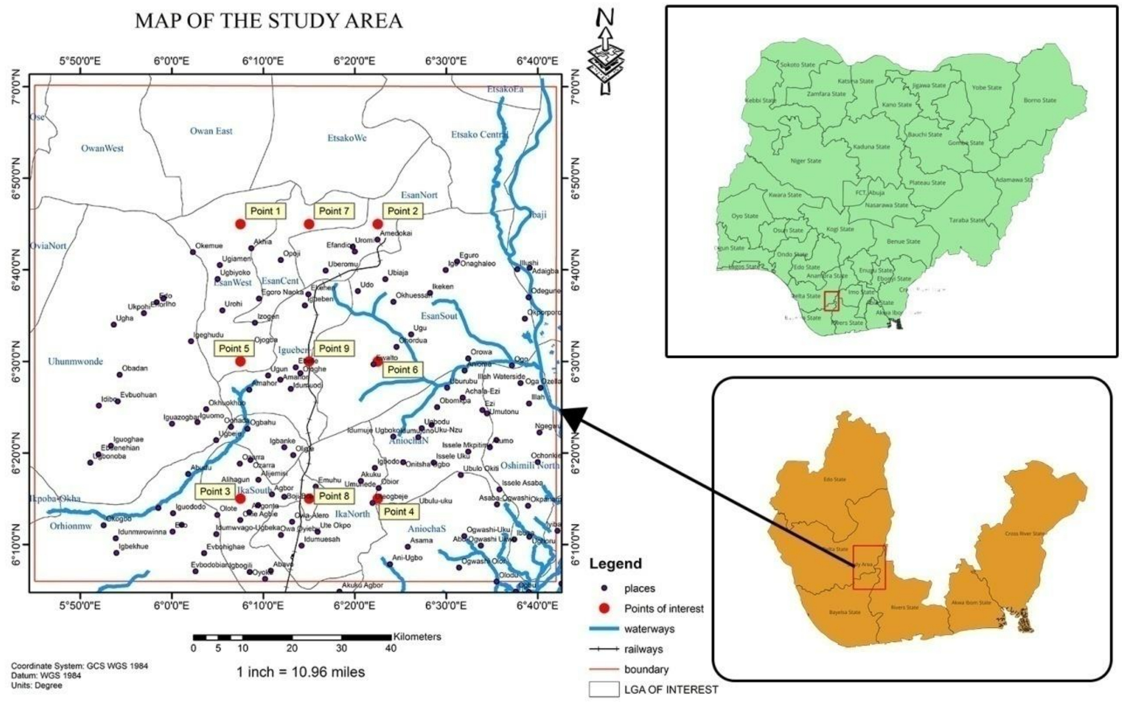

Figure 1. Study area also showing the Nine sectioned locations.

A. Location and Geology of the research area

North-western part of Niger Delta, occupies parts of Edo and Delta States lies within (Lat.6.08^0N – Lat. 7.0^0N) and (Long.5.75^0E – Long.6.72^0E). Nigeria. Geologically, the Niger Delta comprises a vast accumulation of sediments deposited by rivers draining into the Atlantic Ocean over millions of years. Its geological formation is primarily tied to the interplay between tectonic subsidence and sedimentation processes, creating a thick sequence of deltaic deposits [7]. The land area of the region is about 75,000 km², with a maximum sediment thickness range between 9 and 12 km in some area. The Niger Delta basin, known for its complex stratigraphy, which can be categorized into three: the Benin Formation, the Agbada Formation, and the Akata Formation. These formations reflect different depositional environments that have been crucial in shaping the delta's geology. The oldest and the deepest layer, The Akata Formation, primarily composed of organic matter under pressure and vary in thickness between 2000 and 4000m [3]. The overlying Agbada Formation which is over 3700m in thickness consists of alternating sandstones and shales deposited in transitional environments. The Formation, dating primarily from the middle to late Eocene, consists of interbedded sandstones and shales, representing a transition from marine to deltaic depositional environments [1]. The topmost Benin Formation, the youngest and shallowest layer, consists of fluvial sand deposits. It has a variable thickness up to about 2000m in the basin centre but this can differ laterally [3]. This uppermost geological unit is characterized by continental deposits of sands, clays, and gravel.

III. STUDIES AND METHODS

The study investigated the geology of North-western in Niger Delta basin in Nigeria. The aero-gravity data for the research were obtained from Nigeria Geological Survey Agency (NGSA). All necessary corrections had already been applied to the data and the coordinates of the locations for the readings referenced to the World Geodetic System 1984 (WGS84) datum for spatial consistency[5]. The following equipment were used for the research: Aerogravity data of North-western Niger Delta, Geosoft Oasis Montaj, employed for potential field data processing. Golden Software Surfer was used to grid the irregular gravity data into a continuous surface, contour mapping, and visualization of results.

A. Application of Empirical and Spectral Analysis

The methodology employed estimated depths to major crustal discontinuities; specifically, the Conrad discontinuity (upper-lower crust boundary) and the Moho (crust-mantle boundary) using aero-gravity data. Two complementary approaches were applied; an empirical method based on direct Bouguer anomaly relationships, and a spectral analysis method.

B. Application of Empirical relations for estimating Moho Depth

The Empirical methods use known relationships or regressions that link the Bouguer gravity anomaly magnitude to the depth of the crust. Various geophysical observations we have shown an inverse correlation between Bouguer anomaly and Moho depth in which areas of strongly negative Bouguer anomalies tend to have thicker crust (deeper Moho), whereas areas of higher (less negative) Bouguer anomalies indicate thinner crust.[13] and [14] developed global empirical formulas relating average Bouguer anomaly to crustal thickness. [2] also provided an empirical relation for planetary crustal structure. The relations have been applied in global studies and are commonly applied in regional analysis across Nigeria.

The Empirical relations, in kilometre (Km), by Demenistskaya, H_W, Wool lard H_D and Wool lard and Strange H_{WS} in which Bouguer gravity anomaly (BG) values (in mGal) were substituted, to give Moho Depth for each are given below:

$$H_D = 35(1 - \text{TANH}\ (0.0037)\ BG) \quad (1)$$

$$H_W = 32.0 - 0.08BG \quad (2)$$

$$H_{WS} = \frac{40.5 - 32.50\text{TANH}(BG + 75)}{275} \quad (3)$$

The average of the Moho depths for the three Empirical relations gives the crustal thickness for the area [14].

C. Spectral Analysis

Precisely, Power Spectral Analysis involves frequency-domain analysis of the gravity data using 2D Fast Fourier Transform (FFT) and the radially averaged power spectrum interpretation. It is based on the classical technique of [11] , in which gravity field is modelled as a superposition of anomaly sources at various depths and then uses the decay of anomaly power with frequency to determine those depths. The underlying principle is that shallower sources produce higher-frequency (short-wavelength) anomalies, while lower-frequency (long-wavelength) anomalies penetrate from deeper structures. Now in Fourier domain, the amplitude of gravity effects from a buried source decays approximately exponentially with increasing wavenumber k, according to e^{-kz} (where z is the source depth). As a result, the power spectrum which is proportional to amplitude squared decays as e^{-2kz}. Now, the power spectral density is given as

$$\ln P(k) = \ln P_0 - 2kz \tag{4}$$

From this equation, P(k) is the power spectrum at wavenumber K, z is the depth to the beneath source layer. The slope of linear segment of the plot of ln P(k) against k, depth z can be deduced as

$$z = -\frac{m}{2} \tag{5}$$

where m = slope of the linear part.

IV. FINDINGS AND RESULTS

A. Empirical Relations

The results from application of the three Empirical relations [3] [13] and [14] are shown in the Table 1. For each value of the Bouguer readings, the empirical relation was calculated for the three relations and recorded as shown on Table 1. The average range of Crustal thickness for each relations is; between 40.26723km and 63.71149km for Demenistskaya, for Wollard 32.34000km to 35.43935km while for Wollard and Strange relation, is between 32.32043km and 35.43935km. The average crustal thickness for the three Empirical relations ranges from 34.97588km to 44.56542km.

Table 1. Calculated Empirical relations value

H_D /km	H_W /km	H_{WS} /km	Average (H_D+ H_W+ H_{WS}) /km
63.71149	34.54545	35.43935	44.56542
63.08298	34.45818	35.31441	44.28518
61.59060	34.23273	34.99099	43.60477
58.53267	33.92000	34.54710	42.33326
52.93476	33.37455	33.77463	40.02798
49.72567	33.09091	33.37464	38.73040
46.38401	32.77091	32.92147	37.35881
46.09813	32.73455	32.86934	37.23399
40.26723	32.34000	32.32043	34.97588

From Figure 2, 3, 4 and 5 are the Contour Crustal thickness map of the area obtained from Demenistskaya, Wollard, and Wollard and Strange relations respectively.

B. Demenistskaya Relation

The crustal thickness values obtained from this relation, shown in Figure 2, range from 30km to 68km for an an increase interval of 2km. The maximum depth of 68km was revealed at the south central and south-eastern area. Lowest Crustal depth (30km) is at the north-western side as the Crustal thickness width between 42-60km travers's parts South of West to North of East in the area.

C. Woollard Relation

The calculated minimum and maximum Crustal thicknesses in the area are 32.6km and 35 km respectively at 0.2km interval, Figure 3. Maximum value of 35km for the crustal depth is noticed at the South-eastern part of the area while the minimum is 31.6km in the north-western side where the thickness ranges between 31.6km to 34.2km.

D. Woollard and Strange Relation

This gives a Crustal thickness between 32.4 km and 36km, in which the minimum and maximum values exist in the north-western and south-eastern parts respectively with an increase interval of 0.2km, Figure 4. Portion of the area with minimum and maximum Crustal thicknesses is separated by a crustal thickness between 33km and 35km. This stretches from south-western part to eastern section.

E. Average Empirical relation

Calculated average thickness values obtained from Demenistskaya, Wollard and Woollard and Strange are shown on Figure 5. From the figure, average crustal thickness between 31.5 km to 45.5km can be observed at an increase interval of 0.5km. Minimum Moho depth of 31.5km resides in the north-western part while the highest thickness of value 45.5km can be found in South-eastern section. Moho depth from 34.5 42km could be seen in the Southeast-Northeast trend on the map. This trend can be observed on Figures 2, 3 and 4 of the empirical relations. In the north-western part, where the lowest thickness exists, the Crustal thickness ranges between 31.5 to 34.5km, at the South-eastern section where the highest crustal thickness is located, the values range between 42km and 45.5km.

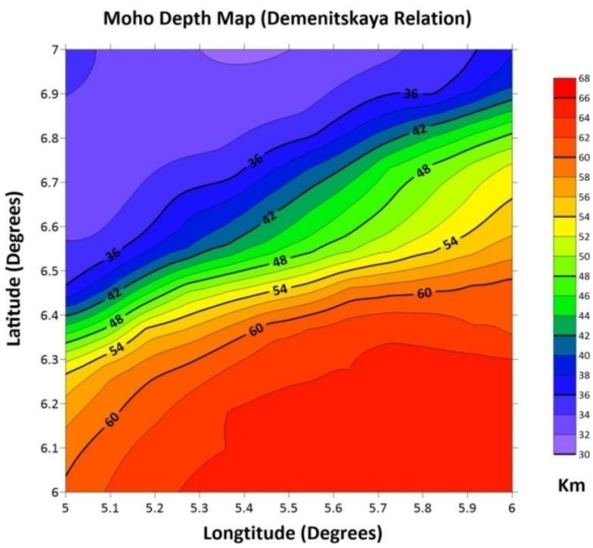

Figure 2. Contour map of Moho depth for Demenistskaya relation.

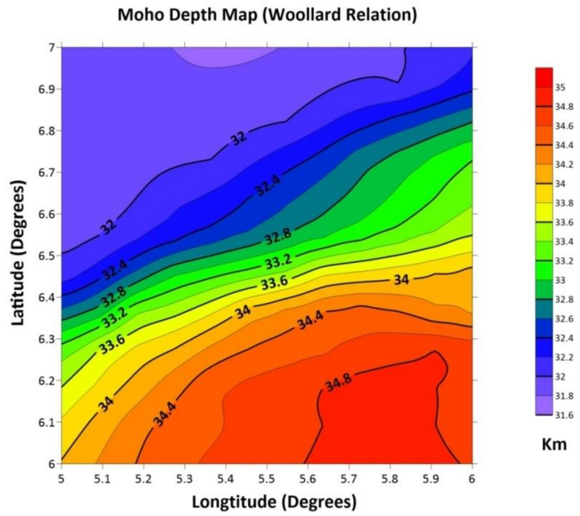

Figure 3. Contour map of Moho depth for Woollard relation.

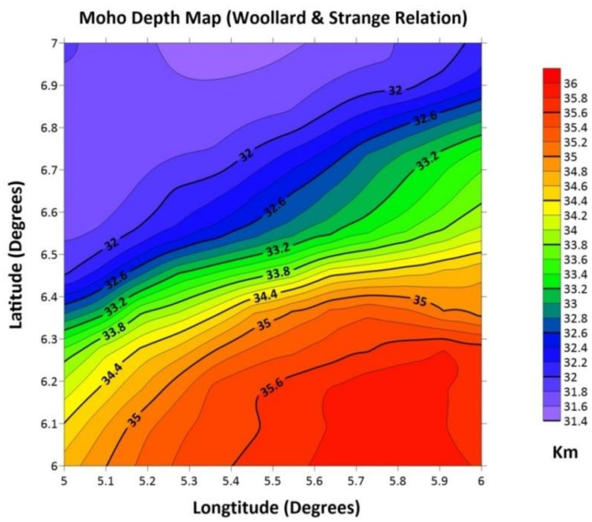

Figure 4. Contour map of Moho depth for Woollard and Strange relation

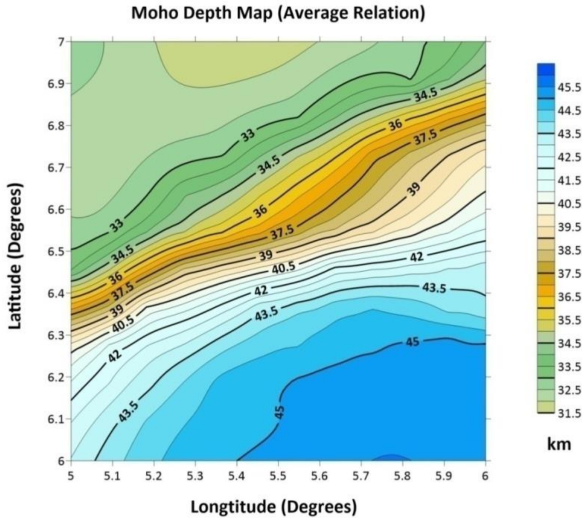

Figure 5. Contour map of Moho depth for Average Relation

F. Spectral Analysis

Bouguer anomaly map was partitioned into nine sections (Figure 6), using Oasis Montaj Geosoft. From each sectioned, Spectral graph was generated showing the logarithm of spectral energy against frequency (cycle/second) (Figure 7 to Figure 15). The Bouguer map delineates deep epocentral (-37.9 mGal) and a relatively basement flanks(-4.3mGal). The Southern parts accommodate Bouguer anomaly values ranging from -33.1mGal to – 22.7mGal. The northern part has Bouguer values ranging between -22mGal and -4.3mGal an indication of relatively uplifted flank compared to the Southern area

From each spectrum, three linear segments were identified giving three slopes M_1, M_2 and M_3 (Table 2). These values generated for each graph were used estimate the Basement depth (M_1), average depth to Conrad Discontinuity (M_2) and the average depth of Moho Discontinuity (M_3).

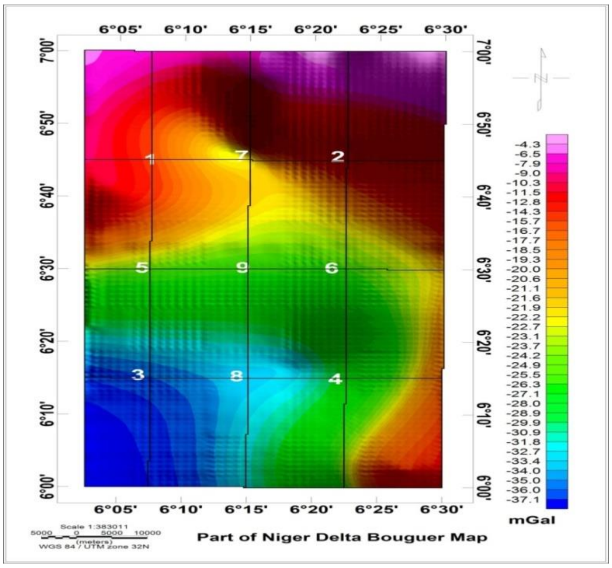

Figure 6. Bouguer Map for the study area

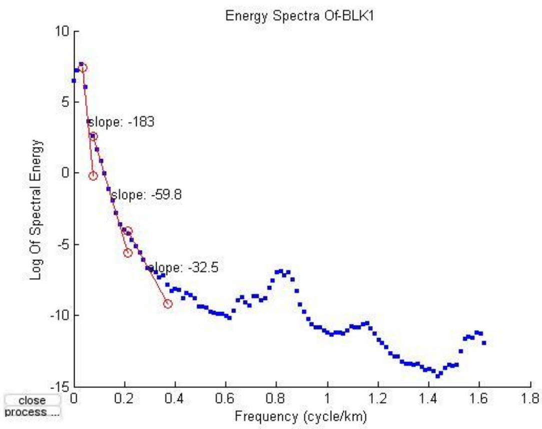

Figure 7. Energy spectrum plotted against frequency of the section

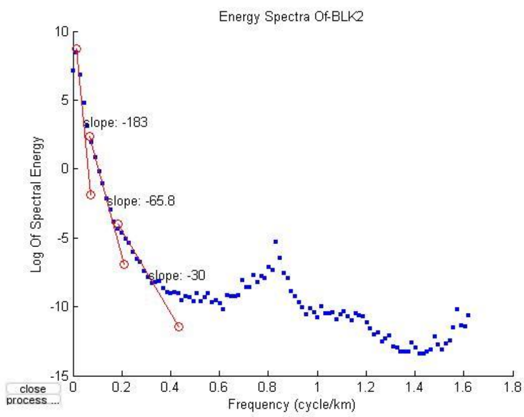

Figure 8. Energy spectrum plotted against frequency of the section

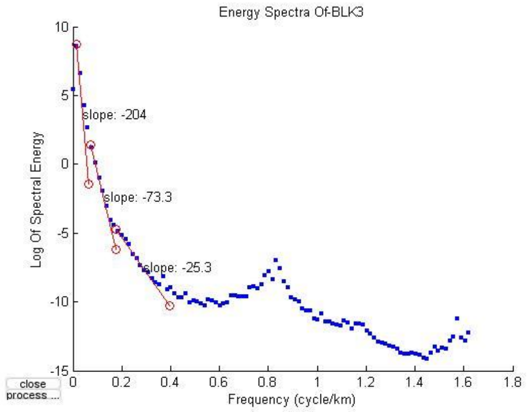

Figure 9. Energy spectrum plotted against frequency of the section

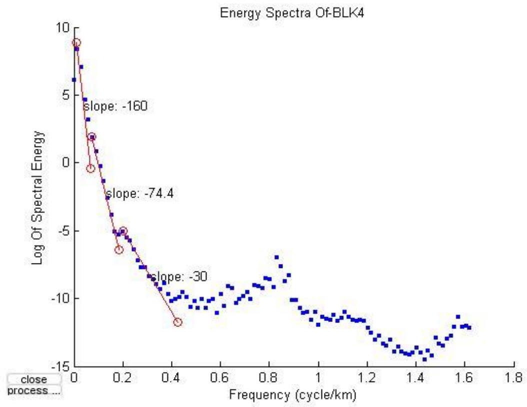

Figure 10. Energy spectrum plotted against frequency of the section

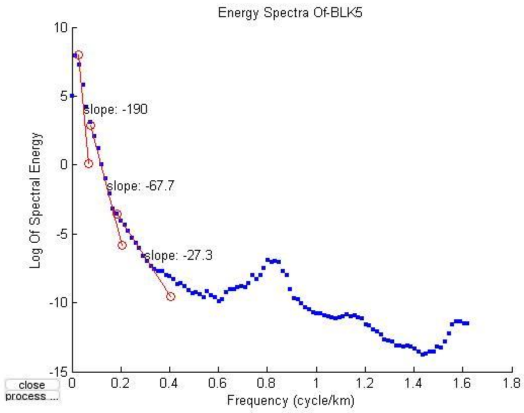

Figure 11. Energy spectrum plotted against frequency of the section

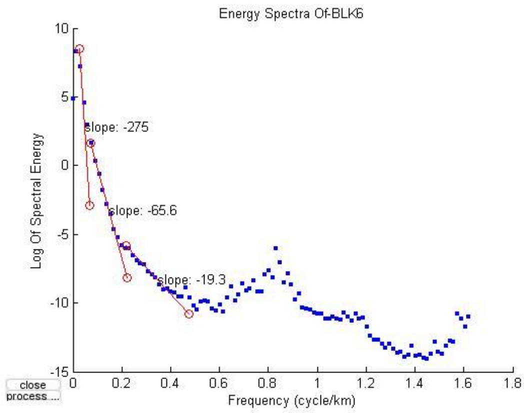

Figure 12. Energy spectrum plotted against frequency of the section

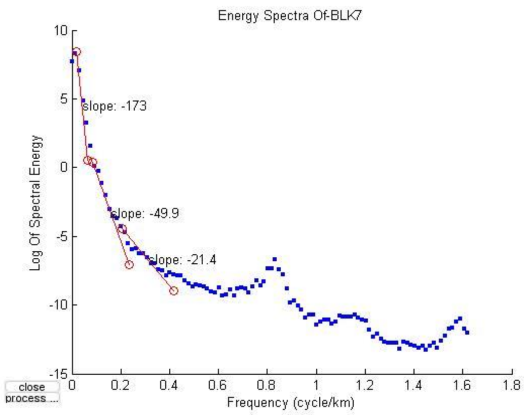

Figure 13. Energy spectrum plotted against frequency of the section

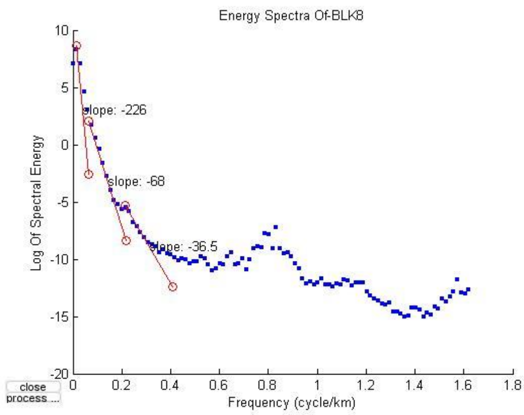

Figure 14. Energy spectrum plotted against frequency of the section

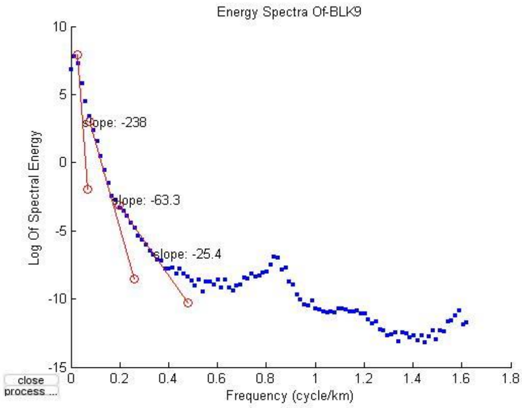

Figure 15. Energy spectrum plotted against frequency of the section

Table 2. Values of Spectral Plot and the corresponding Depth.

Section	**Slope M_1**	**Slope M_2**	**Slope M_3**	**Basement depth (km)**	**Conrad depth (km)**	**Moho depth (km)**
1	-32.5	-59.8	-183.0	5.18	9.52	29.14
2	-30.0	-65.8	-183.0	4.78	10.48	29.14
3	-25.3	-73.3	-204.0	4.03	11.67	32.48
4	-30.0	-74.4	-160.0	4.78	11.85	25.48
5	-27.3	-67.7	-190.0	4.35	10.78	30.25
6	-19.3	-65.6	-275.0	3.07	10.45	43.79
7	-21.4	-49.9	-173.0	3.41	7.95	27.55
8	-36.5	-68	-226.0	5.81	10.83	35.99
9	-25.4	-63.3	-238.0	4.04	10.08	37.90

Basement depth: Figure 16 represents the Basement depth map which lies between 3.1km (minimum) at the eastern section and 5.9km (maximum) at the central southern part. From the map, stretch of Basement thickness that ranges between 4.9km and 5.9km can be observed at the northeast and south-western section, separated by a low range flank between 3.7km and 4.8km. In addition, basement depth (4.11km – 4.6km) in northeast-southwest trend can be observed on the map.
Conrad Depth: The contour map of Conrad depth, Figure 15, shows that the thickness ranges from 18km (minimum) at the north central to 12km (maximum) at the south-eastern part of the map. From the map, thickness increases the North towards the South.

Moho Depth: The map on Figure 17 shows Moho depth of range (25km-44km) in which the minimum and the maximum are located at south-eastern and eastern parts respectively. Lower crustal thickness (25km-32km) can be observed in the northern and southern parts but intruded by the highest thickness range between 33km and 44km in the central eastern side.

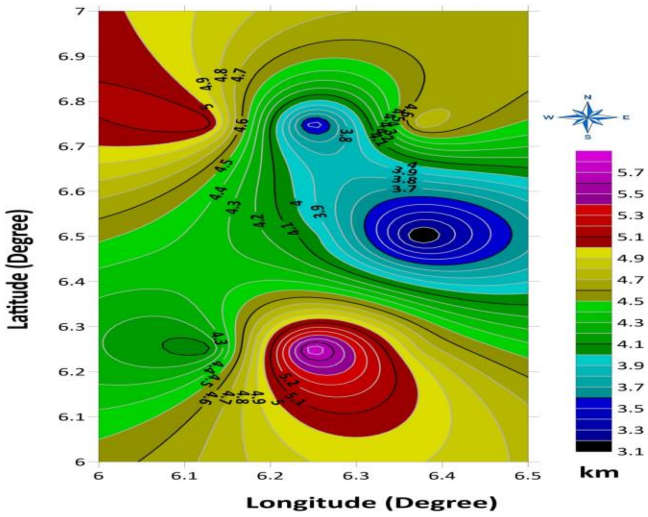

Figure 16. Contour map of Basement depth at 0.2km interval

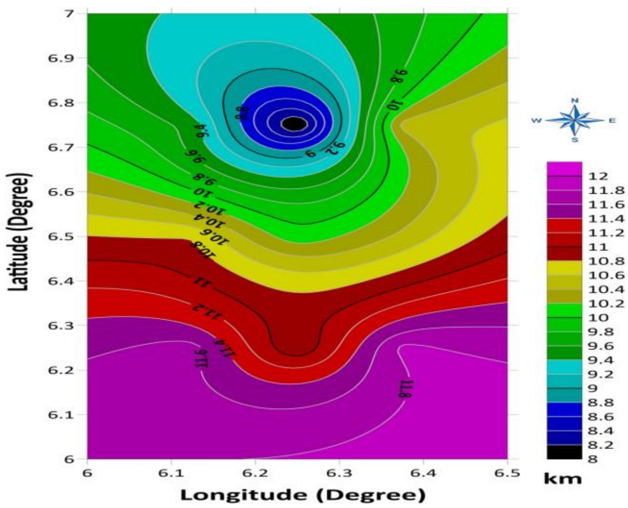

Figure 17. Contour map of Conrad depth at interval 0.2km.

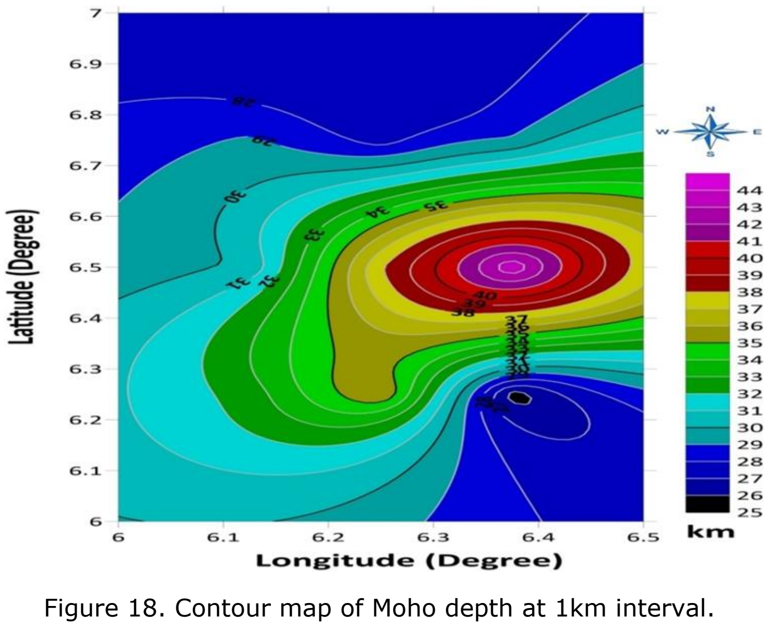

Figure 18. Contour map of Moho depth at 1km interval.

V. CONCLUSION

The integration of Empirical relations, which offer a generalized primary crustal framework and Spectral analysis that provides finer resolution of discontinuities within the Crust, has given reliable outcome from this research. The three Empirical relations give calculated average Crustal thickness values between 34.98 and 44.57km. The Spectral analysis has revealed depths range (3.07km – 5.18km), (7.95km-11.85km) and (25.48km – 43.79km) for Basement depth, Conrad depth and Moho depth respectively. The Bouguer anomaly contour map has revealed lower values in the Southern part (-37.1mGal to – 22.7mGal) than in Northern section (-22.7mGal to -4.3mGal). Thus indicating deeper sediment accumulation in the South than in the North, which is the general trend in the Niger Delta Basin i.e. progressive decrease in Crustal thickness towards the Ocean.

A high-resolution Gravity survey which provides remarkable increased gravity database over a smaller grid interval can be employed to improve the spatial accuracy of contour maps in order to expose smaller structural details. This research can be improved upon by integrating deep Seismic reflection or Refraction data to validate the interpreted depth of the discontinuities.

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