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Crustal structure of southern Benue Trough, Nigeria from 3D inversion of gravity data

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3D Moho interface has been computed from the airborne Bouguer anomaly beneath the southern part of the Benue Trough (BT), using the MATLAB program 3DINVER.M. From the study, the maximum Moho depth of 27.5 km and the minimum Moho depth of 18.1 km were computed. Interpretation of the gravity data of the southern part of the BT suggests that igneous input contributed greatly to the understanding of its concomitant deep crustal processes. The Moho depth elevation from the area is calculated to be around 9.4 km. This is in agreement with the Moho uplift within the study region as suggested by earlier researchers.

Key words: Lower Benue trough, crust, mantle, bouguer gravity data, 3DINVER.M.

INTRODUCTION

Gravity method is one of the oldest geophysical survey methods used by geophysicists. It was the first geophysical technique to be used in oil and gas exploration and despite being eclipsed by seismology, it has continued to be an important method in a number of exploration areas. Like magnetics, radioactivity and some electrical techniques, gravity method is a natural- source method. Local variations in densities of rocks near the surface cause minute changes in the gravity field. Gravity method is often regarded as a potential field method. Gravity is an inherent property of mass and the gravity effects of local masses are very small compared with the effect of the background field of the earth as a whole. Gravity data played an important role in the recognition of the structure and the evolution of sedimentary basins (Ali et al., 2014). Gravity anomaly at long wavelength usually suggests the undulations possibility in the topographic interface and the lateral variations in its physical properties (densities); while, short wavelength anomaly may suggest density variations related to the nature of the basin fill. These could encompass the compaction, facies changes and basic to intermediate intrusive (Ali et al., 2014). Gravity data can be used to study the internal tectonic and stratigraphic framework, basement and the crustal structure (Agagu and Adighije, 1983; Ali et al., 2014).

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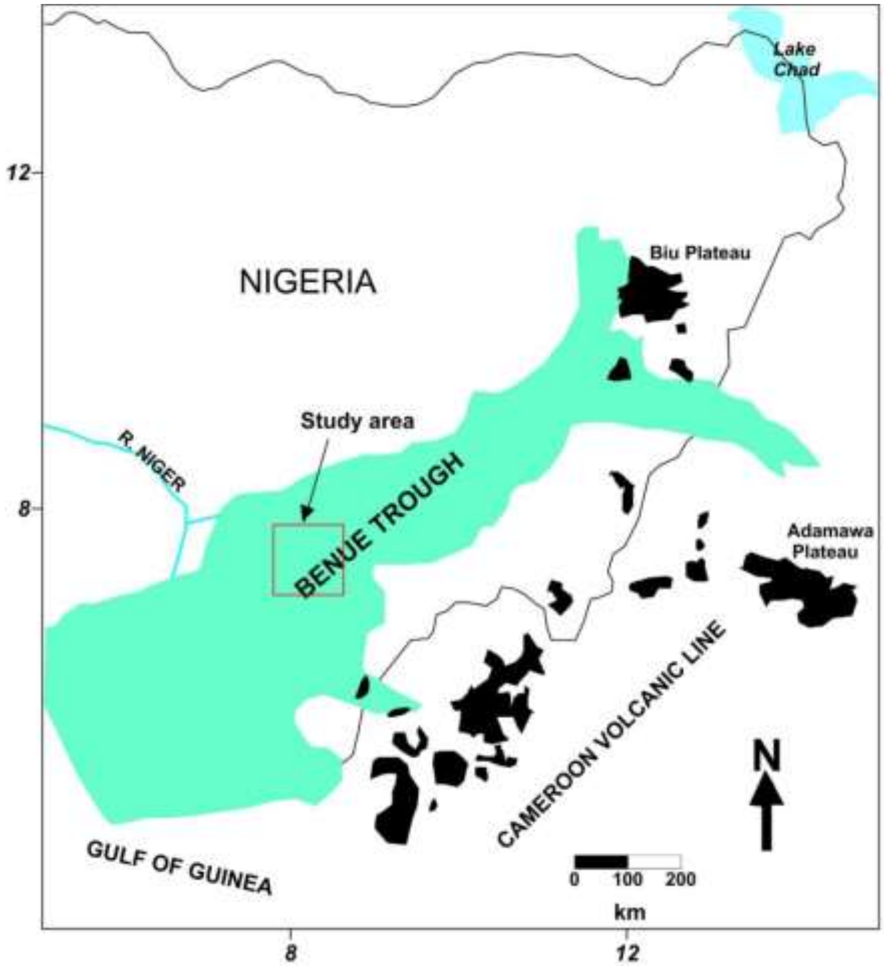

Figure 1. Simplified sketch geological map showing the volcanic areas in the region of study. The red square shows the area of study (Modified after Fairhead and Okereke, 1988; Maluski et al., 1995; Tokam et al., 2010).

Thus, understanding the structural basement framework, thickness and the physical properties of crust and mantle is very important, especially in hydrocarbon prospect. Also, gravity method is still widely used as an exploration tool to map subsurface geology and to estimate ore reserves for massive ore bodies (Mandal et al., 2013, 2015; Biswas et al., 2014a, b; Biswas and Sharma, 2016).

Interpretation of gravity data can be carried out both quantitatively and qualitatively. Quantitative interpretation includes making numerical estimates of the depth and dimensions of the sources of anomalies; this often takes the form of modeling of sources which could, in theory, reproduce the anomalies recorded in the survey (Biswas, 2015, 2016; Singh and Biswas, 2016; Biswas et al., 2017). Several methods of interpretation in gravity prospecting include: The Euler-3D method, local wave number method, analytical signal method, source parameter imaging (SPI) method, forward and inverse modeling method (Biswas, 2015, 2016).

Benue Trough of Nigeria is a SW-NE Cretaceous intra-continental basin that formed an integral part of the West and Central African Rift Systems (WCARS; Fairhead and Okereke, 1988; Tokam et al., 2010; Anudu et al., 2014). Its origin is related very closely to the separation and development of Africa from south America and the opening of south Atlantic Ocean and Gulf of Guinea between the late Jurassic and the early Cretaceous times (King, 1950; Wright, 1968, 1981; Grant, 1971; Ajayi and Ajakaiye, 1981; Benkhelil, 1989; Ofoegbu and Onuoha, 1991; Jassen et al., 1995; Anudu et al., 2014). The Trough is of economic importance for its mineralization and hydrocarbon potentials. Granites and gneisses formed the Precambrian crystalline basement rocks of the region (Ofoegbu, 1984). The geological settings of the Benue Trough (Nigeria) offers unique opportunity to address or solve many regional scale geodynamic problems. The Trough has gotten numbers of magic Mesozoic to Cenozoic magmatism (Figure 1). Three periods of magmatic activity were recorded within the Trough (Maluski et al., 1995). Magmatic activity of 147-

106 Ma is reported from the northern (around Biu plateau) section of the Trough; whereas the other two periods of 97 to 81 Ma and 68 to 49 Ma are restricted to the southern portion of the Trough. The magmatic rocks reported from the region are of different grades: gabbros, dolerites, camptonites, nepheline syenites, granophyres, trachytes, phonolites, rhyolites and basalts (Nwachukwu, 1972; Uzuakpunwa, 1974; Adighije,1981; Ofoegbu and Onuoha, 1991; Maluski et al., 1995). The magmatic activity in the Benue Trough predated its tectonic evolution (Maluski et al., 1995). The volcanic intrusions are interpreted in the region from gravity and magnetic data and are distributed beyond surface exposure which is believed to restrict the economic development of some parts of the region (Adighije, 1981; Ajayi and Ajakaiye, 1981; 1986; Ofoegbu, 1984; Fairhead and Okereke, 1988; Benkhelil, 1989; Anudu et al., 2014; Oha et al., 2016). The Adamawa and Biu plateaus as shown (Figure 1) are the continental part of the alkaline Cameroon volcanic line, as it has a spatial link with Benue Trough (Maluski et al., 1995; Tokam et al., 2010).

There are published results of the gravity interpretation for the crust (Moho) estimated below the southern portion of the Benue Trough (Adighije, 1981; Fairhead and Okereke, 1987, 1988; Okereke, 1988; Fairhead et al., 1991). The crustal studies from seismological data include that of Akpan et al. (2016). The Moho depths vary between 19 and 26 km from the regional gravity studies below the southern portion of the Benue Trough (Adighije, 1981; Fairhead and Okereke, 1987; 1988; Okereke, 1988; Fairhead et al., 1991); whereas, from the seismological data, the Moho depth was calculated between 23 km and 22 km (Akpan et al., 2016).

In this paper, the gravity data of the southern part of the Benue Trough provided by the Nigerian Geological Survey Agency (NGSA) was used and the crustal structure of this area was studied. For the interpretation approach, the 3DINVER.M function by Gómez-Ortiz and Agarwal (2005) was used and the geometrical properties (density) of the interface associated with the crustal discontinuities below the study area from the gravity data was determined.

Geology of the area

The study area is made up of the Cretaceous to Recent sedimentary succession (Figure 2) (King, 1950; Stoneley; 1966; Wright, 1968; Nwachukwu, 1972; Benkhelil, 1982, 1989; Ofoegbu, 1984, 1985; Ofoegbu and Onuoha, 1991; Guiraud and Maurin, 1992; Akpan et al., 2016).

The study area comprises of six Cretaceous sediments formations. These are the Asu River group, the Eze-Aku formation, Awgu formation, Nkporo formation, Bassange and the Lower coal formations.

The Asu River group formed the oldest Cretaceous sediment in the Benue Trough. It consists of shale and limestone with intercalations of sandstone. The shales have been highly fractured and are fissile in nature (Ofoegbu and Onuoha, 1991). The Eze-Aku shale consists of blackshale, siltstone and sandstones; while the Eze-Aku sandstone consists mainly of sandstones. Awgu formation is made up of shale and limestone of Coniacian age. Nkporo formations are mainly shales and mudstones. Bassange formations consist of sandstones and ironstones; but the Lower coal formations consist of coal, sandstones and shales.

METHODOLOGY

Determination of the geometric distribution of densities within the subsurface is fundamentally challenging in any gravity study. Parker (1973) calculated the gravity anomalies caused by an uneven, homogeneous media using series of Fourier transforms.

$$F(\Delta g) = -2\pi G\rho e^{(-\omega\phi)} \sum_{n=1}^{\infty} \frac{\omega^{n-1}}{n!} F[h^n(x)] \quad (1)$$

Here F(Δg), is the Fourier transform of the gravitational field, G is the universal gravitational constant, ω is the wavenumber, ϕ is the mean horizontal depth to the interface and ρ is the density contrast between the two interface (that is, mantle and the crust), g is the gravity anomaly, h(x) is the depth to the interface (positive downwards) and n is the number of iteration.

Parker (1973) Equation 1 was modified by Oldenburg (1974) for the calculation of the depth of the undulating surface from gravity data. This was done simply by rearranging the equation (1) above to get;

$$F[h(x)] = \frac{F[\Delta g(x)]e^{(-\omega\phi)}}{2\pi G\rho} - \sum_{n=2}^{\infty} \frac{\omega^{n-1}}{n!} F[h^n(x)] \quad (2)$$

In this relationship, the topographic interface, h(x) can easily be calculated iteratively by assuming the mean depth ϕ and the density contrast (ρ). This is possible firstly by assuming that h(x) = 0 and taking the inverse Fourier transform of equation (2) (Oldenburg, 1974; Gómez-Ortiz and Agarwal, 2005). This procedure gives the first estimate of the topographic interface h(x). The result is then substituted into equation (2) for subsequent estimation until a desired solution is obtained. Once the depth to the interface h(x) is greater than zero and does not intercept any topography, then the process tends to converge (Oldenburg, 1974; Gómez- Ortiz and Agarwal, 2005).

For monitoring the convergence of Equation 2, Oldenburg (1974), used the following relation:

$$R_n = \text{max over all k} \left| \frac{\omega^{n-1}}{n!} F\left[h^n(x)\right] \right| \quad (3)$$

Since the convergence of the Equation 2 is performed until criterion is obtained, when $R_n / R_1 < \mu$, where μ is some arbitrary small number. However, in the real case of computation, the above convergence criterion may not be sufficiently enough since the

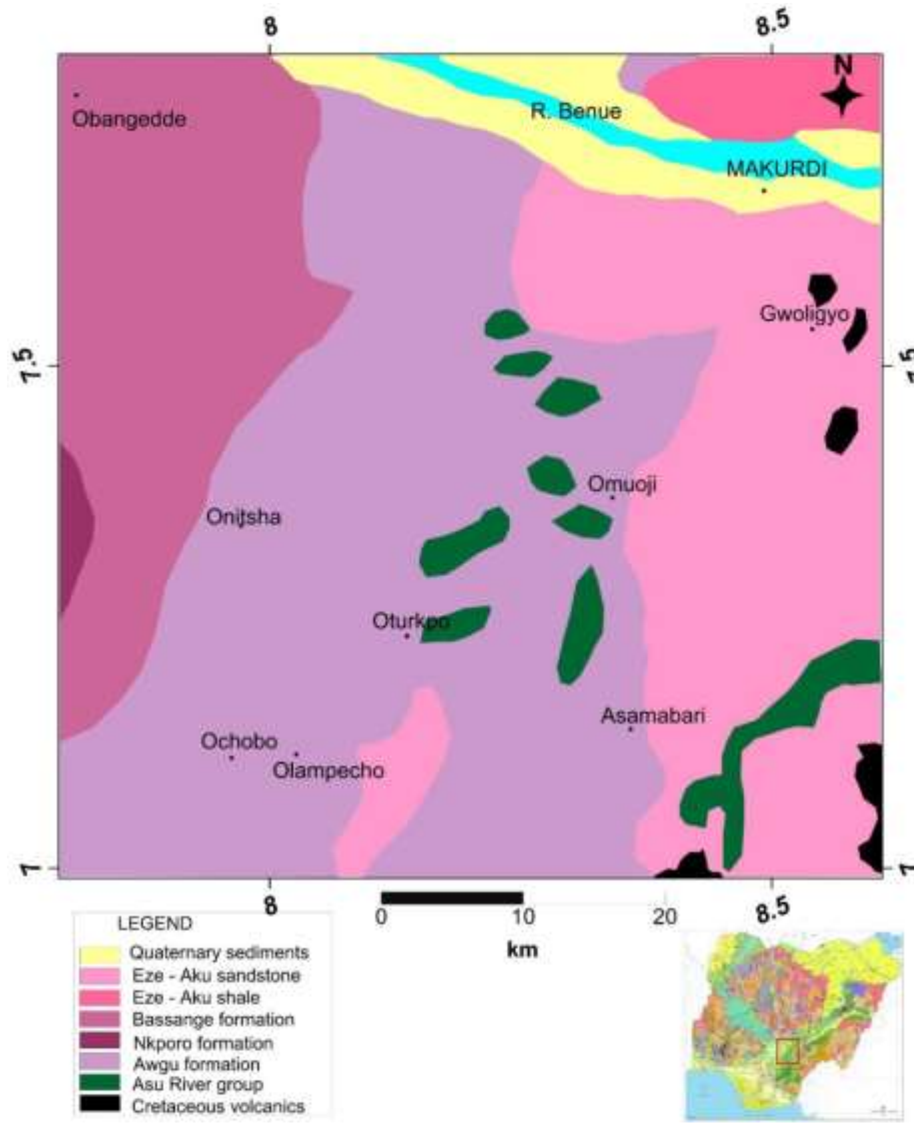

Figure 2. Detailed geological map of the study area.

term ($e^{\omega\phi}$) in Equation (2) may be affected by short wavelengths. To overcome this, the short wavelengths emanating from the near surface features need to be filtered since not only would their signals cause problem to the inversion process itself, but it may not be in association with depth of the targeted interface (Gómez-Ortiz and Agarwal, 2005).

Therefore, Gómez-Ortiz and Agarwal (2005) used the cosine filter (4) for filtering of the gravity data in wave number domain. This relation, high-cut-filter, HCF (k) is defined as:

$$\begin{Bmatrix} \mathrm{HCF}\ (k) = \left\{ \frac{1}{2}\left[1+\cos\left(\frac{k-2\pi \mathrm{WH}}{2(\mathrm{SH}-\mathrm{WH})}\right)\right]\right\}, \\ \text{for WH} < k < \mathrm{SH} \\ \mathrm{HCF}\ (k) = 1, \text{for } k < \mathrm{WH} \\ \mathrm{HCF}\ (k) = 0, k > \mathrm{SH} \end{Bmatrix} \tag{4}$$

$k = \frac{1}{\lambda}$ is the frequency defined as the reciprocal of the wavelength λ. Where WH and SH are said to be the smaller and larger frequency parameters respectively.

3DINVER.M function

The computer program 3DINVER.M function is developed in MATLAB environment for 3-D inversion of gravity anomalies of density interfaces (Gómez-Ortiz and Agarwa, 2005). The input parameters include; the number of rows and columns and the data spacing of the gridded input gravity data, density contrast (ρ), associated with two media (crust and mantle), mean horizontal depth (ϕ) to the interface, convergence criterion and the roll off frequencies for the high-cut-filter.

In the program, direct and inverse Fourier Transform (FFT and IFFT) are built. The FFT is used to compute a matrix with

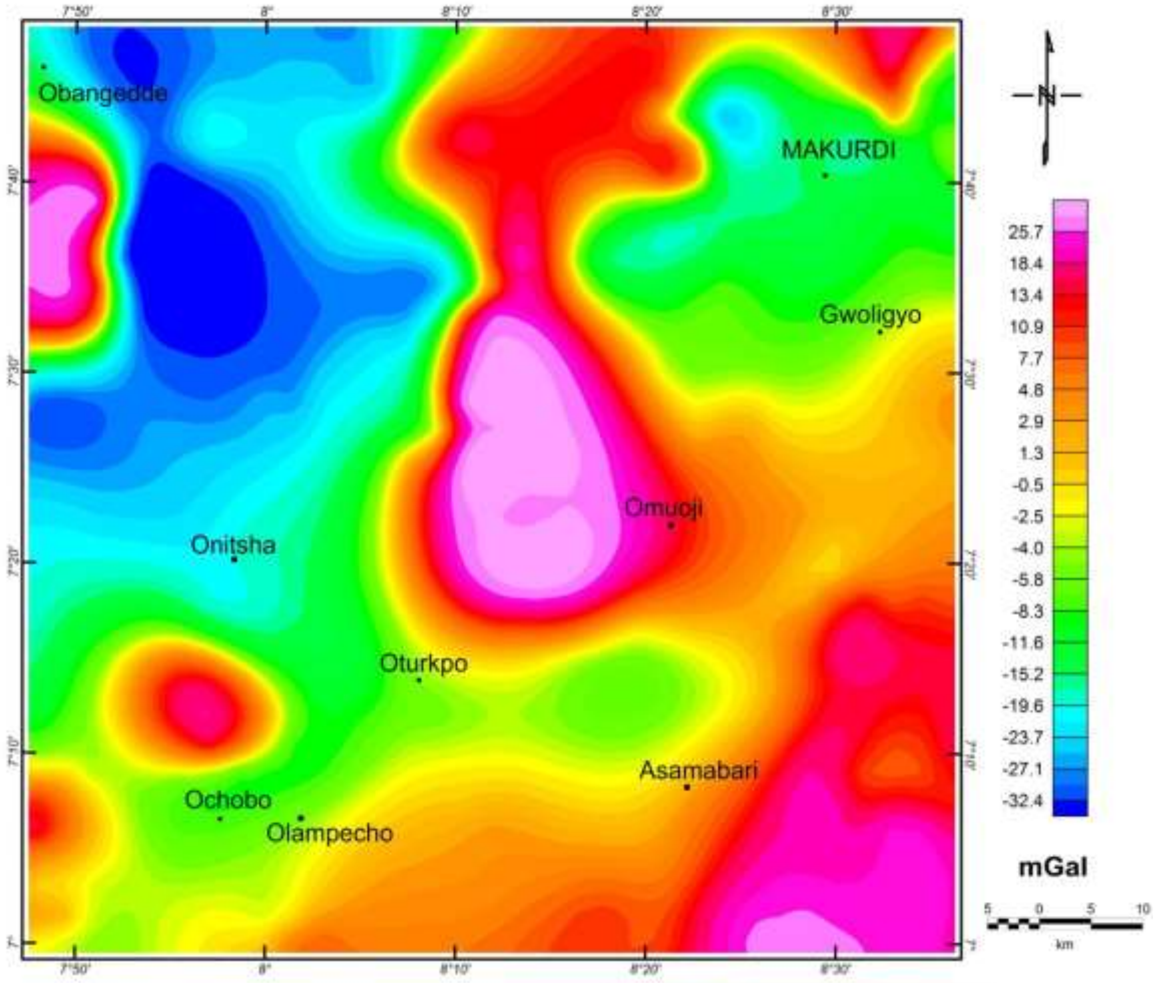

Figure 3. Complete Bouguer gridded anomaly map of the study area.

amplitude spectrum displayed on the computer monitor. This is done after the data must have been feed into the program using the ASCII text editor, read and stored. The data has to be of one-dimensional array (that is, only the column containing the gravity anomaly is required). The IFFT is used for the calculation of the topography in space domain after the commencement of the iterative procedure. The result is then used to compute the second term in Equation 2. The second term is filtered newly and on applying the IFFT, root mean square (RMS) error between the new topography and the first one is computed. If the RMS value is lower than the pre-assigned value (that is, the convergence criterion), then the process is terminated; and if not the new topography is used to compute the third term of the series and so on. Hence, the iterative procedure continued until the convergence criterion is reached.

At this point, three graphs are displayed: the inverted Moho depth grid, the gravity anomaly due to the inverted topography (Moho) and the difference between the input gravity anomaly and the one due to the inverted topography (Moho). This is accompanied with the RMS value and the iteration at which the procedure terminated; thus, two output files of ASCII are taken. One pertaining the depth to the density interface (Moho depth) and the other is associated with the gravity anomaly derived from the forward modelling (Gómez-Ortiz and Agarwa, 2005).

RESULTS AND INTERPRETATION

Figure 3 shows the complete Bouguer anomaly map of the study area associated to the Moho depth. The data has an aerial extend of 90 x 90 km, at square grid interval of 2 x 2 km. For the inversion process, the grid needs to be extended to avoid the problem of edge effects that could arise (Gómez-Ortiz and Agarwal, 2005). The original grid was therefore expanded to the size of 222 x 222 km of same square grid interval of 2 x 2 km. The density contrast of 0.5 g/cm^3 between the mantle and the crust was chosen and the mean crust depth of 23 km (Akpan et al., 2016) for the inversion. The filter cut-off due to the short wavelength at 0.01 was set, due to the high wavelength at 0.013.

The result of the 3DINVER.M function is as shown (Figure 4). This shows the crustal depth discontinuity (Moho) under the study area. The result was achieved after the forth iteration with the RMS error of 0.0053 km established at the criterion convergence of 0.02 km. The

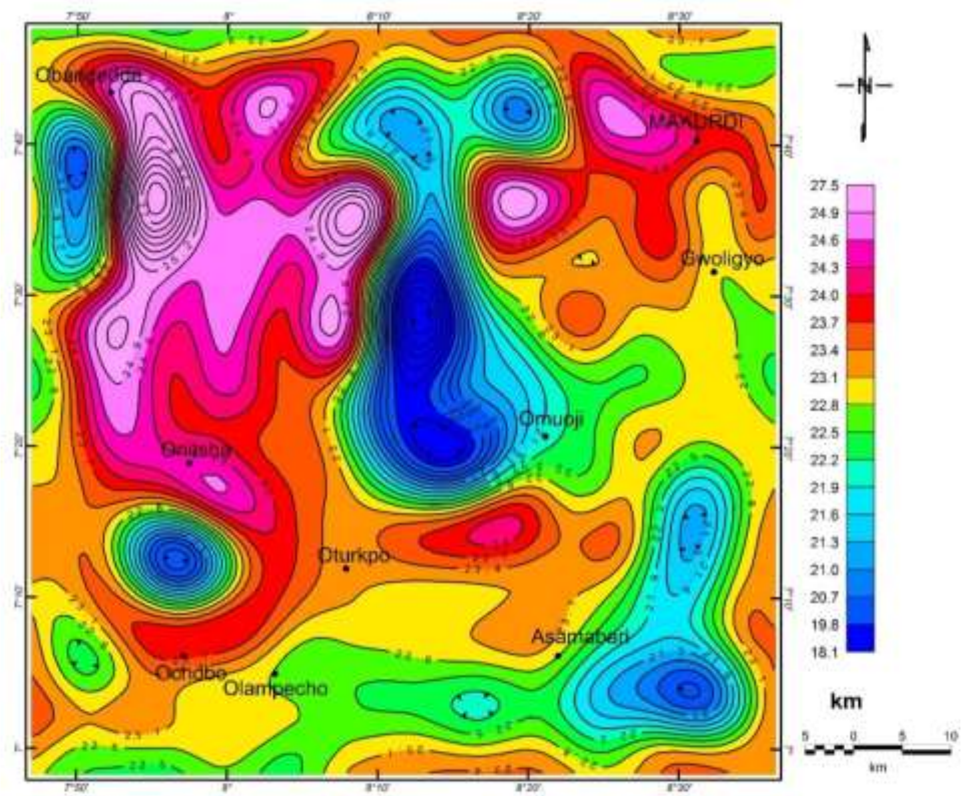

Figure 4. The estimated Moho discontinuity beneath the study area derived from the 3DINVER.M algorithm.

maximum Moho depth of 27.5 km was recorded as shown (Figure 4). This is consistent with the NW trend of the negative gravity low. The central thinning of the Moho depth is consistent with the central prominent gravity high. The Moho depth here (beneath the central positive Bouguer anomaly) is minimum (18.1 km); thus, the crustal uplift under the study area is 9.4 km. The Moho result from the 3DINVER.M function was accompanied by an inverted gravity anomaly (Figure 5) computed using Equation 1. This is observed to be correlating very well with the original gravity anomaly with the exception of the edges. Figure 6 shows the calculated difference between the original gravity anomaly and the inverted one. The difference read between – 0.5m and 1.3 mGal. This difference is very insignificant; thus, to some extent it could be interpreted that the gravity anomaly has been recovered using this algorithm.

DISCUSSION

The study area, the southern part of the Benue Trough (BT), includes the parts of the Lower Benue Trough (LBT) and the Anambra basin from the western end. The region of the low gravity anomaly lay precisely over the Anambra basin. The LBT is interpreted as the portion that has been affected by enormous intrusions than the other parts of the BT region (Maluski et al. 1995; Anudu et al., 2014). The intrusive bodies beneath the LBT contribute greatly towards the understanding of the geodynamic processes in the BT (Adighije, 1981; Anudu et al., 2014). The processes of igneous intrusions and underplating have been part of the tectonic content of every rifted sedimentary basins globally. The presence of igneous intrusions in a sedimentary basin is a recurring phenomenon in its stratigraphic record. Magmatism beneath the BT of the Nigerian Peninsular and its imprints appear to affect almost the entire geological units of the region which is reflected from the interpreted central axial positive gravity in the region (Adighije, 1981).

Anambra Basin is one of the energy-rich inland sedimentary basins in Nigeria, perhaps because of its proximity to the Niger Delta basin (Anthony and Onuoha, 2008). It is approximately a triangular shaped embayment covering about 3 km square area with a total sedimentary thickness of over 9 km (Agagu and Adighije, 1983; Ola-Buraimo, 2013). Combined Cretaceous-Tertiary sediments of more than 12 km beneath Anambra basin is interpreted (Agagu and Adighije, 1983). Anambra basin harbours the largest deposit of coal and lignite in Nigeria. Coal mining in

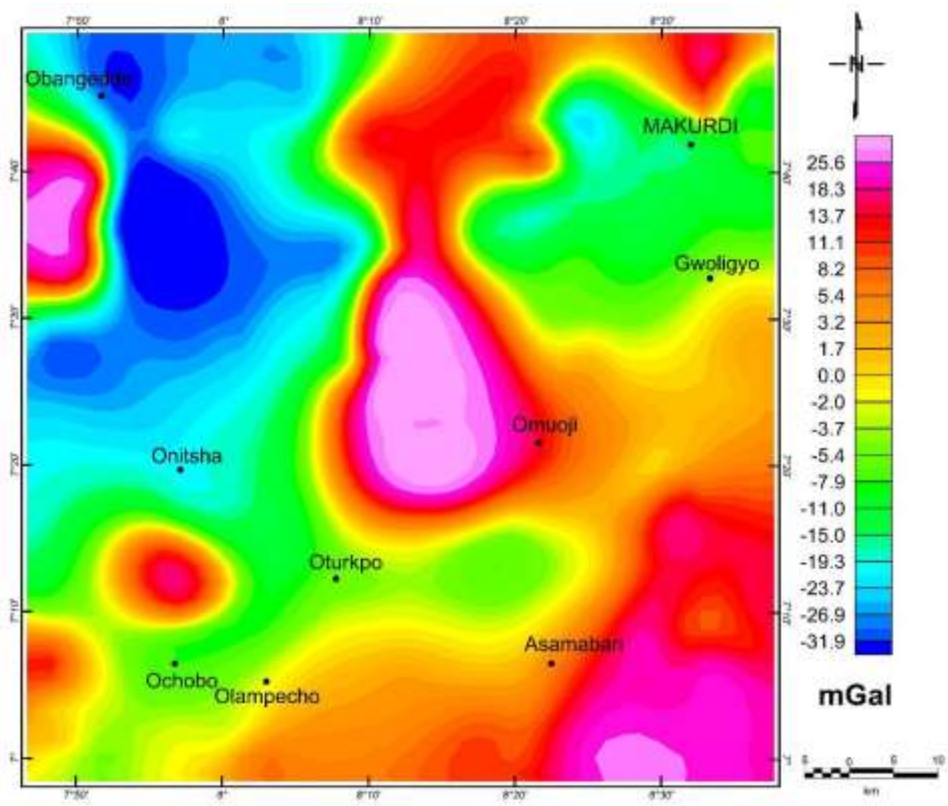

Figure 5. Inverted Bouguer anomaly derived as the result of the Moho inversion program.

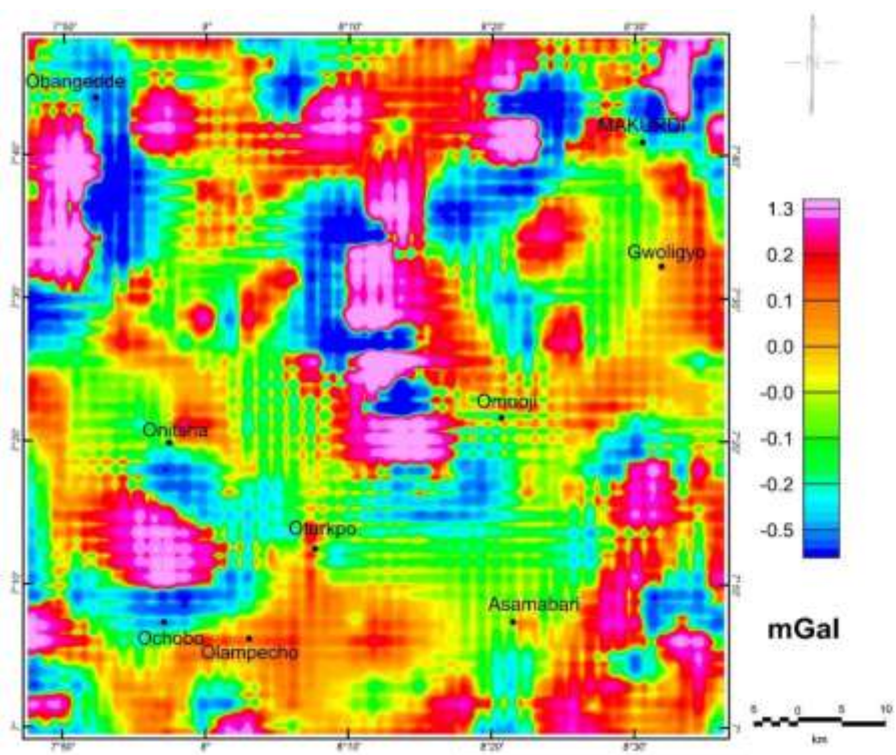

Figure 6. The difference between the original Bouguer anomaly and the inverted Bouguer anomaly.

Nigeria started in Enugu of the Anambra basin. The discovery of Coal at the Udi ridge of Enugu area in 1909 by Albert Kitson has helped in turning the region into a strategic British business area.

The results of the interpretation above may suggest that the central gravity high between Oturkpo and Omuoji area may be as a result of the crustal swallowing and basement. The north- western negative gravity around Obangedde and Onitsha is interpreted a s an area of thick sediments or sedimentary basins and thicker crust. The low Moho depth observed around the area of Asamabari is consistent with the Cretaceous volcanism around this area. The crust has been thinned to 9.4 km based on the average Moho depth of 27.5 km recorded in this study. The minimum crustal structure (Moho depth) of 18.1 km was recorded over the central gravity high around the area of Omuoji, north of Oturkpo. The estimated crustal structure (Moho depth) of this area under study is in good agreement with the published result of 19 km to 26 km from previous studies. Interpretation of the gravity data of the southern part of the Benue Trough suggests that igneous input contribute greatly to the understanding of its concomitant deep crustal processes.

The present algorithm, 3DINVER.M has been demonstrated in the present study towards understanding the geometry of density interface and mapping the crustal discontinuities beneath the study area from the gravity data. The algorithm is an excellent tool that can be used to compute the geometry of density interface topography.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interest.

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