Full Length Research Paper

Investigation of possible cause of gravity anomalies in parts of the Niger Delta Basin, Nigeria

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Possible cause of gravity anomalies in parts of the Niger Delta Basin, Nigeria was investigated using three methods of gravity data interpretation; Euler-3D deconvolution, source parameter imaging (SPI) and forward and inverse modeling. The estimated depths from the interpretation techniques used show much similarity. Quantitatively, the results obtained from the SPI method showed a minimum to maximum depth of 1264.11 to 9354.57 m to the anomalous body. The results obtained from Euler-3D deconvolution method showed a depth range of 2136.40 to 9167.57 m to the anomalous body using a structural index of 3. The results from the forward and inverse modeling revealed a depth range of 793 to 7586 m to the anomalous body. Qualitatively, the gravity signatures in profiles 1, 2 and 3 possibly depict antiformal geologic features whereas the gravity signatures in profiles 4 and 5 possibly depict synformal features/basin geometries.

Key words: Gravity data, Niger Delta, source parameter imaging, Euler deconvolution, forward and inverse modeling, anomalous body.

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.

In the mining industry, gravity method is still widely used as an exploration tool to map subsurface geology and estimate ore reserves for some massive ore bodies (Biswas and Sharma, 2016; Mandal et al., 2015; Biswas et al., 2014a; b; Mandal et al., 2013). Gravity method is sometimes applied to specialized shallow applications including archaeology (Lakshmanan and Montlucon, 1987; Deletie et al., 1988; Brissaud et al., 1989), weapons inspection (Won et al., 2004) and detection of faults and paleo-channels in hydrologic investigations (Hinze, 1991; Grauch and John, 2002).

Gravity prospecting involves measurements of variations in the gravitational field of the earth. The variation arises from the differences in density between subsurface rocks. The causative body has a different density from the surrounding bedrocks or sediments and represents a subsurface zone of anomalous mass responsible for gravity anomalies. In as much as this method involves changes in the force of gravity at the surface due to lateral density changes in the subsurface, it is actually the difference in acceleration due to gravity that is being measured. The strength of the gravitational field is directly proportional to the mass and hence to the density of the subsurface features.

Interpretation of gravity data can be carried out both quantitatively and qualitatively. It is aimed at mapping the surface and subsurface regional structures (intrusive bodies, syncline structures, anticline structures, contacts, faults, basement rocks, mineralization and thickness of sedimentations or depth to anomalous bodies). Qualitative interpretation involves the description of the survey results and the explanation of the major features revealed by a survey in terms of the types of likely geological formations and structures (intrusive bodies, syncline structures, anticline structures, contacts, faults, basement rocks and mineralization).

Quantitative interpretation involves making numerical estimates of the depth and dimensions of the sources of anomalies and this often takes the form of modeling of sources which could, in theory, replicate the anomalies recorded in the survey (Biswas et al., 2017; Singh and Biswas, 2016; Biswas, 2016; Biswas, 2015). 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, 2016; Biswas, 2015). The beginning stages of gravity data interpretation generally involve the application of mathematical filters to observed data after ensuring that the gravity data has been reduced (corrected). The specific goals of these filters vary, depending on the researcher's interest. The general purpose is to enhance anomalies of interest and/or to gain some preliminary information on location of the source anomalies.

The purpose of this study is to investigate the possible causes of gravity anomalies in parts of the Niger Delta Basin, Nigeria, by employing three methods of gravity interpretation. This will include the determination of; the depth to anomalous bodies, the isolated/prominent shallow depth anomalous bodies, and the possible type of geophysical feature/structure describing the anomalous bodies.

Location and geology of the study area

The study area which lies between latitudes 5°15'N and 5°45'N and longitudes 6°45'E and 7°15'E, falls within the Niger Delta Basin (sedimentary Basins) of Nigeria. It consists of three geologic formations. These formations include: Benin formation, Ogwashi-Asaba formation and Ameki Formation (Figure 1).

Stratigraphically, the Benin formation (Pliocene) is overlain by a lateritic overburden and underlain by the Ogwashi-Asaba formation which is in turn underlain by the Ameki formation of Eocene to Oligocene age. The Ameki formation overlies the impervious Imo shale group characterized by lateral and vertical variations in lithology. The Imo shale of Paleocene age is underlain in succession by Nsukka formation, Ajali Sandstones and Nkporo Shales of the Anambra Basin of Southern Nigeria (Reyment, 1965; Uma, 1989; Mbonu et al., 1990; Amajor, 2005; Nwankwo et al., 2011) (Figure 1).

Source of data

The land gravity data used in this work was obtained from Bureau Gravimetrique Internationale (BGI). The information contained in the data include longitudes, latitudes, altitudes, observed gravity values, free-air corrected values and Bouguer gravity values. The Bouguer gravity values signify that all necessary corrections have been applied to the data.

MATERIAL AND METHODS

Interpretation of gravity data is aimed at mapping the subsurface regional structures. This was performed qualitatively and quantitatively. Quantitative interpretation was done by employing three methods: Euler-3D method, source parameter imaging (SPI) and forward and inverse modeling method to estimate the depths to source anomalies.

Qualitative interpretation of the gravity data was carried out by applying standard filters using the magmap module in geosoft Oasis Montaj. The early stages of interpretation exercise involve the application of mathematical filters (downward and upward continuation, derivative based filters, polynomial fitting or trend surfaces and analytical signals) to observed data. The general
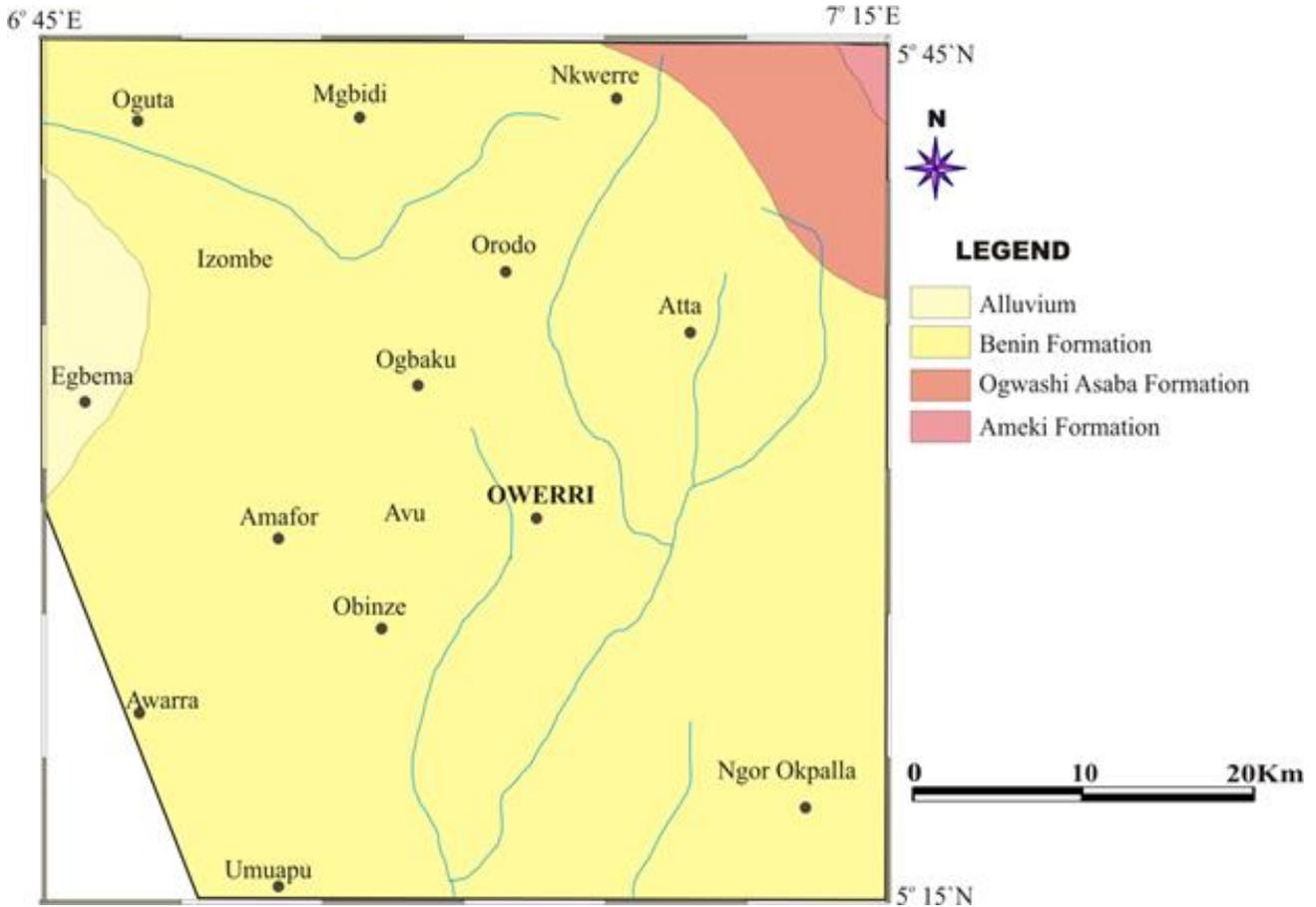
Figure 1. Geological map of the study area.

purpose is to enhance anomalies of interest and/or to gain some preliminary information on source location. The Bouguer anomaly contour map of the study area was produced. The residual Bouguer anomaly contour map of the study area was also produced after polynomial fitting filtering was applied to the Bouguer values. To show clearly areas of isolated anomalies with either the high or low Bouguer values, a 3D view of the residual Bouguer anomaly map was produced. For location purposes, a residual anomaly base map was also produced.

Oasis montaj software was employed in computing the SPI image and depth. SPI method made the task of interpreting gravity data significantly easier. Source parameter imaging technique (SPI) is an extension of the local wave-number method (Thurston and Smith, 1997). This method estimates the depth of source anomalies from the local wave number of the analytical signal. In 2D, the local wave number K is defined as the derivative of the phase of the analytic signal (θ) with respect to distance (Bracewell, 1965; Nabighian, 1972).

$$K = \frac{\partial \theta}{\partial x}$$
(1)

Where,

$$\theta = \tan^{-1}\left[\frac{\partial f(x,z)/\partial z}{\partial f(x,z)/\partial x}\right]$$

The analytical signal of the potential field, A(x, z), is given by

$$A(x,z) = \frac{\partial f(x,z)}{\partial x} - j\frac{\partial f(x,z)}{\partial z}$$
(2)

Where, f is the potential field.

This technique was used to obtain the depth estimate for each source anomaly. Euler-3D deconvolution method is an interpretation technique used for estimating the depth of anomalous bodies using the Euler's homogeneity equation. In depth estimation of gravity anomalous bodies using this method, the vertical component of gravity anomalous field Tz, must satisfy the Euler's homogeneity equation (Hood, 1965) which is given by:

$$(x-x_o)T_{zx} + (y-y_o)T_{zy} + (z-z_o)T_{zz} = N(B_z-T_z),$$
(3)

Where, Tz is the gravity anomalous field (vertical component) of
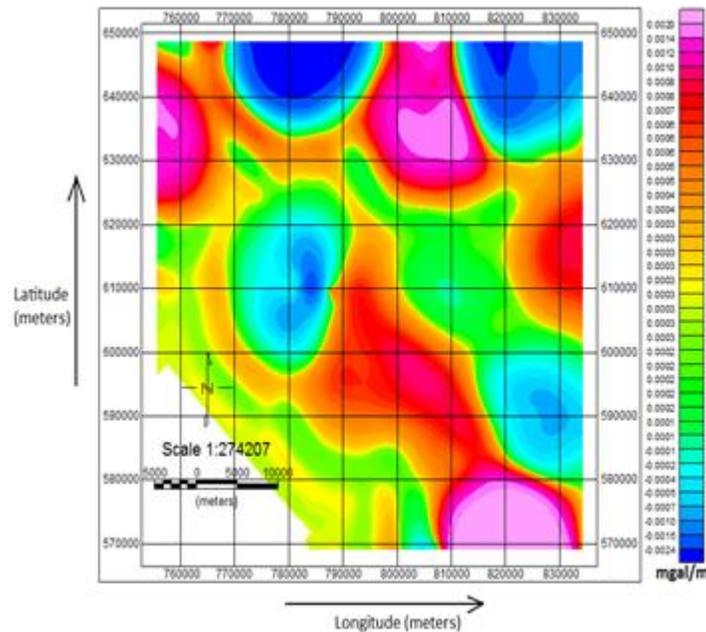
Figure 2. First vertical derivative base map (Residual).

a body having a homogeneous gravity field. x_o, y_o and z_o are the unknown coordinates of the source body centres or edges to be estimated and x, y and z are the known coordinates of the observation point of the gravity and the gradients. The values Tzx, Tzy and Tzz are the measured gravity gradients along the x, y and z directions. N is the structural index, which is a measure of the rate of change with distance of a field (Thompson, 1982) and B_z is the regional value of the gravity to be estimated (Reid et al., 1990; Changyou et al., 2000). Oasis montaj software was also employed in computing the Euler-3D image and depth.

Forward and inverse modeling technique involves the comparison or fitting of the calculated field of a hypothetical source (models) with that of the observed data; the model is adjusted in order to improve the fit for a subsequent comparison or fit. Once a reasonable fit is obtained and the model results are guided by the geology of the area, certain deductions can be made. These include depth to the source anomalies, positions and dimensions of the anomalous bodies, density of the anomalous bodies and the type of geological feature/structure representing or describing the anomalous bodies

The forward and inverse modeling was employed with the aid of the potent-3D program contained in the Oasis montaj software. Interpretation of gravity data using Potent starts with observation of the image of the observed data. The first step in interpreting the observed data was to take profiles on the residual Bouguer map. In interpreting the observed data, five profiles were taken along different parts of the residual Bouguer map.

RESULTS AND DISCUSSION

Figures 2, 3, 4 and 5 show the results of the application of the first vertical derivative, second vertical derivative,

analytical signal and upward continuation, respectively to the Bouguer values. The results from filtering and the altitude values were gridded using the minimum curvature (O'connel et al., 2005) in Oasis montaj software with a grid cell size of 160 meters (Figures 2, 3, 4, 5 and 6).

In upward continuation, gravity field data from one datum surface were mathematically projected upward to level surfaces above the original datum (Figure 5). The upward continuation achieves spatial resolution, by increasing the signal to noise ratio thereby attenuating the effect of noise. The first and second vertical derivatives filters compute the vertical rate of change in the gravity field with depth. The derivative filters (Figures 2 and 3) suppressed the effects of the long wavelengths (low frequencies). The analytical signal (quaternion) relates the vertical derivative of the gravity field to the horizontal derivative of the same gravity field and this was used to define the edges and boundaries of anomalous densities (Figure 4). Figure 6 reveals the height of each gravimeter observation site from the geoid (WGS84 terrestrial reference system). The effect of any gravity anomaly depends on the lateral variation in the density of the area.

The Bouguer gravity data was gridded using a grid cell size of 160 m. The result was then contoured using the contouring option in Oasis montaj software. Figure 7 shows the Bouguer anomaly contour map with a contour interval of 2 mgal indicating a maximum of 20 mgal and a
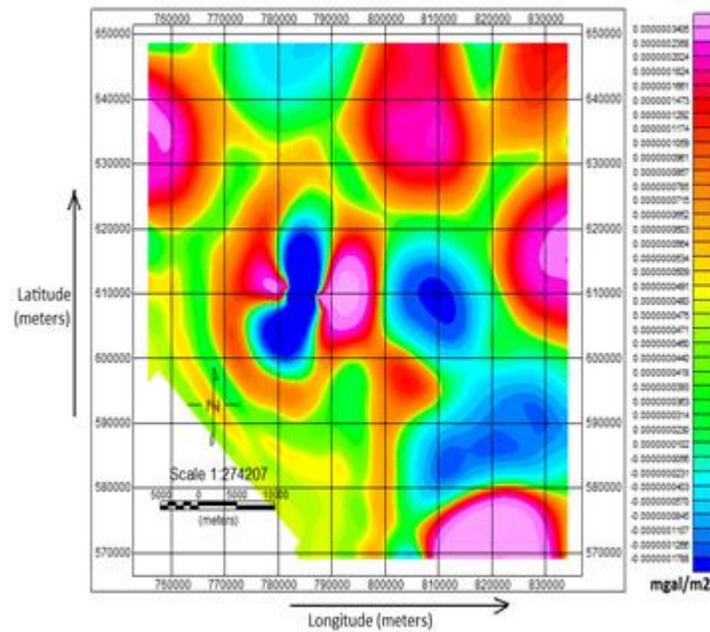
Figure 3. Second vertical derivative base map (Residual).
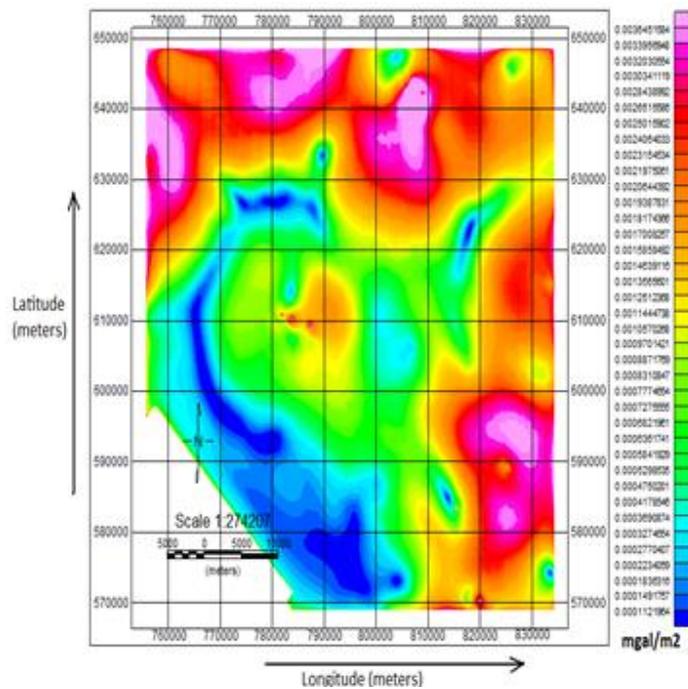
Figure 4. Analytical signal base map (Residual).

minimum of -28 mgal. The high anomaly values roughly occupy the northern and central part of the study area while the low anomaly values occupy mostly the southern part of the study area. Residual Bouguer anomaly map
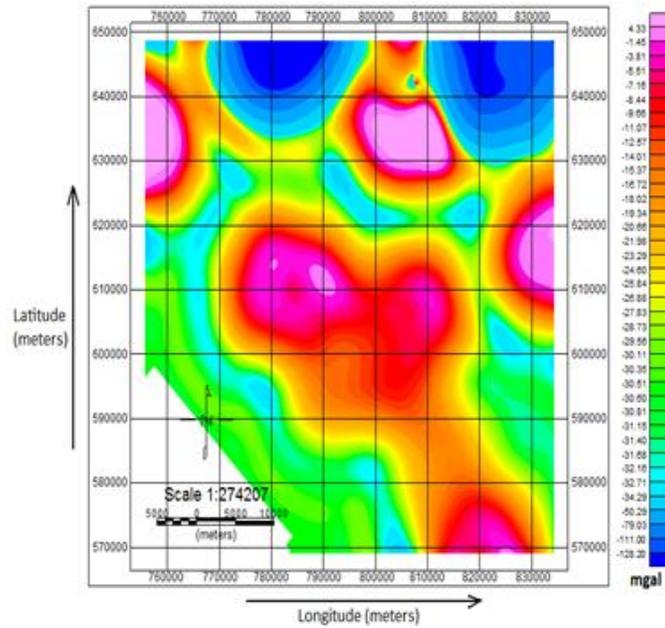
Figure 5. Upward continuation to 100 m (Bouguer values).
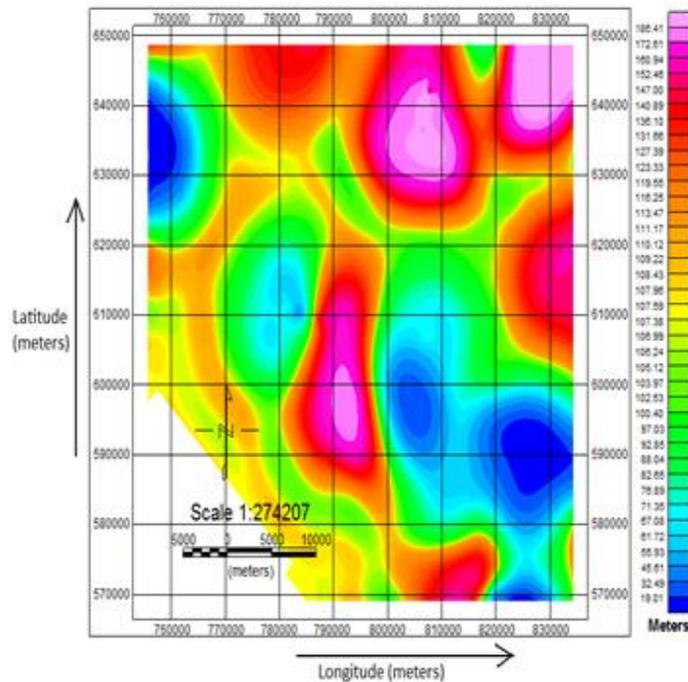
Figure 6. Altitude base map (Relief map).

was also produced after a polynomial fitting. Filtering of second-order was applied to the Bouguer values to separate regional anomaly from local anomaly. The result of the filtering was contoured after gridding using a grid
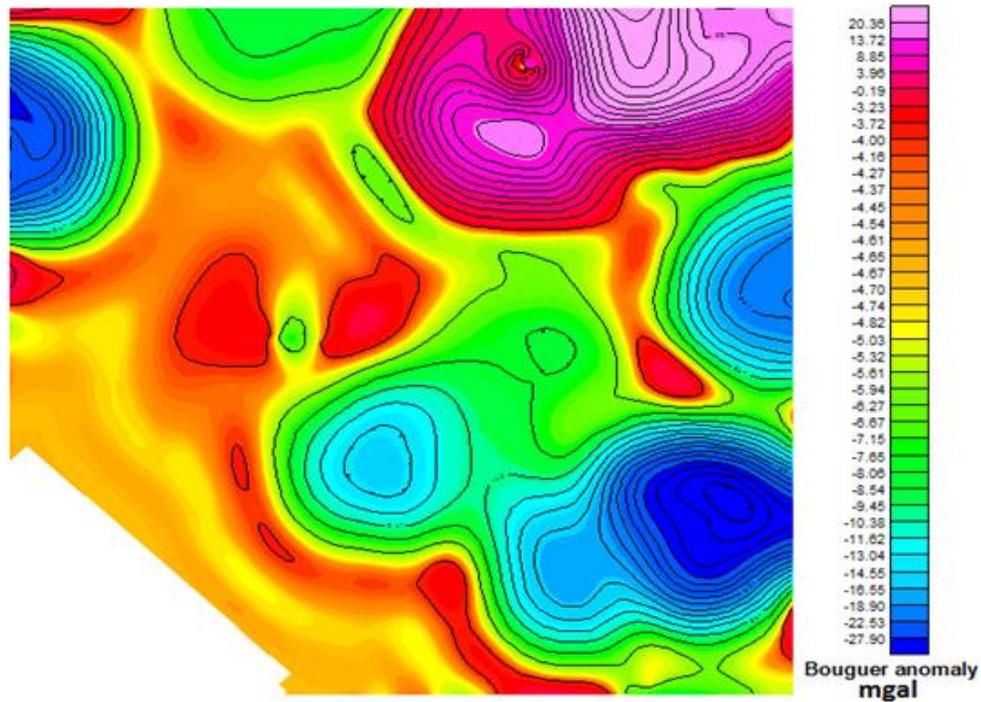
Figure 7. Bouguer anomaly contour map of the study area (contour interval of 2 mgal).
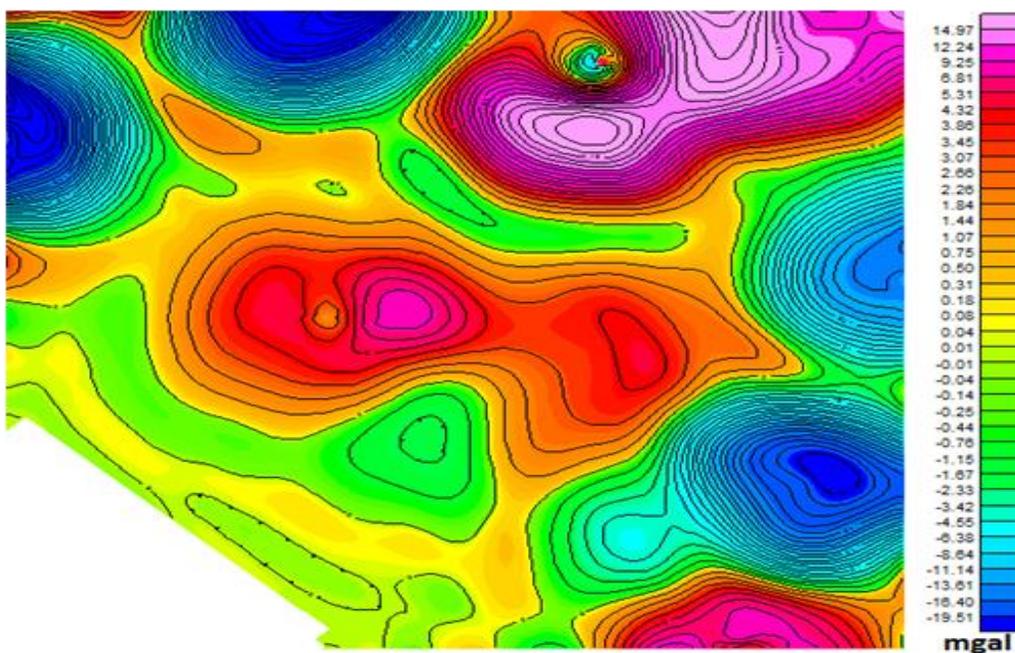
Figure 8. Residual Bouguer anomaly contour map of the study area (contour interval of 1 mgal).

cell size of 160 m (Figure 8). A 3D-view diagram of the residual Bouguer anomaly map (Figure 9) was produced to show clearly areas of prominent or isolated anomalies with either high and low Bouguer values. Figure 10
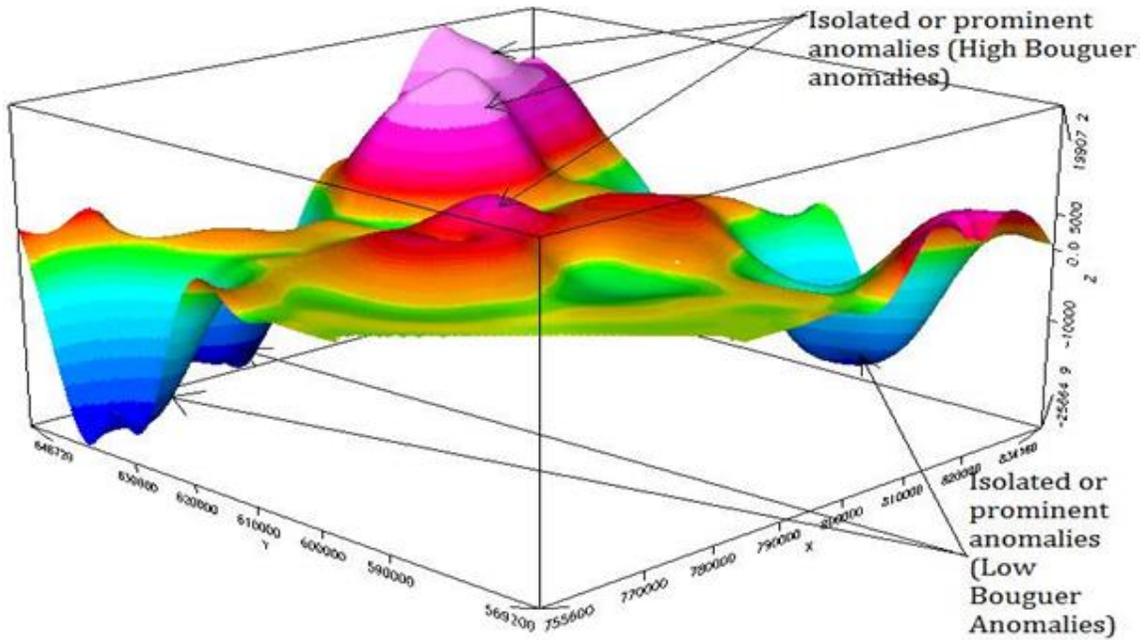
Figure 9. 3D-view of the residual Bouguer anomaly map.
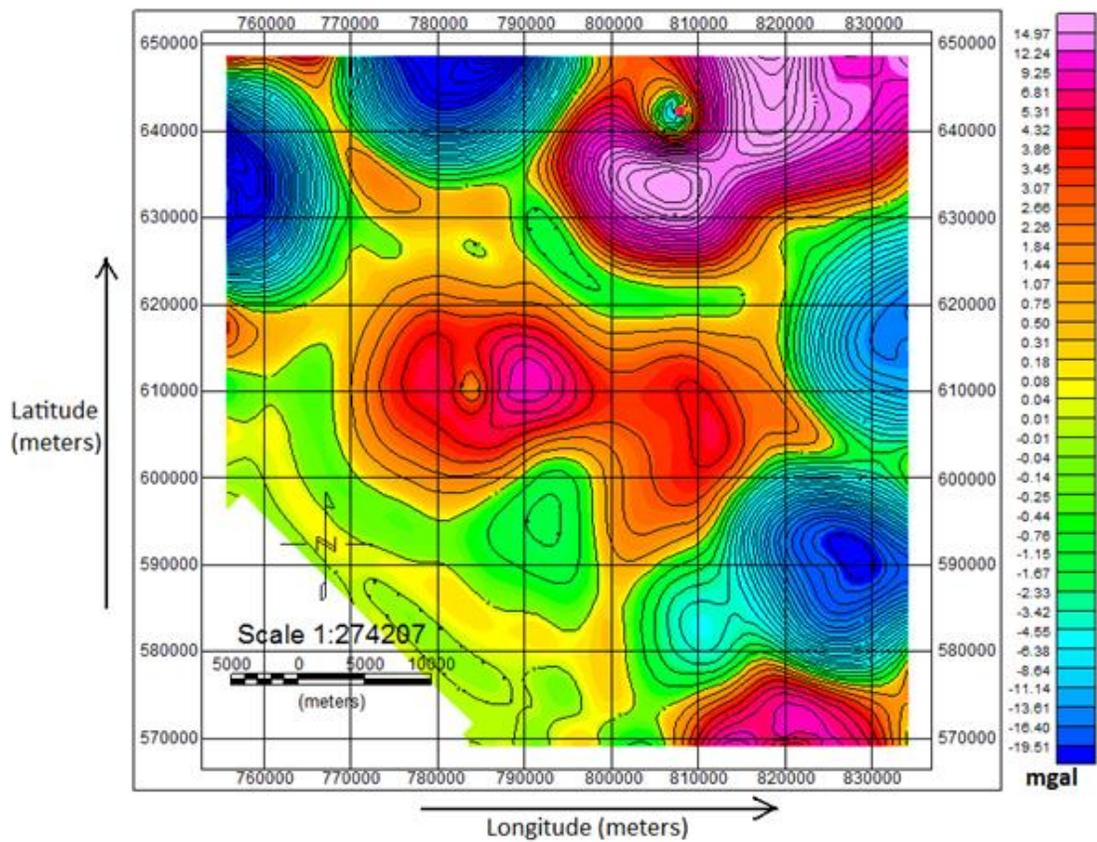
Figure 10. Residual Bouguer anomaly base map of the study area.
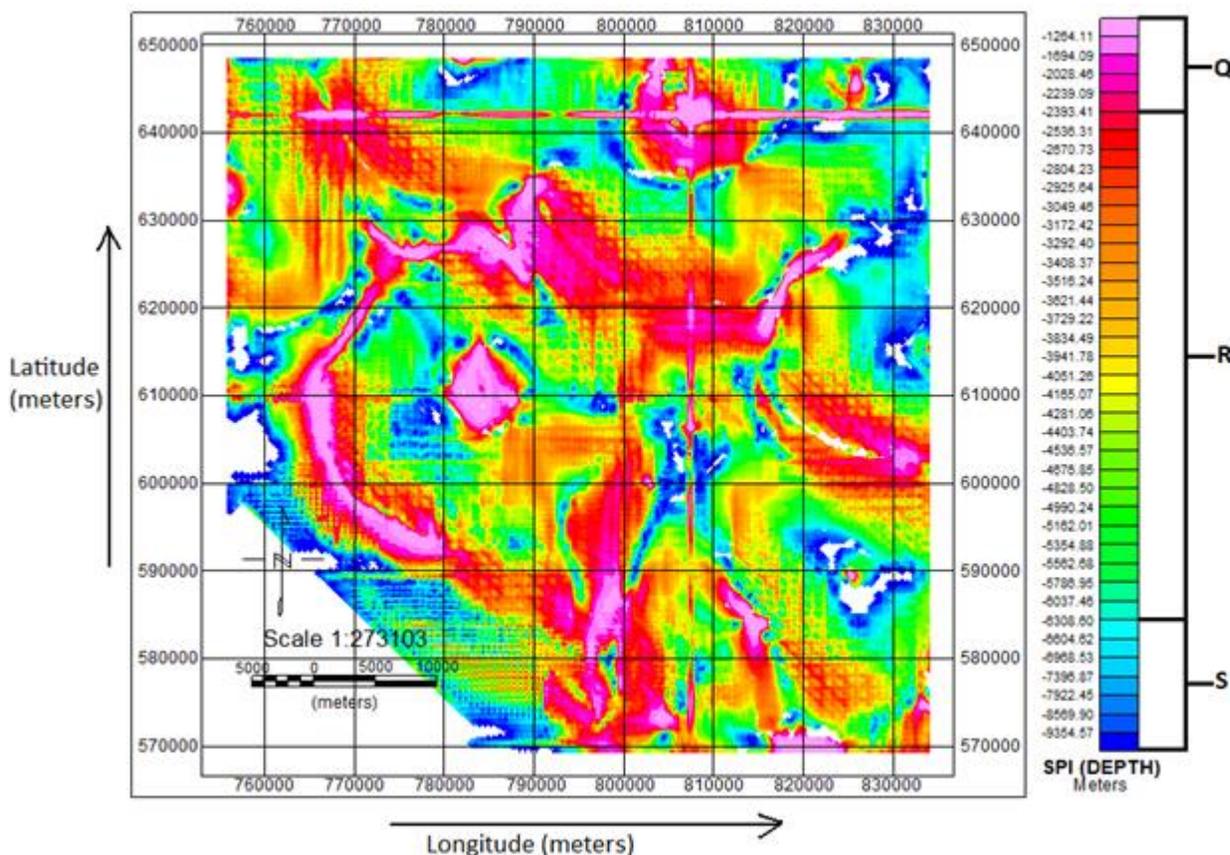
Figure 11. Source parameter imaging (SPI) depth result.

shows the residual Bouguer anomaly base map of the study area where the vertical and horizontal lines represent the longitude and latitude, respectively.

Oasis montaj software was used in computing the SPI depth distribution for the study area. The SPI grid and its legend in Figure 11 present a set of colours, indicating different depths to gravity anomalous bodies with different density contrasts. The light blue to deep blue colours at the lower end of the legend show areas of deepest lying anomalous bodies (that is the depth range 'S' from 6308.60 m to 9354.57 m). The light pink to dark pink colours indicates areas of shallowest depth lying anomalous bodies (that is the depth range 'Q' from 1264.11 m to 2393.41 m). The colours (green, yellow, orange and red) in between the pink and blue colours represent areas of less deep to shallow depth lying anomalous bodies (that is the depth range 'R' from 6308.60 to 2393.41 m). The negative sign attached to the values in the legend signifies depth (vertical distance below the earth's surface).

The Euler-3D deconvolution depth result for the study area was produced using the Euler deconvolution module in the Oasis montaj software. This was done using the structural index (SI) of 3, because most of the models used in this research were sphere-like models. Sphere or compact body at a distance is normally associated with structural index of 3 (Reid, 2002). From the Euler-3D result in Figure 12, the light to dark pink colours at the upper end of the legend portray areas of shallowest depth lying gravity anomalous bodies (that is the depth range 'T' from 2136.40 to 4367.35 m) whereas the light to dark blue colours indicate areas of deepest seated gravity anomalous bodies (that is the depth range 'V' from 8182.77 to 9167.57 m). The colours (red, orange, yellow and green) in between the pink and blue colours signify areas of shallow to less deep seated gravity anomalous bodies (that is the depth range 'U' from 4367.35 to 8182.77 m). The negative sign attached to the values in the legend signifies depth (vertical distance below the earth's surface) (Figure 13).

Profile 1 lies approximately between 795,000 and 815,000 m Easting and 625.000 and 640.000 m Northing on the residual Bouguer anomaly base map (Figure 13). From gravity interpretation studies (Dobrin, 1976;
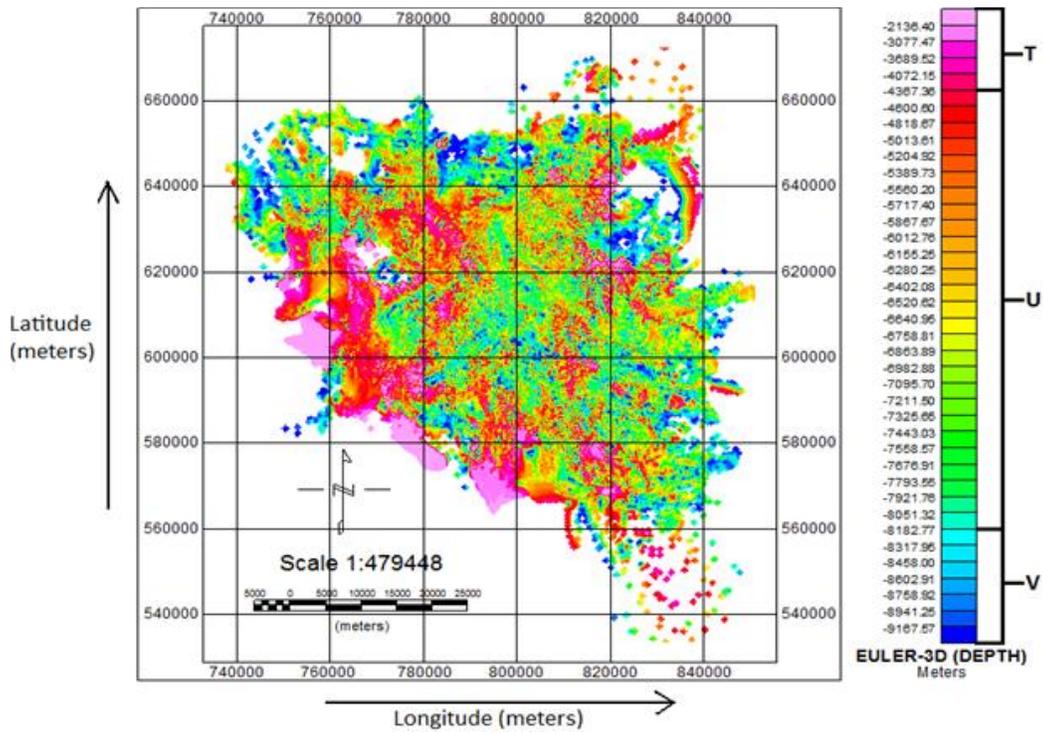
Figure 12. Euler-3D depth result (SI=3).
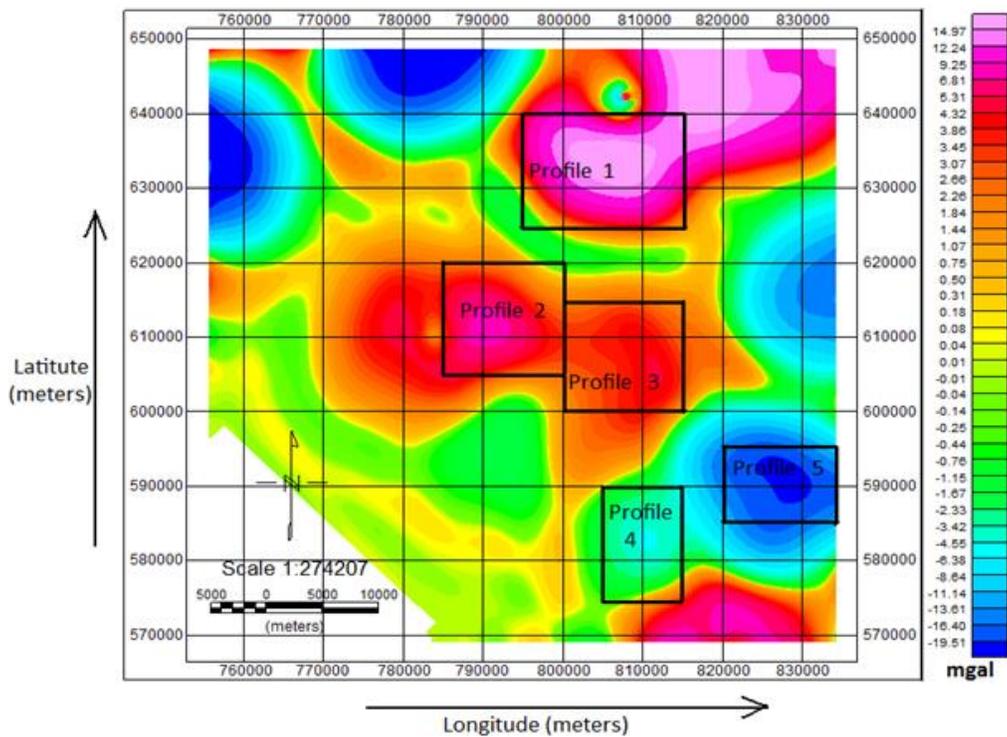
Figure 13. Residual Bouguer anomaly map showing the selected areas or profiles.
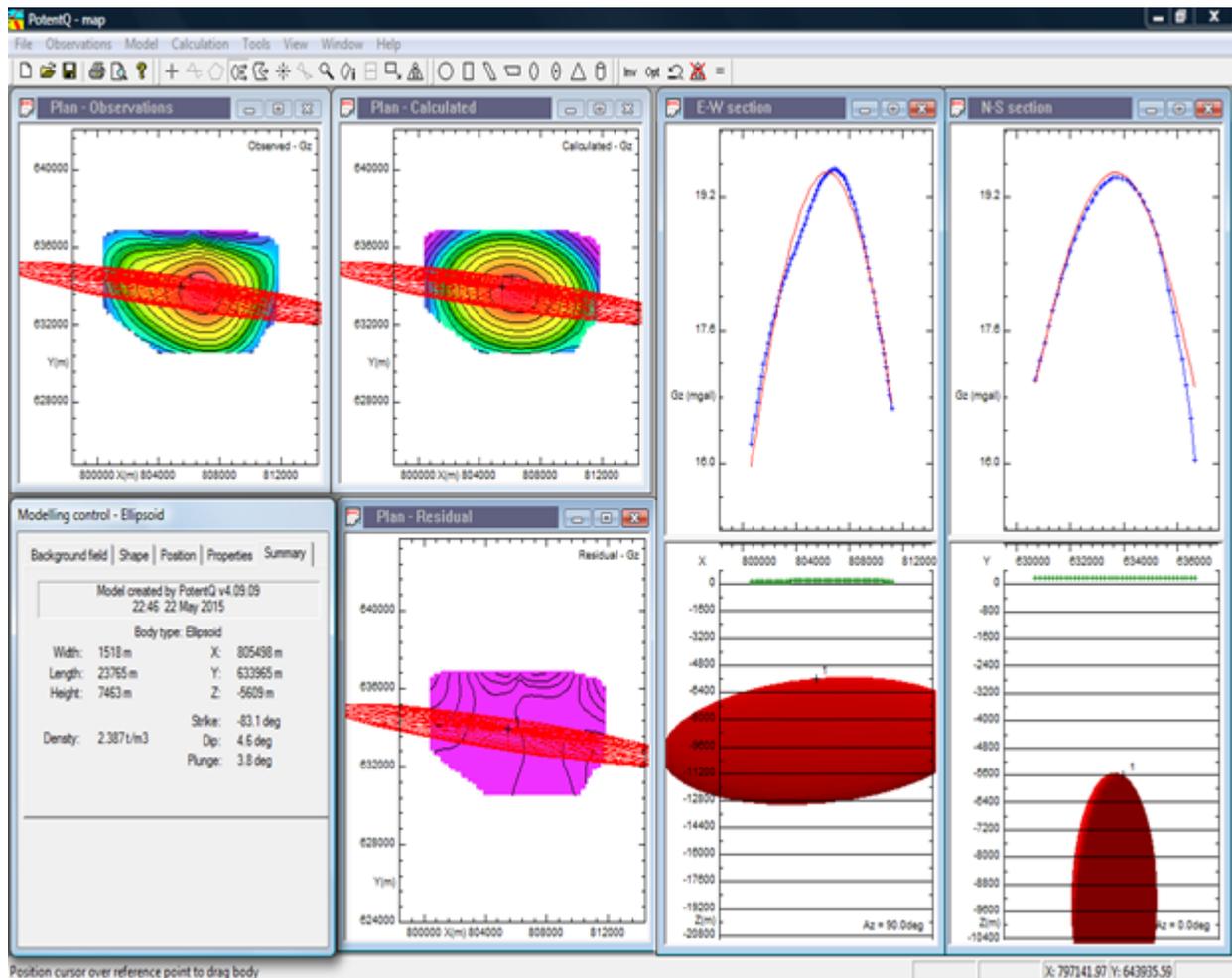
Figure 14. Forward and inverse modeling result of profile 1.

Carmichael, 1984; Dobrin and Savit, 1988; Corine, 1996), the gravity profile in Figure 14 possibly describes an antiformal feature. The model (ellipsoid) showed a depth of 5609 m (5.6 km) to the anomalous body. The density of the anomalous body was revealed to be 2.387 g/cm^3. The gravity signature shown in Figure 14 suggests that the anomalous body is denser than the surrounding bedrocks.

Profile 2 roughly lies between 785,000 and 800,000 m Easting and 605,000 and 620,000 m Northing on the residual Bouguer anomaly base map (Figure 13). According to these gravity interpretation studies (Dobrin, 1976; Carmichael, 1984; Dobrin and Savit, 1988; Corine, 1996), the gravity signature in profile 2 possibly describes an antiformal subsurface feature (Figure 15). The model (sphere) revealed the density of the anomalous body to be 2.347 g/cm^3. The depth to the anomalous body was 7586 m (7.6 km).

Profile 3 lies roughly between 800,000 and 815,000 m Easting and 600,000 and 615,000 m Northing on the residual Bouguer anomaly map (Figure 13). From gravity interpretation studies (Dobrin, 1976; Carmichael, 1984; Dobrin and Savit, 1988; Corine, 1996), the gravity profile in Figure 16 possibly depicts an antiformal geologic feature. The model (prism) revealed the density of the anomalous body to be 1.751 g/cm^3. The depth to the anomalous body was revealed to be 793 m (0.79 km).

Profile 4 is located on the Southeastern part of the study area (Figure 13). It lies approximately between 805000 and 815000 m Easting and 575000 and 590000 m Northing. From gravity interpretation studies (Corine, 1996), the gravity profile in Figure 17 possibly depicts a synformal geologic feature (basin structure). The model (ellipsoid) revealed the density of the anomalous body to be 2.595 g/cm^3. The depth to the anomalous body was depicted to be 2412 m (2.4 km). Profile 5 is located on
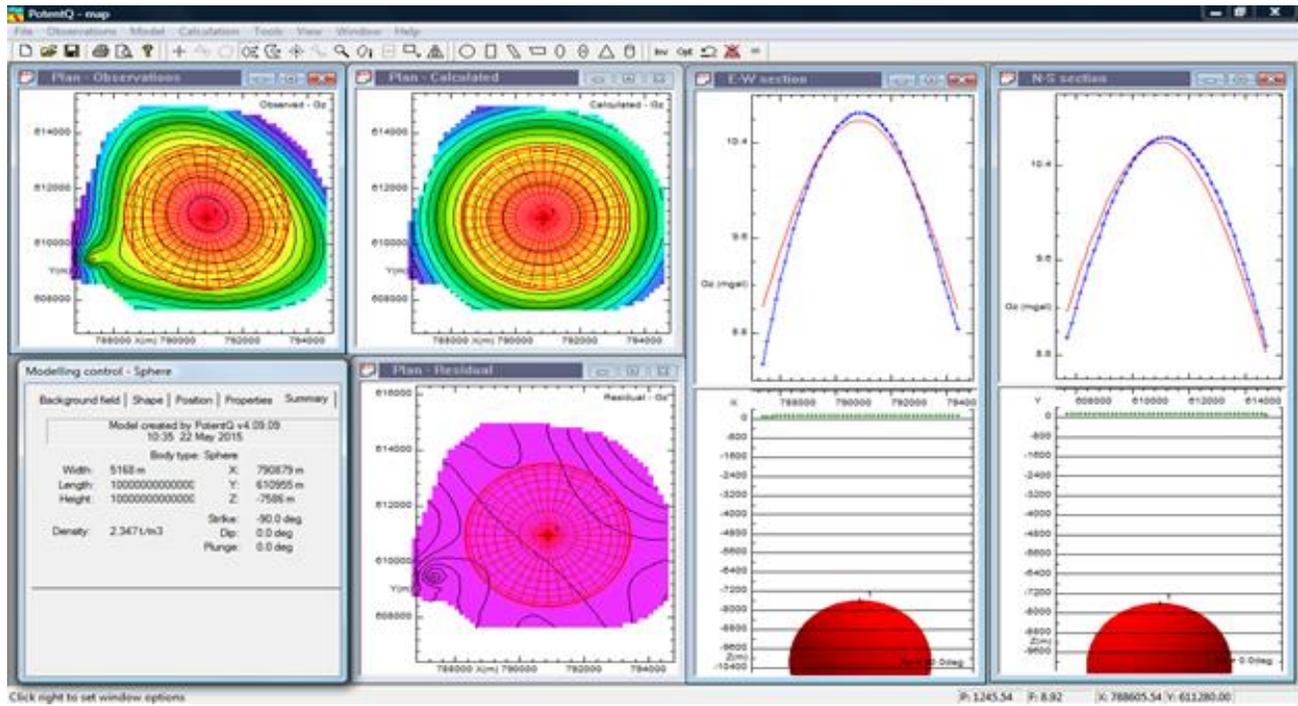
Figure 15. Forward and inverse modeling result of profile 2.
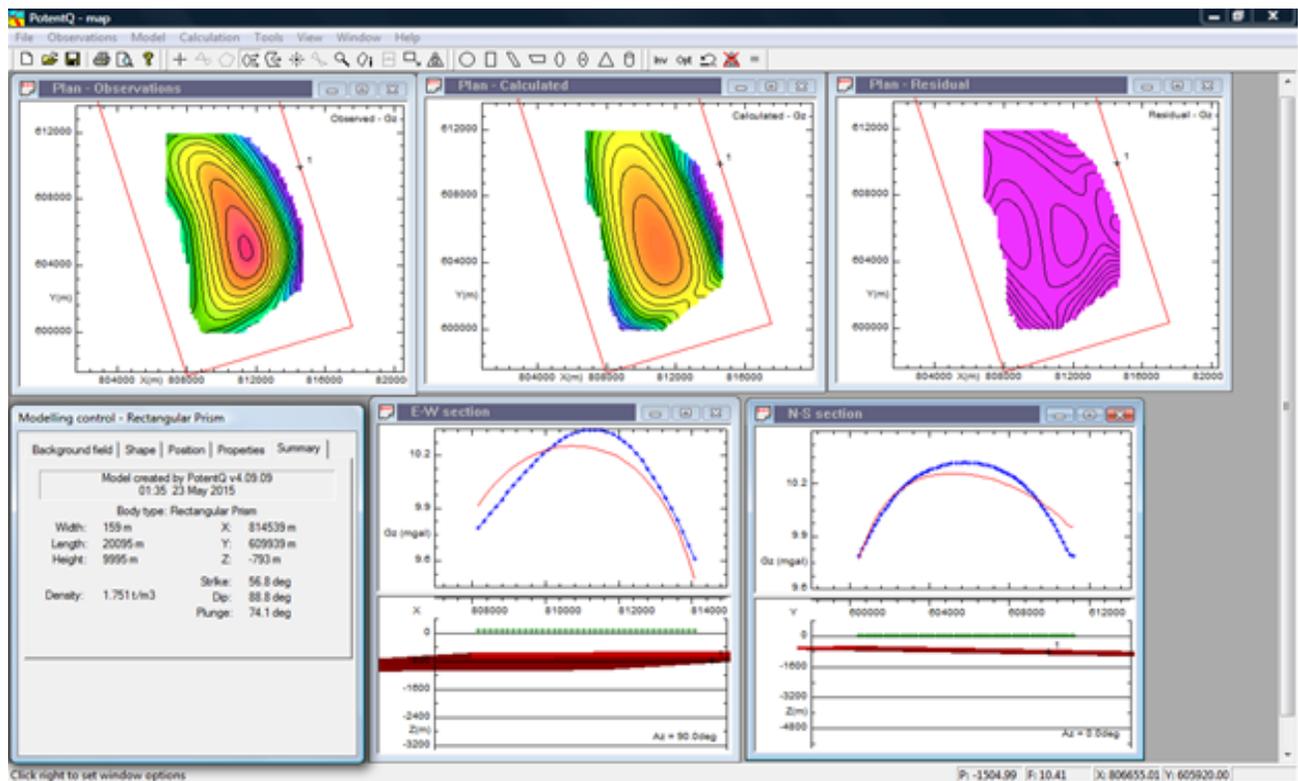
Figure 16. Forward and inverse modeling result of profile 3.
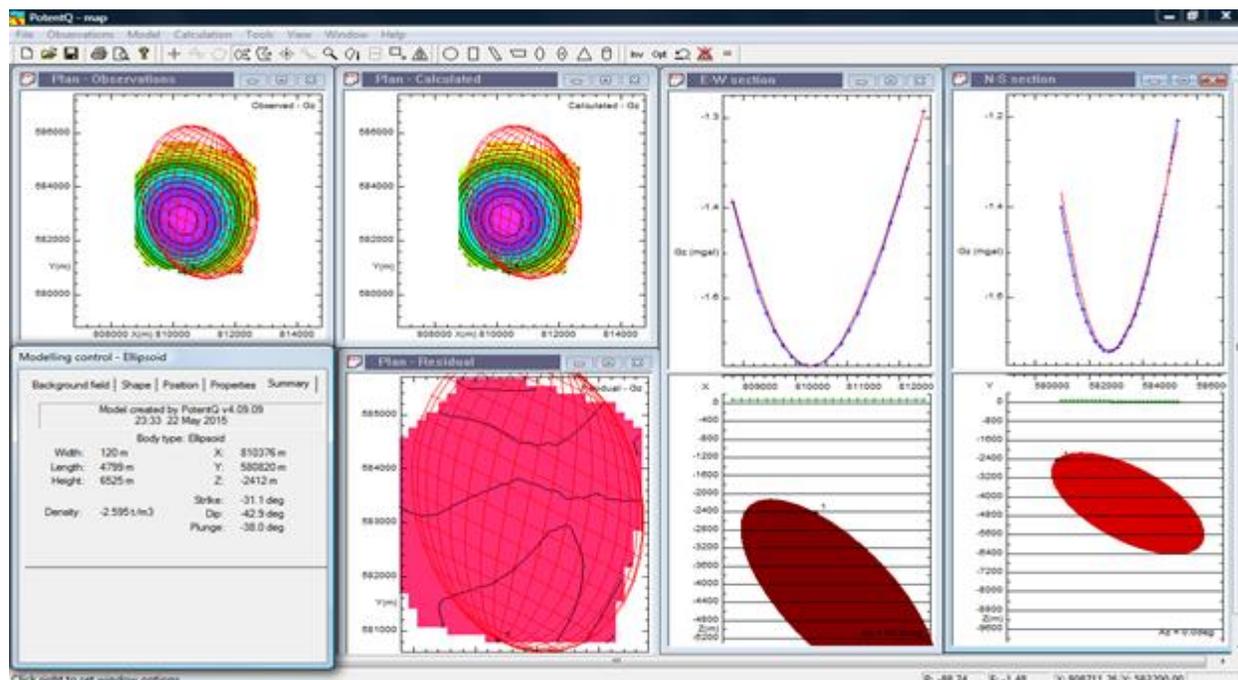
Figure 17. Forward and inverse modeling result of profile 4.

the Southeastern part of the study area (Figure 13). It lies approximately between 820000 and 835000 m Easting and 585000 and 595000 m Northings.

According to these gravity interpretation studies (Dobrin, 1976; Carmichael, 1984; Corine, 1996), the gravity profile in Figure 18 possibly depicts a faulted synformal geologic feature. The model (ellipsoid) revealed the density of the anomalous body to be 2.954 g/cm^3 and the depth to the anomalous body was revealed to be 3369 m (3.4 km).

The gravity signature shown by the model result suggests that the anomalous body is less dense than the surrounding bedrocks. The model result is shown in Figure 18. Table 1 is the summary of the modeling results.

Conclusion

Land gravity data of parts of the Niger Delta, Nigeria has been interpreted using Euler-3D deconvolution, source parameter imaging (SPI) and forward and inverse modeling techniques in order to study the possible cause of gravity anomalies in the area. Some of the results obtained from these interpretation techniques are in agreement with results obtained by some previous researchers who worked in the study area. Hospers (1965) revealed a sediment thickness of about 8 km in the

Niger Delta Basin and is similar to the depth obtained in this research (the maximum depths of 9.4 km from SPI, 9.2 km from Euler 3D deconvolution and 7.6 km from forward and inverse modeling).

Jacques et al. (2003) revealed major shale structures and faults within the Niger Delta Basin which were also revealed in this study. Ali et al. (2012) also revealed a depth to basement range between 0 to 10.7 km in the lower Niger Delta Basin which is similar to the depth range obtained in this research (1.3 to 9.4 km for SPI, 2.1 to 9.2 km for Euler 3D deconvolution and 0.8 to 7.6 km for forward and inverse modeling). Ezekiel et al. (2013) revealed grabens and faults in Njaba sub-basin in Imo state and such features were also revealed by this research.

Quantitatively, the results obtained from the SPI method showed a minimum to maximum depth of 1264.11 to 9354.57 m to the anomalous bodies. The results obtained from Euler-3D deconvolution showed a depth range of 2136.40 to 9167.57 m to the anomalous body using a structural index of 3. These results from the forward and inverse modeling as shown in Table 1 indicate a depth range of 793 to 7586 m. The estimated depths from the interpretation techniques employed fairly agree.

Qualitatively, the gravity signatures in profiles 1, 2 and 3 possibly depict antiformal geologic features whereas the gravity signatures in profiles 4 and 5 possibly suggest synformal features.
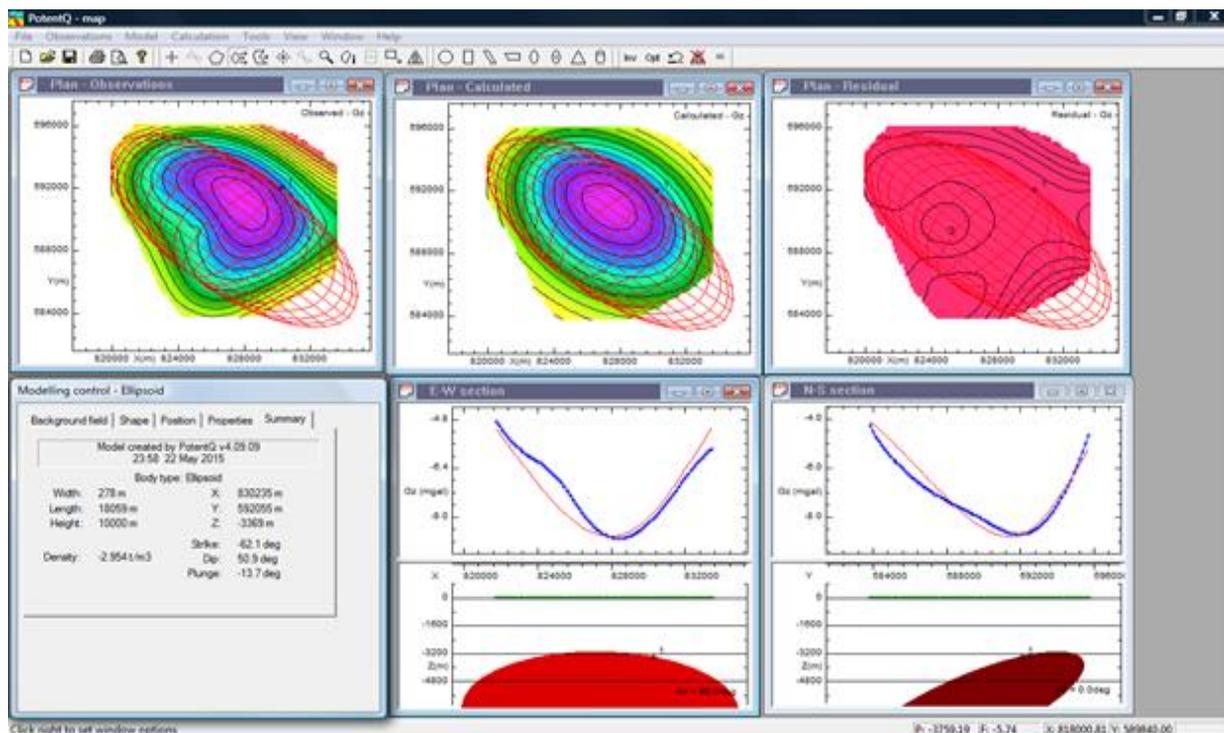
Figure 18. Forward and inverse modeling result of profile 5.

Table 1. Summary of the modeling result.

Profile	Model	Density of the anomalous body (g/cm^3)	Possible geological feature/structure describing the anomalous body	Depth (m)
1	Ellipsoid	2.387	Antiformal feature	5.609
2	Sphere	2.347	Antiformal feature	7.586
3	Rectangular prism	1.75	Antiformal feature	793
4	Ellipsoid	2.595	Simple synformal feature (basin structure)	2.412
5	Ellipsoid	2.954	Faulted synformal feature (graben)	3.369

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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