DETERMINATION OF THE CRUSTAL THICKNESS WITHIN NORTHERN BIDA BASIN, NORTH CENTRAL NIGERIA, USING GRAVITY DATA

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Abstract: Determination of the crustal thickness within northern Bida Basin is bounded by latitudes 8° 30′ N and 11° 00′ N and longitudes 4° 00′ E and 7° 00′ E is situated in the northern part of the Bida Basin. Empirical relation method, power spectral method and modelling were used to estimate the crustal thickness within the study area using Bouguer Gravity Data. The empirical relation method shows that the average crustal thickness ranges from 33 to 47 km, the results obtained from the power spectral method gives an average crustal thickness ranges between 29 and 47 km. Within the study area, a straight line equation ($H_C = 39.09 - 0.142BG$) was derived such that for any given Bouguer anomaly value, the crustal thickness can easily be estimated from the equation. Crustal thickness was obtained by taking an average between the results obtained from the two modelling profile. The results obtained revealed that the crustal thickness within the study area ranges from 39 to 47 km. The average crustal thickness obtained from two model profile fall within the range of average Moho depth of Nigeria (32 to 44 km) and Africa (39 km). The study area is stable tectonically since Nigeria lies within a plate (Africa) and has a considerable Moho depth range.

Keywords: Power spectral, 2-D modelling, Conrad discontinuity and Moho discontinuity

Introduction

The variation of crustal thickness from place to place makes it necessary to know the thickness of the crust of an area; however, the determination of crustal thickness is a geophysical problem worldwide. The high or low crustal thickness of the study area gives an indication of its stability or instability in terms of tectonic activities. The aim is to estimate the crustal thickness of the study area and ascertaining the magnitude of tectonic stability. Rivero *et al.* (2002) estimated depth to moho from gravity values using two different methods Empirical relation method and Spectral Analysis of the radial wave number. However, 55 km was adapted as depth to moho discontinuity.

The study area is located within the northern part of the Bida Basin. The northern Bida Basin stretches out from Gulu in the southern part to Kontagora in the northern part of Niger State, where it meets crystalline rock of the Basement Complex framework. The study area is bounded by latitudes 8° 30′ N and 11° 00′ N and longitudes 4° 00′ E and 7° 00′ E. Gravity method of geophysical survey depends on Earth's gravitational field to measure and define anomalous density within the Earth. Gravity anomalies are computed by subtracting a regional field from the measured field. This separation between regional field and measured field yields the Gravity anomalies that connect with source body density variation (Donald *et al.,* 1995). The distance between the Earth's surface and the Moho is known as the crustal thickness.

Geology of the area

The study area is located within the northern part of the Bida basin. The northern Bida basin stretches out from Gulu in the southern part to Kontagora in the northern part of Niger State, where it meets crystalline rock of the Basement Complex framework which occupies a gently down warped trough (Udensi and Osasuwa 2003) revealed that the origin of the Bida basin occurred closely associated with crustal dynamics of the Santonian Orogeny of South western Nigeria and close by Benue Trough. Ojo (2012) suggested the presence of deep–seated rift in the crust under the Bida basin, Nigeria possibly due to occurrence of massive bodies of basic rocks indicated by research results. Thickness of sedimentary formations in the basin was estimated to reach 2,000 metres thick by gravity survey (Ojo and Ajakaiye, 1989). Fig. 1 (Geological Map of Nigeria) shows the location of the study Area and Fig. 2 is the geological map of the area.

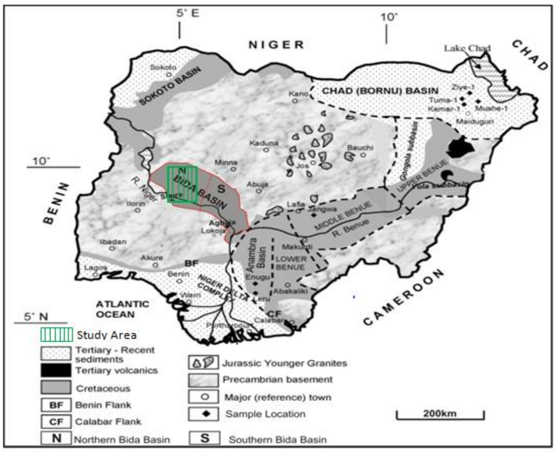

Fig. 1: Location of the study area on a geological map of Nigeria (Source: Obaje *et al*., 2004)

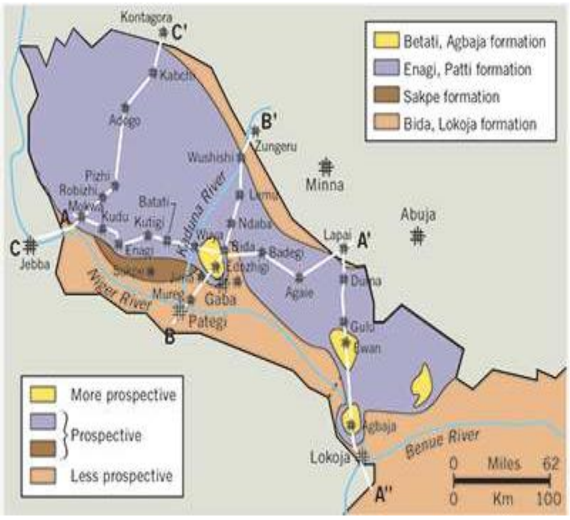

Fig. 2: Geology map of the study area

Materials and Methods

Materials

The Bouguer gravity anomaly map of the study area was prepare from the gravity data which was acquired from the Nigeria Geological Survey Agency (NGSA) for this research.

About 957 gravity data point was used to prepare a complete Bouguer anomaly map.

Equipment

Materials used for this research study including the following: Gravity data of the study area, Oasis Montaj software, Surfer 10 software, Excel software
and Work station (Laptop).

Methods

This study basically integrate the use of three different methods to determine the crustal thickness of the study area.

I. The Empirical Relation
II. The Spectral Analysis
III. 2- D Modeling

Determination of Crustal thickness by empirical relations method

Empirical relation

The available data set comprises of Bouguer gravity data anomaly of the study area will be gridded at an interval of 10 km. The Bouguer gravity anomaly data values will be substituted into the following empirical relation below, which will aid in calculating the crustal thickness of the study area using Demeniskaya, Woollard and Woollard and Strange (Megwara *et al.,* 2014). The outcome of the below process will be useful for the determination of the crustal thickness, deducing the geological history of an area, and also essentially in tectonic study (Udensi, 2000).

The empirical relation equations are as follow:

$$H_D = 35(1 - TANH(0.037BG)) \quad (1)$$

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

$$H_{WS} = \frac{40.50 - 32.50TANH\ ((BG + 75)}{275} \quad (3)$$

Where H_D, H_W and H_{WS} are in km and BG is mGal. The average of value estimated from the computed relation at any given location is the crustal thickness at that particular location (Rivero *et al.*, 2002). To calculate the crustal thickness in each of the equations above, the computed Bouguer gravity values were fed into Excel program, to attain the crustal thickness at a particular location, the average values of the crustal thicknesses were obtained and contoured.

Determination of Crustal thickness by power spectral method

Power spectral method is a technique broadly used in determining the depth of geological sources; it is also use in detecting a discontinuity. It is also a quantitative method based on the properties of the energy spectrum of large gravity data sets. It uses the two-dimensional (2-D) Fast Fourier Transform to transforms gravity data from space domain to frequency domain, (Saada *et al.*, 2013). It also makes it easier to consider the average depth of a source anomaly. The Bouguer gravity data were transformed from the space domain to the wave-number domain by means of a Fast Fourier Transform (FFT) in order to analyze the frequency content of the information. In the OASIS environment, the main map was sectioned into nine maps for easy execution of the crustal thicknesses. The Moho (d) is calculated by:

$$d = \frac{mN}{2\pi} = \quad (4)$$

where k, m, and N are the wave number, the slope of the average spectrum and number of gravity data, respectively.

Estimation of Crustal thickness by two dimensional modeling (2-D)

The 2 – D gravity modeling is an essential tool to study the crustal structure and usually the final stage in gravity interpretation. Gravity data reveal a regular relationship between crustal structure, crustal composition (density) and the surface elevation. Bouguer anomalies are enough to give evidence of changes in mass distributions in the lower and the upper mantle, for any regional scale (Tealeb and Raid, 1986). The modeling technique commonly involues using a residual gravity anomaly, in this technique the interpreter must use a density contrast between the body of interest and the surrounding material, in the process of modeling Bouguer gravity anomalies the density of the body is used (Mariita, 2007).

The model system is based on the geology of the area and the geophysical data obtained from the gravity data. The gravimetric model will be performed using the GM, sys program, which is hosted by the interface of Oasis Montaj 6.4.2. Gravity modeling is considered an important tool to study the crustal structures. This method is straight forward, which is by means of trial and error method, varying the body geometry allow to obtain a good fitting between theoretical and observed anomalies (Tealeb and Raid, 1986).

Results and Discussion

Interpretation of the Bouguer gravity anomaly map of the study area

The Bouguer gravity anomaly map (Fig. 3) of the study area shows that the area is characterized by series of negative Bouguer anomalies with visible closures. The closures observed on the map signify structural alignment due to the tectonic activities that took place in the study area. The negative anomalies observed on the Bouguer map are attributed to low-density bodies within that area or due to the existence of a huge down wrap of sediments in that particular area. High Bouguer anomalies are represented by 'H' while the low Bouguer anomalies are represented by 'L' on the map. High closures are attributed to intrusive rocks that intruded into the sedimentary cover while the low Bouguer anomalies may be due to basement relief.

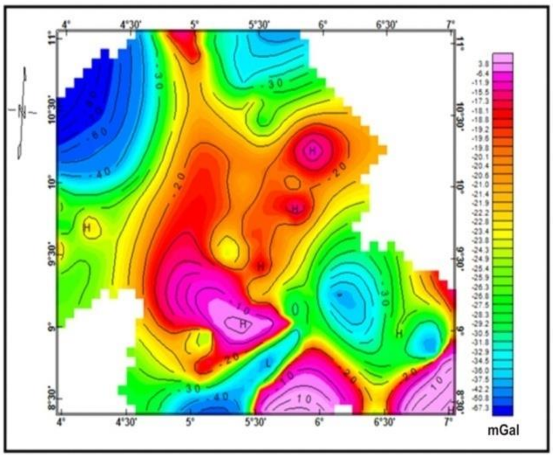

Fig. 3: Bouguer gravity anomaly map of the study area
Contour Interval is 5 mGal; Colour Bar at the Right indicates Interval Values and the Anomaly Intensity.

Analysis of the empirical relation methods

The results of the crustal thicknesses obtained by using the empirical relation methods developed by Demenistskaya (H_D), Woolard (H_W), and Woolard and Strange (H_{WS}) showed the respective samples of the crustal thickness results obtained from each of the empirical relation methods (Table 1) developed for the whole Earth. Figs. 4, 5 and 6 are the respective contoured crustal thickness maps produced from the results obtained from each of the empirical relation.

The contoured map (Fig. 4) produced by using the results obtained by Demenistskaya (H_D) empirical relation formula shows higher values that represents the crustal thickness at each point compared to the values on the contoured maps produced by using the results obtained by Woolard (H_W) (Fig. 5) and Woolard and Strange (Fig. 6) empirical relation formulae. The crustal thicknesses on Figs. 4, 5 and 6 indicate different values at the same point, therefore, the average values of the three thicknesses were obtained and contoured using "SURFER 10" in order to obtain a point value (crustal thickness) for each particular location.

Fig. 7 represents the contoured average crustal thickness map of the study area using empirical relation method. The map has a crustal thickness ranges from 33 to 47 km.

Table 1: Results of average Crustal thickness obtained by using the formulae developed by Demenistskaya (H_D), Woolard (H_W) and Woolard and strange (H_{WS})

Longitude (Degree)	Latitude (Degree)	H_D (Km)	H_W (Km)	H_{WS} (Km)	Average (Km)
6.7708	8.5000	24.814	31.352	30.96749	29.04439
5.4306	8.5278	65.313	34.848	35.87524	45.34541
5.5278	8.5486	50.439	33.024	33.27193	38.91152
5.0208	8.5694	64.321	34.624	35.55151	33.38785
5.4861	8.5903	65.503	34.896	35.94473	45.44807
5.6528	8.5972	50.439	33.024	33.27193	38.91152
6.8958	8.6111	20.946	31.080	30.60159	27.54240
5.0417	8.6528	56.301	33.528	33.98315	41.27075
5.5417	8.6597	65.313	34.848	35.87524	45.34541
6.9583	8.6875	20.946	31.080	30.60159	27.54240
5.0903	8.7014	55.805	33.480	33.91512	41.06681
5.7639	8.7014	47.276	32.792	32.94693	37.67174
5.6111	8.7431	66.984	35.352	36.60696	46.31440
6.9722	8.7847	29.100	31.632	31.34694	30.69293
5.1319	8.7847	54.862	33.392	33.79056	40.68147
5.8264	8.8056	55.805	33.480	33.91512	41.06681
5.6806	8.8125	65.313	34.848	35.87524	45.34541
6.8889	8.8333	65.892	35.000	36.09545	45.66238
6.7917	8.8403	65.377	34.864	35.8984	45.37990
5.0833	8.8681	60.055	33.944	34.57516	42.85808

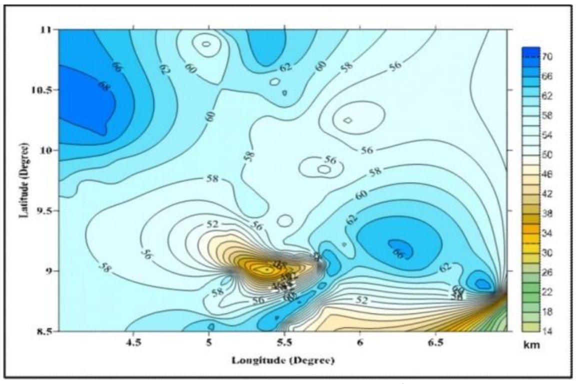

Fig. 4: Demenistskaya (H_D) Contour Map of Crustal Thickness of the Study Area. [Contour Interval is 2 km. Colour Bar at the Right Indicate Values of the Crustal Thickness in the Area]

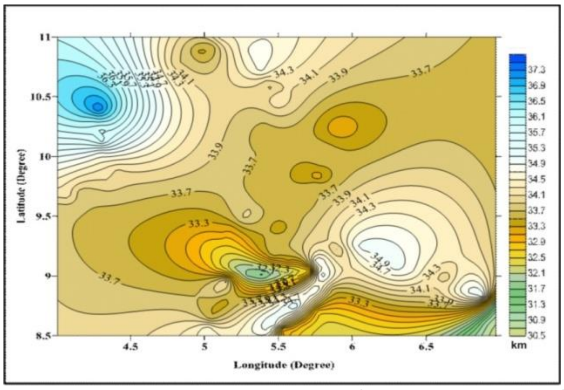

Fig. 5: Woolard (H_W) Contour Map of Crustal Thickness of the Study Area. [Contour Interval is 0.2 km. Colour Bar at the Right Indicate Values of the Crustal Thickness in the Area]

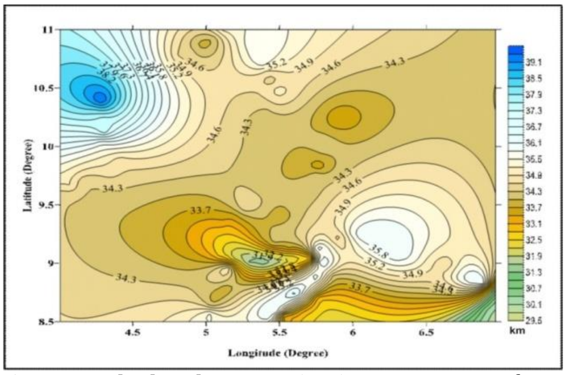

Fig. 6: Woolard and Strange (H_{WS}) Contour Map of Crustal Thickness of the Study Area. [Contour Interval is 0.2 km. Colour Bar at the Right Indicate Values of the Crustal Thickness in the Area]

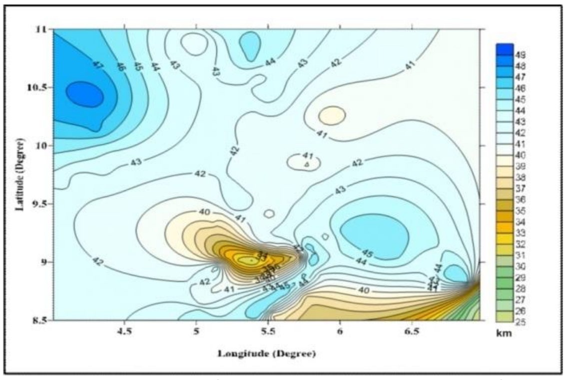

Fig. 7: Contour Map of Average Crustal Thickness of the Study Area from Empirical Method. [Contour Interval is 1 km. Colour Bar at the Right Indicate Values of the Crustal Thickness in the Area]

The high crustal thickness on Fig. 7 may be ascribed to high-density bodies within that location or due to the existence of low accumulation of sediments while the low crustal thickness may be as a result of low-density bodies within that area or due to high accumulation of sediments.

Power spectrum analysis

Figure 8 is one of the nine plots of the logarithm of the power spectrum against the frequency. The plots were drawn in order to calculate approximately the average crustal thickness. On each plot, three straight lines segments were displayed and labelled $slope_{(1)}$, $slope_{(2)}$ and $slope_{(3)}$. The slopes of the different segments provide an estimate of the thicknesses of different boundaries. $Slope_{(3)}$ is used to calculate the boundary between crust and mantle which is known as the Moho, $slope_{(2)}$ is used to calculate the boundary between the upper crust and the lower crust known as Conrad and $slope_{(1)}$ for calculating the sedimentary thickness. The Moho (H_3), Conrad (H_2) and sedimentary thickness (H_1) were calculated using equation (5)

$$H = \frac{-Slope}{2\pi} \tag{5}$$

Table 2 shows the average values of the Moho (H_3), Conrad (H_2) and the sedimentary thickness (H_1) obtained from sectioning of the Bouguer gravity anomaly map of the study area into nine sections. The values of the Moho (H_3) and the Conrad (H_2) obtained were contoured using "SURFER 10" in order to produce the respective spectral maps of the study area. Figs. 9 and 10 represents the Moho (H_3) and the Conrad (H_2), respectively. Fig. 9 shows a maximum crustal thickness of 46 km and minimum of 34 km. Fig. 10 shows that the crustal thickness over the study area ranges from 26.5 to 35.5 km.

Table 2: Results of the depth to Moho (H_3), Conrad (H_2) and the basement (H_1)

Section	Longitude (Degree)	Latitude (Degree)	Slope$_{(1)}$	Slope$_{(2)}$	Slope$_{(3)}$	Moho(H_1) (Km)	Conrad(H_2) (Km)	Sedimentary Thickness (H_3) (Km)
A	5.50	9.750	-297	-207	-83.5	47.2479	32.9303	6.9223
B	4.75	9.750	-258	-209	-97.8	41.0436	33.2485	8.5223
C	6.25	9.750	-279	-193	-106	44.3843	30.7031	9.1661
D	4.75	9.125	-312	-174	-68.6	49.6341	27.6806	6.8268
E	6.25	9.125	-245	-158	-72.5	38.9755	25.1352	8.3863
F	4.75	10.375	-306	-190	-108	48.6796	30.2259	9.5957
G	6.25	10.375	-268	-206	83.2	42.6344	32.7712	6.8746
H	5.50	9.125	-185	-150	-64.2	29.4305	23.8626	5.4423
I	5.50	10.375	-289	-234	-98.1	45.9752	37.2256	7.8134

Table 3: The Average depths obtained by the empirical relation method and the power spectral method (Moho)

Longitude (Degree)	Latitude (Degree)	Empirical Depth (Km)	Spectral (Moho) Depth (Km)	Average Depth (Km)	Bouguer Value (mGal)
5.50	9.750	41.387	47.127	44.2570	-37.712
4.75	9.750	42.199	41.173	41.6860	-20.149
6.25	9.750	42.770	44.378	43.5740	-25.168
4.75	9.125	40.412	49.441	44.9265	-17.956
6.25	9.125	45.618	38.987	42.3025	-36.572
4.75	10.375	44.332	48.624	46.4789	-30.909
6.25	10.375	40.658	42.655	41.6565	-20.898
5.50	9.125	39.099	29.667	34.3839	-14.295
5.50	10.375	43.070	45.976	44.5230	-22.755
5.13	9.125	35.839	39.744	37.7915	-7.519
4.75	8.875	41.851	49.345	45.5980	-21.807
4.75	9.500	40.963	44.043	42.5030	-16.729
5.13	8.875	42.406	39.744	41.0750	-16.261
5.13	9.500	41.108	42.073	41.5905	-19.068
5.88	9.125	44.081	35.272	39.6765	-27.788
6.25	9.125	45.618	38.964	42.2910	-37.028
6.25	9.500	44.420	41.966	43.1930	-31.551
5.88	8.875	41.684	35.276	38.4800	-22.233

Relation between the values obtained from the power spectral method
(Moho) and the empirical relation method

The results obtained from power spectral analysis (Moho) gives the average thickness of each section within the study area while empirical relation analysis gives an exact thickness of a point picked. To obtain a final crustal thickness over the study area, the values obtained from the power spectral method (Moho) were added to the corresponding values obtained from the average empirical relation method and an average between the two methods was calculated for each point. Table 3 shows the sample results of the final crustal thickness obtained over the study area with their corresponding Bouguer anomaly values. Fig. 11 is the final crustal thickness contour map of the study area.

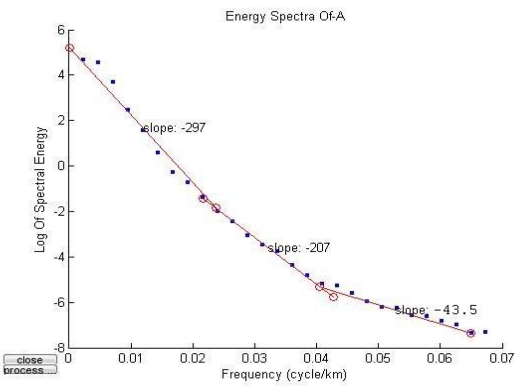

Fig. 8: Plot of the log of spectral energy against frequency

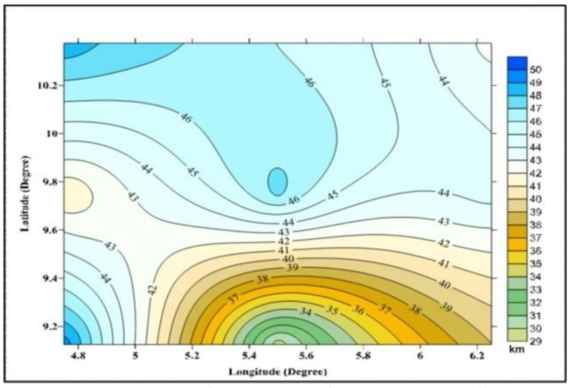

Fig. 9: Contour Map of the Depth of the Moho (H_3) from Spectral Method over the Study Area. [Contour Interval is 1 km. Colour Bar at the Right Indicate Values of the Crustal Thickness in the Area]

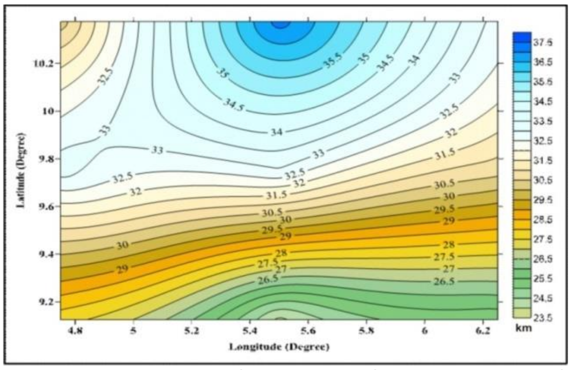

Fig. 10: Contour Map of the Depth of the Conrad (H_2) from Spectral Method over the Study Area. [Contour Interval is 0.5 km. Colour Bar at the Right Indicate Values of the Crustal Thickness in the Area]

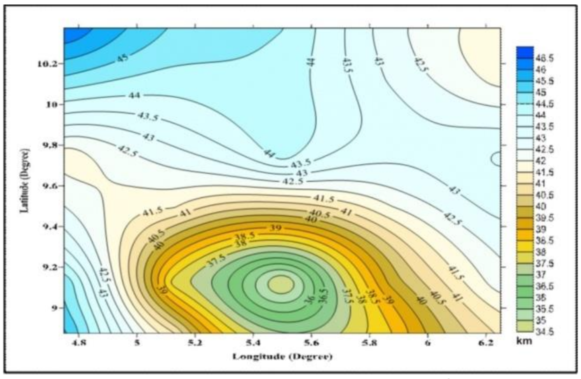

Fig. 11: Final Crustal Thickness Contour Map of the Study Area. [Contour Interval Is 0.5 Km. Colour Bar at the Right Indicate Values of the Crustal Thickness in the Area] where H_C is the crustal thickness in kilometres and BG is the Bouguer anomaly values in mGal

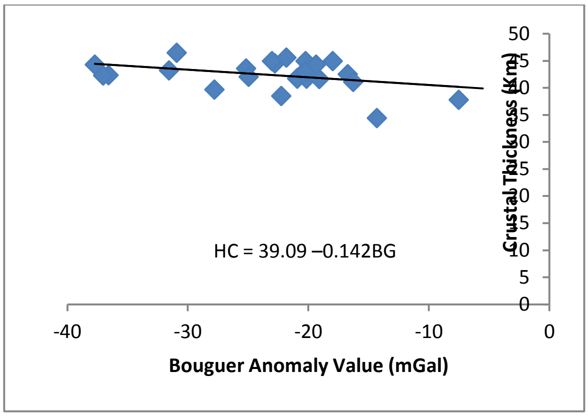

Fig. 12: Graph of crustal thicknesses against Bouguer anomaly values

Equation (6) was derived for the crustal thickness within the study area such that for any given Bouguer anomaly value, the crustal thickness can easily be estimated from the equation. The equation was obtained by plotting the values of the average crustal thickness against their corresponding Bouguer anomaly values. On the graph (Fig. 12), the straight line equation obtained shows a relationship between the crustal thickness and Bouguer anomaly values over the study area. The obtained equation is given as:

$$H_C = 39.09 - 0.142BG \qquad (6)$$

Modelling analysis along profile AA'

Profile AA' (Fig. 13) cut across the study area in NW-SE direction. The depth scale is seen to be divided into 3 main boundaries such as the basement depth, the Conrad discontinuity and the Moho discontinuity. The profile AA' has a horizontal distance of about 370 km. However, the observed and the calculated values were matched, and the depth result was obtained as shown in Fig. 14. The sedimentary cover over the study area is seen to have fault which is a potential trap to hydrocarbon and it comprises of members such as Sakpe Ironstone, Doko member, Jima member, etc. with deepest depth of about 8 km. The Conrad discontinuity which is the boundary separating the upper crust from the lower crust is seen to have a depth range of 21 km to 28 km across profile AA'. The upper crust made of migmatite has a density of 2.72 gm/cm^3 which overlies the lower crust made of migmatite - gneiss of density 2.8 gm/cm^3. The Moho discontinuity which separates the crust from the underlying mantle has a minimum depth of 38 km and a maximum depth of 47 km along this profile. The region is seen to have a highly densed mantle of density 3.2 gm/cm^3 underlying a less densed crust of 2.8 gm/cm^3.

Modelling analysis along profile BB'

Profile BB' (Fig. 13) cut across the study area in N-S direction. The depth scale is seen to be divided into 3 main boundaries which are the basement depth, the Conrad discontinuity and the Moho discontinuity. The sedimentary cover over the study area is seen to comprise of members such as Jima member, Doko member, Enagi siltstone etc. with deepest depth of about 8 km. The Conrad discontinuity which is the boundary separating the upper crust from the lower crust is seen to have a depth range of 23 to 37 km across profile BB' which is in line with the result obtained from spectral analysis. The upper crust made of migmatite has a density of 2.72 gm/cm^3 which overlies the lower crust made of migmatite - gneiss of density 2.8 gm/cm^3. The Moho discontinuity which separates the crust from the underlying mantle has a minimum depth of 40 km and a maximum depth of 47 km along this profile. The region is seen to have a highly densed mantle of density 3.2 gm/cm^3 underlying a less densed crust of 2.8 gm/cm^3. The profile BB' has a horizontal distance of about 275 km. However, the observed and the calculated values were matched, and the depth result was obtained as shown in Fig. 15.

It is known that the empirical and spectral analysis result is a precursor to modelling; the result from the modelling technique is adopted as the crustal thickness of the study area. The average crustal thickness of the study area from modelling technique ranges from 39 to 47 km, which shows that the is stable tectonically because Nigeria lies within a plate (Africa) free of diastrophic activities, unlike other countries like Nepal that lies in a plate boundaries where tectonic activities are predominant.

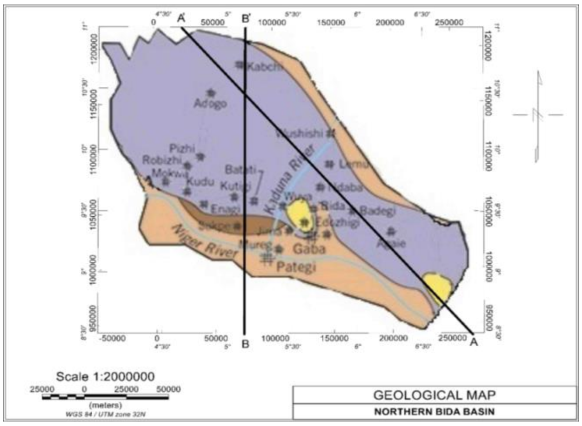

Fig. 13: Geological map of the study area showing the profile lines AA' and BB'

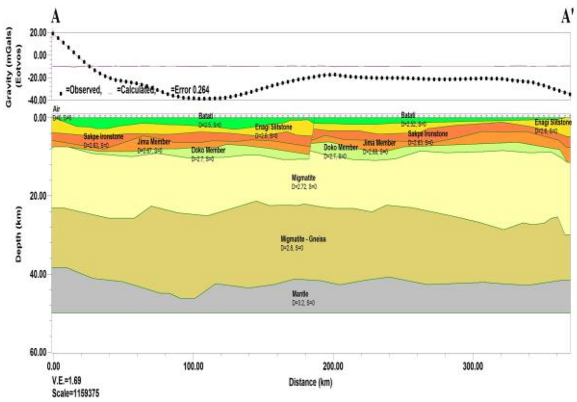

Fig. 14: Gravity model representing profile AA'

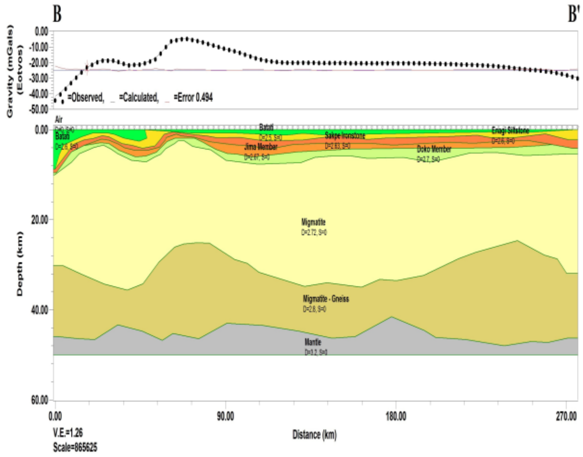

Fig. 15: Gravity model representing profile BB

Conclusion

The Bouguer gravity anomaly map (Figure 4.1) of the study area shows that the area is characterised by series of negative Bouguer anomalies with closures. The closures observed on the map signify structural alignment due to the tectonic activities that must have taken place in the study area. The negative anomalies noticed on the Bouguer map are attributed to low-density bodies within that area or due to the existence of a huge down wrap of sediments.

The spectral analysis shows that the Moho depth ranges between 29 and 47 km while Conrad and the Sedimentary thickness ranges from 23 to 37 km and 5 to 9.5 km respectively. The empirical relation method result shows that the average crustal thickness obtained ranges from 33 to 47 km, which is within the reasonable range compare to the Moho depth estimated from the spectral analysis.

However, two gravity profile (AA' and BB') have been investigated with 2-D modelling to estimate the three depth scale, the sedimentary thickness, Conrad, and the Moho depth in which the Conrad have a depth range of 21 to 28 km and 23 to 37 km in profile AA' and BB' respectively and density of 2.72 gm/cm^3 in both profile. The average crustal thickness obtained from two model profile ranges from 39 to 47 km which fall within the range of average Moho depth of Nigeria (32 to 44 km) and Africa (39 km). The study area is stable tectonically since Nigeria lies within a plate (Africa) and has a considerable Moho depth range.

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