Mapping magnetic lineaments and subsurface basement beneath parts of Lower Benue Trough (LBT), Nigeria: Insights from integrating gravity, magnetic and geologic data

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In this study, we present the analysis of the aeromagnetic data of parts of the Lower Benue Trough. Lineament analysis of the aeromagnetic data demonstrated four tectonic trends of the basement terrain. The lineaments are in the northeast to southwest (NE–SW), east, northeast to west, southwest (ENE–WSW), north to south (N–S), and east, southeast to west, northwest (ESE–WNW) directions. The NE–SW and ENE–WSW are the most dominant whereas the N–S and ESE–WNW are the minor trends. The estimated magnetic basement using spectral analysis vary between 3.5 and 5 km and the shallow magnetic sources (depth to top of intrusions) vary between 0.24 and 1.2 km. The result of the basement estimation from the magnetic data is comparable with the previous results from other studies as well as with the basement depth estimated from the gravity data of part of the present study area are incorporated in the study. From the gravity data, we identified sub-basin around Makurdi and basement of the sedimentary basin (5 km) is estimated using GPSO algorithm and Oasis Montaj (Geosoft).

Keywords. Aeromagnetic data; Benue Trough; vertical derivative; magnetic lineaments; GPSO; inversion of gravity data.

1. Introduction

Magnetic measurements and interpretations play an important role in understanding the variations in earth's magnetic field resulted from the underlying basement rocks' magnetic properties (magnetic susceptibilities), geological structures and their geometric shapes and sizes (Abdelrahman *et al.* 2007, 2012; Abdelrahman and Essa 2015; Abo-Ezz and Essa 2016; Biswas 2016; Biswas and Acharya 2016; Essa and Elhussein 2017). At short wavelengths, the data reflect the susceptibility

changes that could be associated with the sedimentary rocks and at long wavelengths the magnetic anomalies could reflect the susceptibility changes in the underlying basement (metamorphic and basic igneous) rocks (Telford *et al.* 1998). Magnetic data allow us to delineate the lateral changes in susceptibility associated with the underlying structures and by doing so information about the structural trends and its lithological changes can be inferred. To delineate the subsurface structural features from magnetic data, numerous magnetic edge enhancing techniques have been developed

and used by many researchers (Nabighian 1972; Cordell and Grauch 1985; Roest *et al.* 1992; Phillips 1998; Verduzco *et al.* 2004; Salem *et al.* 2007).

Gravity method plays a vital role in recognition of sedimentary basins (Rao *et al.* 1994; Ali *et al.* 2014). There are varieties of techniques and methods for the interpretation of gravity anomalies over or due to sedimentary basins (e.g., Rao *et al.* 1993, 1994; Chakravarthi 1995; Chakravarthi and Sundararajan 2005). The structure of the sedimentary basins is often derived from the gravity anomalies with constant density contrast throughout the section of the basins (Bott 1960). However, the density contrast of sedimentary rocks is not practically constant (Rao *et al.* 1993, 1994; Chakravarthi 1995; Chakravarthi and Sundararajan 2005).

The Nigerian Benue Trough is of economic importance for its mineralization potential. It is an elongated rift system, which trends roughly in the NE–SW direction. It is bounded to the NE by the Chad basin and to the SW by the Niger Delta region. The origin of the trough was firstly proposed by King (1950). Stoneley (1966) and Wright (1968) put forward the graben origin of the trough relating it to the readjustment of the African plate after the Cretaceous opening of the Gulf of Guinea. The Benue Trough has been divided into three

sub-troughs, viz., the Upper Benue Trough (UBT), Middle Benue Trough (MBT) and the Lower Benue Trough (LBT) as shown in figure 1. The trough is filled in with Cretaceous sediments of Albian to Maastrichtian ages of 6 km in the Lower Benue Trough, 5 km in the Middle Benue Trough and 4 km in the Upper Benue Trough (Ofoegbu 1984; Ofoegbu and Onuoha 1991). Granites and gneisses made up the Precambrian crystalline basement rocks (figure 1) (Ofoegbu 1984). The intruded basement Quaternary volcanism consists of numerous granitic intrusive to thin dyke-like bodies and basaltic lavas (Nwachukwu 1972; Uzuakpunwa 1974; Olade 1978; Adighije 1981).

Number of published magnetic data (Anudu *et al.* 2014; Oha *et al.* 2016) have studied the basement structures beneath parts of the Lower Benue Trough (LBT). Anudu *et al.* (2014) and Oha *et al.* (2016) delineated five geological lineaments trending NE–SW, NW–SE, ESE–WNW, ENE–WSW and N–S. In this paper, we attempted revising the concealing basement structures beneath parts of the LBT using the high-resolution aeromagnetic data and interpreted in terms of the geological history of the region. We used qualitative analysis of the magnetic anomaly in order to extract the structural trends in our interpretation approach. We performed the spectral analysis and computed

Figure 1. Geological map of Benue Trough. Red box shows the study area.

the depths to the top of the causative sources over the study area. We interpret the estimated depth values in terms of the basement and shallow magnetic sources (intrusions). We have also done inverse modelling of the gravity data using GPSO and Oasis Montaj (Geosoft).

2. Geology and tectonics of the study area

The origin and sequence of events that lead to the development of the Nigerian Benue Trough have been well discussed and published by authors (King 1950; Stoneley 1966; Wright 1968; Nwachukwu 1972; Olade 1978; Benkhelil 1982, 1989; Ofoegbu 1984, 1985; Guiraud and Maurin 1992; Anudu *et al.* 2014). The study area (Lower Benue Trough) is underlain by deposited sequence of Cretaceous sedimentary rocks. Figure 2 depicts the geological map of the study area with the Cretaceous formations from the Asu River group up to the Nsukka formation been in order of their decreasing age. The Precambrian basement complex is made up of essentially, the granitic and magmatic rocks as can be seen from the eastern and the southeastern margin of the map (figure 2).

The Asu River group formed the oldest Cretaceous sediment in the region. 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 black shale, siltstone and sandstones whereas the Eze-Aku sandstone consists mainly of sandstones. Awgu Formation is made up of shale and limestone of Coniacian age. The Awgu Formation is overlain by the Nkporo Formation of mainly shale and mudstone. Bas-sange Formation consists of sandstones and ironstones, whereas the lower coal formation consists of coal, sandstones and shales. Nsukka Formation is made up of false-bedded sandstone of Campanian age.

The sediments are strongly affected by the intense compressional folding that occurred during the mid-Santonian tectonic episode leading to the production of the hundreds of anticlines and synclines (figure 2) (Nwachukwu 1972; Benkhelil 1989). This development is in connection to the complete orogenic cycle (sedimentation, magmatism, metamorphism and compressive tectonics) along this trough (Benkhelil 1988), which resulted

Figure 2. Sketch of the geological and tectonics of the study area (after Nigerian Geological Survey Agency 2009). The white dots shows the centre of blocks (e.g., B1, B2, ..., B25). The white line (P1P1') shows the location of profile for the 2D gravity inversion.

Figure 3. Sketch of the mineral resource map of the study area (after Nigerian Geological Survey Agency 2009).

to the numerous intrusive (mainly basalts) invaded the Awgu shale, Eze-Aku group and Asu River group (figure 2) (Ajayi and Ajakaiye 1981; Maluski *et al.* 1995; Anudu *et al.* 2014).

The Eze-Aku sandstone and the Albian Asu River shale are major host of lead–zinc, barite and fluorite and other metalliferous mineral deposits (figure 3) (Nwachukwu 1972; Akande *et al.* 1989; MMSD 2010).

3. Analysis of high-resolution aeromagnetic data

The entire country (Nigeria) is covered by high-resolution aeromagnetic data through Nigerian Geological Survey Agency (NGSA). The data for this area was therefore arranged officially from the agency. The data is in its digitised form. Figure 4 shows the total aeromagnetic intensity (TMI) map of the area. Direct interpretation of total magnetic intensity can be very complicated due to the fact that interferences from many surrounding magnetic sources (such as pipe lines, power lines and railways and so on) can contribute to the observed magnetic anomalies.

Reduction to pole (RTP) is an operator that can take care of asymmetric nature of the anomalies and transform them to symmetric form, reproducing the magnetic anomalies with their magnetization centred over their causative sources (Rozimant *et al.* 2009). Figure 5 shows the reduced to the magnetic pole (RTP) produced at geomagnetic inclination of 15° and amplitude correction of 40. The map shows anomalies that are correlated to known geologies. From the map, we demarcated the areas of high magnetic anomalies into thirteen zones superimposed on them, the geological units. As it can be seen from the RTP map, the zone H4, corresponds to the Precambrian basement rocks. The zones H3 and H6 correlated very well with the intrusions in the Aghila Hills (Ofoegbu and Onuoha 1991) and Workum Hills (Ofoegbu and Onuoha 1991; Oha *et al.* 2016), respectively. Zone H5 correlates with Eze-Aku shale injected by intrusive rocks. The Cretaceous sedimentary rocks around Makurdi and Oturkpo are intruded by basalts (Maluski *et al.* 1995). Therefore, the high magnetic anomalies H2 and H10 are observed to be very well correlated with the volcanic rocks intruded in the Eze-Aku sandstone around Makurdi down

Figure 4. High-resolution aeromagnetic map of the study area.

to an area southwest of Oturkpo area. Volcanic intrusion has also been reported few kilometres (around 12 km) north of Wannube (Ajayi and Ajakaiye 1981). The magnetic high, H1 could be due to the observed intrusions in association with lead–zinc (figure 3). The zone H7 does not correlate with any information on the present geological map, but may be due to some near surface intrusions around Igumale area (Oha *et al.* 2016). Zones H8, H9, H11 and H12 do not also correspond to information on the geological map. These could be interpreted due to an uplifted basement rocks. Zone H13 may be due to near surface basaltic lavas/sills and pyroclasts within the Cretaceous down to around Obangedde area (Anudu *et al.* 2014). The zones of low magnetic anomalies could be an area of thick Cretaceous sedimentary rocks.

3.1 Vertical derivatives (VD)

The partial derivative of magnetic data in the vertical direction is defined as what is referred to as

the vertical derivative. This derivative emphasize the local anomalies by enhancing the high frequency (or short-wavelength) anomalies and suppresses the low frequency (or long-wavelength) anomalies in potential field data (Dobrin and Savit 1988). The first and second order vertical derivatives can be calculated respectively using the relations below

$$VD = \frac{\partial^n F}{\partial z^n} = f^{-1} \{ |k|^n f(F) \}, \quad (1)$$

where F is the magnetic field, f and f^{-1} are the Fourier and inverse Fourier transforms, respectively and $|k|$ is the radial wave number. Here n is the order of the vertical derivative (Blakely 1995; Ekinici *et al.* 2013; Ekinici and Yiğitbaş 2015).

Figure 6 shows the first vertical derivative (FVD) map of the RTP–TMI of the study area. Superimposed on the map, the volcanic intrusions and the associated minerals in the area. We zoned the areas affected by the intrusions. Zone 1 is observed to correlate with the lead–zinc mineralization,

Figure 5. The reduced-to-pole map of the study area. The black line (P1P1') shows the location of profile for the 2D gravity inversion.

while zone 2 corresponds to an area of intrusions associated with lead–zinc. Zone 3 fall within an area of volcanic intrusions in association with barite and limestone. Zone 4 is due to intrusions associated with lead–zinc and barite. Zone 5 could be due to the Precambrian basement rocks associated with kaolin. Zone 6 correlates with intrusions and brine and barite. Zones 7, 9–13 do not correspond to any information on the geological map, but could be due to near surface intrusions associated with brine and limestone.

Figure 7 is the second vertical derivative (SVP) map of the RTP–TMI of the area. As on the FVD–RTP–TMI map, we have also superimposed on the SVD–RTP–TMI map, the volcanic intrusions and associated minerals found in the area. The SVD–RTP–TMI shows more emphases on the local anomalies and attenuated the signal due to the deeper features. On the map, we have also demarcated areas of volcanic intrusions and the associated minerals as in the case of the FVD–RTP–TMI (figure 6). These zones also

followed the same explanation as in the preceding paragraph.

Magnetic lineament analysis is carried out on the SVD map. This is done by observing the trends and amplitudes of the anomalies that matches the geological history of the region. Figure 8 shows the interpreted magnetic lineament derived from the present study. It shows the prominent NE–SW and ENE–WSW trends and the subordinating ESE–WNW and N–S trends. The lineaments could be interpreted as the edges of geological bodies and directions of structures which might have been in connection with the thermo-tectonic events and the evolution of the sedimentary basins in the region.

3.2 Spectral analysis

Spectral analysis is a much known technique for the estimation of basement depth to anomalous sources (Bhattacharyya 1965; Spector and Grant 1970; Garcia-Abdeslem and Ness 1994; Maurizio *et al.* 1998).

Figure 6. First vertical derivative map of the study area.

According to Blakely (1995), grid size of 5–6 times the expected depth is required for efficient estimation of depth to top of magnetic sources. On the basis of this, we have divided the RTP–TMI grid into 25 sub-grids (blocks) of 50×50 km with 50% overlap. Each grid is processed to remove the first order trend based on edge points using 10% square maximum entropy expansion. The logarithmic power of the spectrums against the wave number are obtained. The depth estimates of each section can be obtained by substituting the result of the slope of each of the section in the following relationship

$$z = \frac{-m}{4\pi}, \quad (2)$$

where m is the slope and z is the depth (Khalil *et al.* 2016). The estimated depth results are interpreted in terms of the magnetic basement and shallow (intrusive) basement. Figure 9 shows the power spectrum of four blocks, superimposed on them the estimated magnetic basement depth

(km) and the shallow depth (depth to top of intrusive) with respect to the mean sea level. We superimposed the estimated basement depth onto the geological map (figure 10) together with its contour plot. Table 1 shows the estimated basement depth and the shallow depth (depth to top of intrusive) bodies.

From the present magnetic data, we calculated the basement of magnetic sources between 2.1 and 6 km. The dominant basement depth within the area are 3.5 km observed in blocks (B17, B23 and B25) and 5 km observed in blocks (B8, B15, B18 and B19). The shallow depth values vary between 0.24 and 1.2 km. These depths are scattered and could be interpreted as the depth to top of intrusions at various location.

4. Analysis of airborne gravity data

Airborne Bouguer gravity data is collected for the study area from Nigerian Geological Survey Agency (NGSA). The data is acquired at a terrain

Figure 7. Second vertical derivative map of the study area.

Figure 8. Interpreted magnetic lineament from second vertical derivative map.

clearance of 80 m, along NE–SW oriented flight lines with 4000 m flight line spacing. The data is available in digitized sheet maps. The survey was

flown and corrected by Fugro Airborne Surveys in 2010. Figure 11 shows the complete Bouguer anomaly map of the study area. The observed positive gravity anomalies in this area could be interpreted due to the zones of intrusions and shallow basement (Cratchley and Jones 1965; Adighije 1981; Ajayi and Ajakaiye 1981; Agagu and Adighije 1983). The negative anomalies could be a signature of sedimentary basins or area of thick Cretaceous sediments.

4.1 Forward modelling

Here forward modelling is done to generate the synthetic gravity anomalies of given depth of sedimentary basin using equation given in Chakravarthi (1995), where density contrasts $\Delta\rho$ and parabolic density variation α are known. The analytical gravity expression $\Delta g(0)$ at any point on the principal profile of a 2D arbitrary shaped body with parabolic density contrast using polygon approach has been used (Talwani *et al.* 1959). The polygonal concept of parabolic density function is

Figure 9. Example plots of $\log(\text{power spectrum})/\text{wave number (rad/km)}$ of some blocks (B1, B14, B18 and B23) used in the study.

defined as (Rao *et al.* 1993, 1994; Chakravarthi *et al.* 2001)

$$\Delta\rho(z) = \frac{\Delta\rho_0^3}{(\Delta\rho_0 - \alpha z)^2}, \quad (3)$$

where $\Delta\rho(z)$ is the density contrast at any depth (z), $\Delta\rho_0$ is the density contrast extrapolated to the ground surface at $z = 0$ and α is constant.

4.2 Inverse modelling

4.2.1 Particle swarm optimization (PSO)

PSO (Kennedy and Eberhart 1995), a global optimization method, is one of the naturally inspired metaheuristic algorithms using the behaviour of bird flocks and fish schools searching for food (Pallero *et al.* 2015; Ekinici 2016; Essa and Elhussein 2018). The algorithm can be elucidated considering a community of N number of individuals (swarms) searching for exit door in the search space. Initially, each randomly positioned

individual has a velocity that controls its movement in search space. The velocity of an individual depends on its current position and best position achieved by the community in the search space. This method is generally considered simple in concept, easy to implement and computationally efficient (Eberhart and Kennedy 1995; Eberhart and Shi 2001; El-Kaliouby and Al-Garni 2009) having the advantage of not requiring any training, which is a significant time consuming step. The main objective of each individual is to reach the door as soon as possible. The distance between the individual and the door is analogous to the misfit function (RMS error) in the inverse problems. Each iteration updates the location of each individual that corresponds to possible model taking into account its best position achieved so far (P_{best} model) and the best position achieved by any individual of the community (G_{best} model). The velocity and position of the particle is updated using the following equations (Santos 2010; Roshan and Singh 2017)

Figure 10. Geotectonics sketch map showing the estimated magnetic basement values. Superimposed on it, is the contour map of the magnetic basement estimated in the area.

$$v_i^{k+1} = wv_i^k + c_1 \text{rand}^*(P_{\text{best}-i}^k - x_i^{k+1}) + c_2 \text{rand}^*(G_{\text{best}}^k - x_i^{k+1}) \quad (4a)$$

and

$$x_i^{k+1} = x_i^k + v_i^{k+1}, \quad (4b)$$

where, v_i^k is the velocity of i th particle at k th iteration, x_i^k represents current position of i th particle at k th iteration, $\text{rand}()$ is a random number in the range of 0 and 1. The constants c_1 and c_2 are known as cognitive and social coefficients, respectively and w is an inertia weight.

4.2.2 Global particle swarm optimization

Global particle swarm optimization (GPSO) algorithm is improved version of PSO that is efficient and capable of finding the global

optimal solution in very less number of iterations and also avoid trapping in local minima than the standard PSO (Jamian *et al.* 2014). The algorithm is a popular optimization method that is widely used in various applications, due to its simplicity and capability of obtaining optimal results (Jamian *et al.* 2014; Singh and Biswas 2016). Updating process of PSO uses only those G_{best} values having better results while remaining G_{best} values are terminated. This means that all G_{best} achieved in the previous iteration are not participating in taking decision for the current results. In GPSO, previous knowledge and experience guides to take accurate decision for optimum results. Therefore, G_{best} randomly selected among all the previous G_{best} values and used to update the velocity of the particle is called E_{best} . The acceleration coefficient for E_{best} is obtained by averaging cognitive and social constant parameter values. Thus, the new velocity that updates the next position of the particle is given as:

Table 1. *Estimated basement depth*

Block number	Depth (magnetic basement) (km)	Shallow depth (km)
B1	5.3	0.79
B2	3.9	0.3
B3	2.3	0.33
B4	4.4	0.65
B5	3.4	–
B6	4.6	0.28
B7	5.1	0.85
B8	5.0	0.29
B9	5.9	0.31
B10	4.4	0.42
B11	3.4	0.25
B12	4.1	0.24
B13	6.0	0.7
B14	4.8	0.28
B15	5.0	0.27
B16	4.2	–
B17	3.5	0.66
B18	5.0	0.82
B19	5.0	0.29
B20	4.6	0.25
B21	2.3	0.32
B22	2.1	0.61
B23	3.5	1.2
B24	3.2	0.34
B25	3.5	0.24

$$v_i^{k+1} = wv_i^k + c_1 \text{rand}_{()}^*(P_{\text{best}-i}^k - x_i^{k+1}) + c_2 \text{rand}_{()}^*(G_{\text{best}}^k - x_i^k) + c_3 \text{rand}_{()}^*(E_{\text{best}}^k - x_i^k), \quad (5a)$$

where the last term is called improvement factor defined as (Jamian *et al.* 2014):

$$IF = c_3 \text{rand}_{()}^*(E_{\text{best}}^k - x_i^k) = \left[\frac{c_1 + c_2}{2} \right] * \text{rand}_{()}^*(E_{\text{best}}^k - x_i^k). \quad (5b)$$

There is a conceptual difference between E_{best} and G_{best} . The G_{best} values for the current iteration are determined by successive comparison of previous G_{best} values. Therefore, the possibility of having similar G_{best} values is zero, whereas E_{best} is randomly chosen value among the G_{best} values. Here IF significantly helps the algorithm to find next accurate particles' position. Thus IF and E_{best} makes the algorithms more powerful and efficient

tool to fast convergence that improves the results obtained from PSO.

The RMS error is calculated from the following equation (Santos 2010)

$$\text{misfit}(\%) = \frac{100}{N} \sqrt{\sum_i^N \left(\frac{v_i^o - v_i^c}{v_i^o} \right)^2}, \quad (6)$$

where N is the number of iteration, v_i^o and v_i^c are the observed and GPSO calculated gravity anomaly, respectively.

4.3 Description of the main program

The computer program inverSEDP for GPSO method has been developed in MATLAB environment to invert the gravity anomalies of density interfaces with parabolic density contrast. The input to the program consists of the number of observations (n), the density contrast observed at the ground surface ($\Delta\rho$), the constant alpha (α) of the parabolic density function, the distance (x) and observed gravity anomaly (g_{obs}) at each anomaly point. The GPSO technique requires upper and lower search range of depth and an arbitrary depth values between the search range, number of iterations and number of models and learning parameter as inputs. The program calculates forward models in given search bound then compare with the previous models and if present model is more accurate and close to the true model then save it. In this way, it minimizes the misfit error. forwardgrav, alter, change, mod, objective, output, gr2dpol used as function file of the program. The gr2dpol function file used to calculate theoretical gravity anomalies of a density interface at each anomaly point on the profile and return to the main program. The process continues until the specified number of iterations is completed. The output consists of the depth of the density interface in km and the calculated anomaly in mGal.

4.4 Application of global particle swarm optimization to synthetic gravity anomalies

Initially, both algorithms, PSO and GPSO were performed and compared their performance on synthetic gravity anomalies at 100 independent iterations after the tuning of the PSO learning/controlling parameter (i.e., c_1 , c_2 , c_3 and w). The learning parameter values have been taken

Figure 11. Complete Bouguer anomaly map of the study area. The line P1P1' shows the profile taken for the 2D inversion.

Figure 12. Convergence performance of PSO and GPSO.

$c_1 = c_2 = c_3 = 1.4$ and $w = 0.7$ for our case. We have used 100 models for both cases. Figure 12 shows the convergence performance of PSO and GPSO. It is clear from the figure that GPSO converges faster than the PSO. PSO converged at 84 iterations with RMS error of 0.089% whereas GPSO converged at 16 iteration with RMS error

of 0.0017%. On the basis of their performance, GPSO was validated and tested on synthetic gravity anomalies and then applied to field gravity anomalies over parts of Lower Benue Trough, Nigeria.

Introducing density contrast for different depth $\Delta\rho(z)$, depth of the basin (z) and value of parabolic density constant (α), we calculated the synthetic gravity anomalies at different depth points on the principal profile.

In generating the gravity anomalies along a profile, we assigned the value of density contrast on the surface $\Delta\rho_0 = -0.65 \text{ gm/cm}^3$ and constant $\alpha = 0.2 \text{ gm/cm}^3/\text{km}$ of the parabolic density function. The density contrast variation with depth has been calculated by equation (3) and then synthetic gravity anomalies have been generated using the equation as proposed by Rao *et al.* (1993). The profile length of 9.5 km has been taken for the study. Thirteen data points have been taken at 0.5 and 1.0 km interval alternatively. Now GPSO method has been applied over synthetic gravity anomalies

Figure 13. Synthetic gravity anomaly and GPSO inverted anomaly of the sedimentary basin and corresponding depth (km). RMS error = 0.028.

Figure 14. 2D inverted gravity anomaly along P1P1' using GPSO.

of the basin to test the algorithms. The synthetic anomalies and GPSO inverted anomalies have been plotted in the same figure 13 and the corresponding depth section has been shown in subplot just below the anomaly plot.

4.5 Application to field data

We applied GPSO method over the airborne Bouguer gravity data of the parts of Lower Benue Trough, Nigeria to find out the basement depth of sedimentary basin. Figure 11 shows the location of P1P1' profile taken at one kilometre interval. We applied GPSO algorithm to find the depth of

basement of sedimentary basin over the profile. The density contrast variation taken for P1P1' is $\Delta\rho_0 = -0.27 \text{ gm/cm}^3$ and density contrast variation is $\alpha = 0.015 \text{ gm/cm}^3/\text{km}$. We applied the proposed algorithms and the maximum depth has been calculated (5.25 km) with RMS error of 0.25 (figure 14). The optimized depth, observed and calculated gravity anomalies has been shown in figure 14. Using the depth information calculated by GPSO method and density information we have done 2D modelling by Oasis Montaj 8.1 (Geosoft). The maximum depth (5 km) obtained by Geosoft also supports the depth calculated by the GPSO method (figure 15).

Figure 15. 2D inverted gravity anomaly along P1P1' using Geosoft.

5. Discussion and conclusions

Analysis of the high-resolution aeromagnetic data of the present study area in relation to the geological information, could be interpreted that, the high magnetic anomalies observed in the area correlated to zones of volcanic intrusions (Ofogebu 1984). The intrusions (at various depth) appeared to spread over almost 70–75% of the area beyond their exposure on the geological map. The intrusions invaded the Cretaceous sedimentary rocks and could also be found within the basement rocks (Ofogebu 1984). The intrusions could be the contributing factor to the positive gravity anomaly observed in the area (figure 11) (Cratchley and Jones 1965; Adighije 1981; Ajayi and Ajakaiye 1981).

The analysis of magnetic lineaments from the derivative aero-data revealed the dominant NE–SW and ENE–WSW trends of lineaments and subordinate N–S and ESE–WNW trends (figure 8). The dominant NE–SW trends were observed by (Anudu *et al.* 2014; Oha *et al.* 2016) in their studies around the north–south and eastern part of this area. The NE–SW trends are interpreted to correlate with the deep seated faults (Oha *et al.* 2016), which may have been reactivated by NE–SW sinistral shear during the opening of the trough (Guiraud and Maurin 1992; Anudu *et al.* 2014).

The NE–SW trend is paralleled to the trough's orientation and it is assumed to control the dextral shear zones of the late Pan-African age (Maurin *et al.* 1986; Anudu *et al.* 2014). The NE–SW trends could be interpreted as the NE–SW trending Neoproterozoic tectonic units of the Brasiliano/Pan-African orogen (de Castro *et al.* 2012; Anudu *et al.* 2014). The ENE–WSE trends were also observed and delineated in (Anudu *et al.* 2014). The trends represent the mega shear zones in Africa called the Central African Shear Zone (CASZ), which resulted from the important tectonic movements that occurred during the Pan-African orogenic cycle (Moreau *et al.* 1987). The ENE–WSW is also a dextral shear zone that is related to the wider mylonite belts pre-dating at the Cretaceous times, the opening of the South Atlantic Ocean (Jorgensen and Bosworth 1989; Djomani *et al.* 1995). The N–S lineaments are minor trends. Anudu *et al.* (2014) in their studies in the lower and middle parts of Benue Trough also delineated the N–S lineaments and suggested them as the minor trends in the area. Their formation may be associated to either the migration of the African plate over the mantle plume or shear movements along the pre-existing ENE–WSW faults in the Pan-African basement (Djomani *et al.* 1995).

We have estimated the basement depth of magnetic sources from the RTP–TMI of the

high-resolution aeromagnetic data of lower Benue Trough using spectral analysis. The basement depth estimated from the magnetic data vary between 3.5 and 5 km. Basement depth from other studies showed depths between 2 and 3 km (Benkhelil 1988) around Ogoja from gravity data. Ofoegbu and Onuoha (1991) estimated the basement depth of 1.5 and 2.5 km around the same Ogoja from magnetic data. In our present study, we estimated the basement depth of 3.4 km north of the Ogoja area. Oha *et al.* (2016) from magnetic data of parts of the present study area, estimated the basement depth of 2.14 km south of block (B1) where we estimated the basement depth of 5.3 km. They also estimated depths of 2.29 and 2.88 km corresponding to block (B3) in the present study (2.3 km) and depth of 3.64 km corresponding to block (B4) in which we estimated the basement depth of 4.4 km.

From the airborne Bouguer gravity data of parts of the study area, we identified sub-basins around Makurdi over the gravity low. The low gravity correlates with low magnetic anomaly (figure 5). The depth to basement of the sedimentary basins are estimated using GPSO algorithm and Geosoft. The basement of the sedimentary sub-basin around the Makurdi is estimated as 5.25 km using GPSO and 5 km using Geosoft. This profile is between blocks (B16, B17 and B25) on the magnetic data (figure 2). The depth estimated within these blocks vary between 3.5 and 4.2 km.

High-resolution aeromagnetic data can be very useful for hydrocarbon as well as mineral exploration. In the present study, we present a more detailed interpretation of the magnetic data of this area in terms of the real geology of the area.

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