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Evaluation of basement topography and structures in the Dahomey Basin and surrounding environs of Southwestern Nigeria, using satellite gravity data

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ABSTRACT

Attempts at regional gravity studies of the southwest Nigerian geologic terrain have been limited due to sparse distribution of gravity stations and prohibitive costs of gravity measurements. The use of satellite-based global gravity data provides a reliable and cost-effective means of regional-scale studies, and the WGM2012 gravity data was employed to evaluate the basement topography and structures. The aim of the work is to map regions in the Nigerian sector of the Dahomey Basin with suitable sediments thickness and fracture systems, capable of hydrocarbon generation and preservation. The Bouguer anomaly data was subjected to series of processing and anomaly enhancement, using the Oasis Montaj software. Observations of anomaly distributions reveal division of the study area into three geologic zones, namely, basement terrain, Dahomey Basin and Niger Delta Basin. The basement structures trend in a general north–south directions, but approximate orientations vary significantly, with abundance of sub-parallel and discordant alignments. The depths to basement range from <2000 to >5000 m, with the southwest being the deepest part of the study area. The results establish the Dahomey Basin as containing the minimum required sedimentary thickness of 3000 m and suitable structures necessary for hydrocarbon generation and accumulation.

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Dahomey basin; satellite; gravity; basement topography; Nigeria

1. Introduction

Gravity measurements in Nigeria are sparsely distributed and the recent effort of the Federal Government of Nigeria in acquiring airborne gravity data of the entire country is yet to achieve its goal of covering every parts of the country. The coverage areas, from north to south include north-central Nigeria, a small portion of south-west Nigeria and the Niger Delta. The purpose for which the acquisitions were made from 2003 to 2010 (NGSA 2005) was to boost the mining industry and support hydrocarbon exploration efforts in the inland basins. In order to deal with coverage gaps and lack of data acquisitions over large areas, global gravity field models are of great importance (Hirt et al. 2013; Sobh et al. 2019). Several global gravity field models exist, and they incorporate data from satellite gravimetry, satellite gradiometry, satellite altimetry and terrestrial gravimetry.

The World Gravity Map (WGM2012) satellite based combined global gravity field model (Bonvalot et al. 2012; Förste et al. 2014; Gilardoni et al. 2016) was utilised for this work. The publicly available Bouguer anomaly data was used in this basin-wide study as the preponderance of long wavelengths in the data makes it very suitable for study large-scale geologic features. Global satellite-based gravimetry was implemented for this study as it provides data points that are evenly distributed all over the study area. The preponderance of long wavelengths in the data also makes it ideal for mapping the large-scale basin floor configuration and for mapping of large-scale geologic structures in the basin, such as the well-discussed Okitipupa Ridge basement uplift.

The Nigerian sector of the Dahomey Basin is a petroliferous basin, with Lower to Upper Cretaceous potential source rocks (Ola and Olabode 2017). However, hydrocarbon prospect of the basin is still limited due to paucity of geologic information, as a result of basin studies that are limited in scope and coverage, due to gaps in data coverage. The consistent data coverage over the entire study area provided by the WGM2012 gravity data will make it possible to derive geological and geophysical interpretations that are presently not possible with available airborne and ground-based data. The purpose of this study is to identify regions within the basin with the required minimum 3000 m thickness of sediments deposition necessary for hydrocarbon generation (Osinowo and Olayinka 2013). The objectives include delineation of basement topography and structures, basin geometry and sediments thickness. This could open up previously unexplored parts of the basin to exploration.

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2. Location and geology of the study area

The study area is located within longitude 2° 30′ E – 6° 00′ E and latitude 6° 00′ N – 7° 30′ N. This covers the southern areas of the basement terrain of southwestern Nigeria, the Nigerian sector of the Dahomey Basin and western parts of the Niger Delta Basin. The study area covers Lagos, Ogun and Ondo states. In addition, the study area stretches eastward into Edo state which is in the south–south geopolitical zone.

The geologic map of the study area, produced from surface expression of outcrops and sediments is presented in Figure 1. The geologic landscape can be divided into almost equal halves of basement and sedimentary terrain. The basement terrain occupies the northern half of the study area and is composed of Precambrian granite, gneiss, migmatite, quartzite and schist. The basement geology is complex and highly fractured. The sedimentary terrain occupies the southern half of the study area and the surface sediments include Cretaceous sands and Tertiary-Recent sands, clay and alluviums (Okosun 1998; Obaje 2009).

The Dahomey Basin contains Cretaceous – recent sediments and the stratigraphic assemblage (Okosun 1990, 1998) consist of the Abeokuta sands unconformably overlying the Precambrian basements. The sands contain clay and shale interbeds, which are then overlain by the predominantly shaly Afowo Formation. The Ewekoro Formation overlies the Afowo Formation and it is famous for limestone deposits. The indicated Ilaro Formation forms part of the Oshosun Formation, which contains a diverse assemblage of sands, shales, clay/mudstones and some limestones. The uppermost and youngest formation is the Benin Formation. The formation is often referred to as the Coastal Plain Sands, and they are grouped together with alluvial deposits. The lithology includes sand and clay deposits.

3. Methodology

The datasets used for this work include the WGM2012 combined gravity field model acquired from the Bureau Gravimetrique International (BGI) and elevation data in the form of the ETOPO2 digital terrain model (DTM).

3.1. Data analysis and processing

The software used is Geosoft Oasis Montaj 8.4 version. WGM2012 Bouguer anomaly data used was provided with 2-arc minute resolution and was re-gridded with a cell size of 1000 m. The radially averaged power spectrum of the data is presented in Figure 2. The spectrum is divided into three parts, namely the

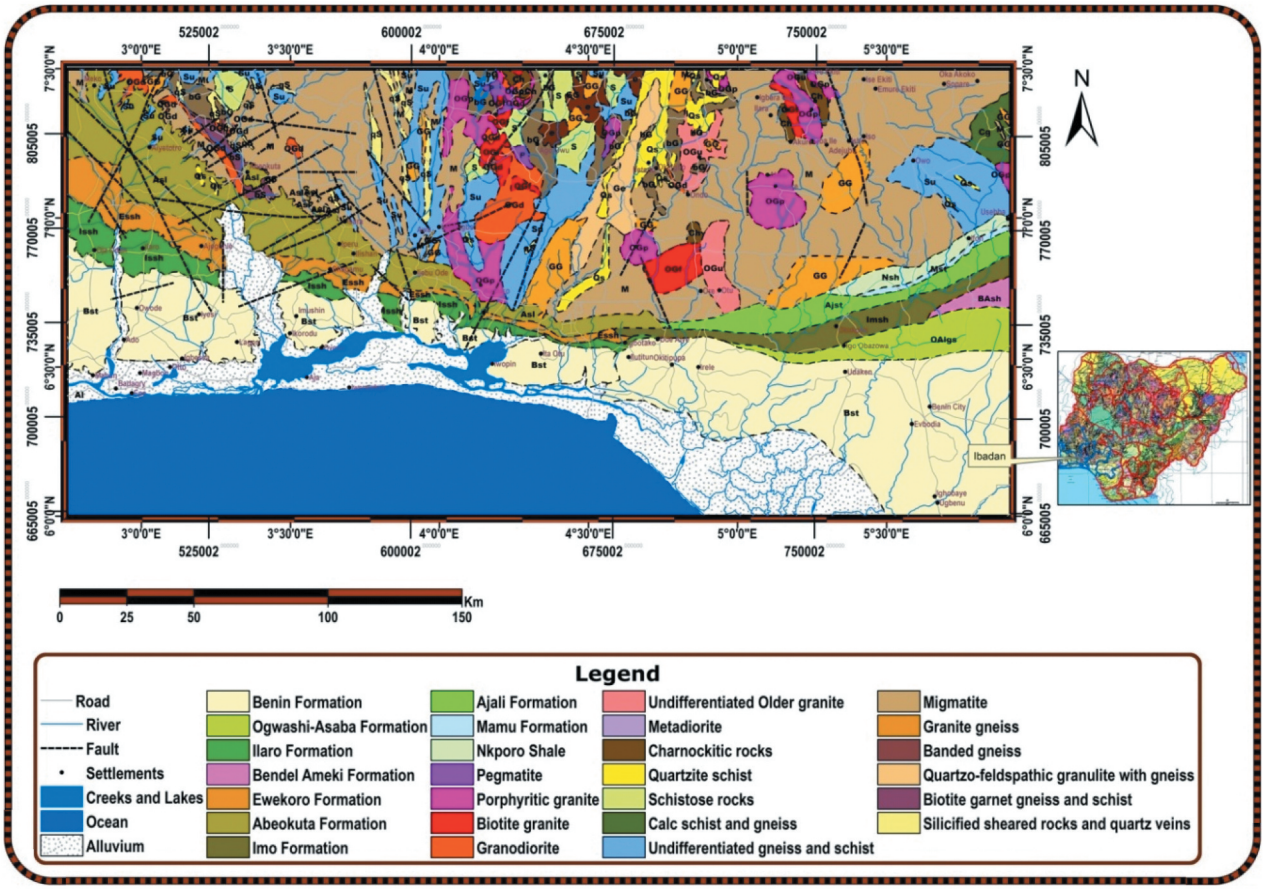

Figure 1. Geologic map of the study area.

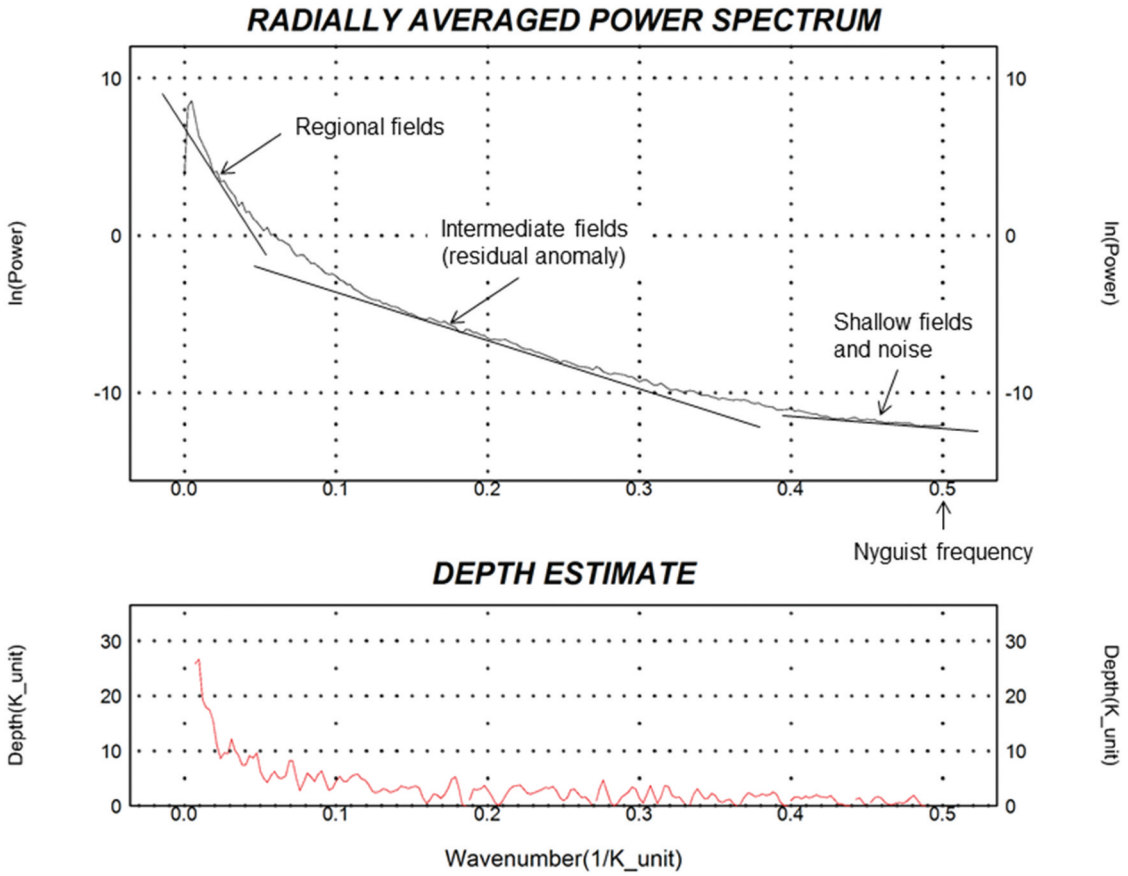

Figure 2. Radially averaged power spectrum of the Bouguer anomaly data.

regional fields, the intermediate fields and the shallow fields, which also contain the noise signals. Estimated depths to source bodies range from <2 to >10 km. Noise and unwanted regional fields in the data were removed simultaneously with the Butterworth band-pass in the wavenumber domain. The short wavenumber cut-off used is 0.0001 m^{-1}, while the long wavenumber cut-off used is 0.00001 m^{-1}. This corresponds to a short wavelength of 10 km and a long wavelength of 100 km.

3.1.1. Basement structures and lineament mapping

The derivatives calculated include x, y, z and total horizontal derivatives. The total horizontal derivative is the vector sum of the x and y derivatives. The tilt derivative was also calculated and is equal to arctan of ratio of vertical (z) to total horizontal derivatives. The derivatives were used in the mapping of shallow basement structures, such as contacts, fractures and other lineament features. The analytic signal was calculated from the x, y and z derivatives. The analytic signal, as used in this work is the vector sum of the horizontal (x and y) and vertical (z) derivatives. The results are used for structural and geologic discrimination. The Centre for Exploration Targeting (CET) University of Western Australia grid analysis algorithm was used for lineament mapping. The algorithm analyses the tilt derivative grid and phase symmetry, involving identification of axes of symmetry. In order to identify points of symmetry in the 2D data, the data is first broken into 1D profiles and analysed over multiple orientations at varying scales. The resultant solution plots are curves, which are then vectorised into straight lines. Lines less than 5 km in length were rejected.

3.1.2. Depth to basement – Euler deconvolution

Estimation of depths to basement was carried out using the 3D Euler deconvolution method (Reid et al. 1990; Zhang et al. 2000). The target depth range was 0 to 10,000 metres (Avbovbo, 1980; Whiteman 1982; Brownfield and Charpentier 2006; Osinowo and Olayinka 2012; Kaki et al. 2013; Osinowo et al. 2014; Ola and Olabode 2018), and attempts were made to use various window size ranging from 2000 to 10,000 m. In the initial calculations, the maximum percentage depth tolerance (dZ) was set to 25%. The solutions were windowed (reduced) with variable parameters in order to eliminate spurious values.

The accepted solutions were generated using a cell size of 1000 m and window size of 10,000 m. The structural index used is 0.0, for dyke model in gravity solutions, which fits the well-publicised presence of ridges and block faulting in the Dahomey Basin. Parameters used for reducing the number of solutions

include maximum percentage depth tolerance (dZ), maximum percentage location tolerance (dXY), maximum/minimum depths and x/y offsets, which represent the horizontal (x and y) distances of individual solutions from the centre of the Euler window. The solutions were windowed to dZ of 15%, dXY of 25%, X-Offset of ± 5000 m and Y-Offset of ± 5000 m.

The remaining solutions were plotted using zone coloured plot, as is the customary practice with 3D Euler solutions. Topographic correction of the depth solutions were done, using ETOPO2 2-Arc Minute digital terrain model (DTM). The depth values were then gridded, using universal Krigging, with 5000 m cell size, and later filtered with a single pass 3 × 3 convolution smoothening filter, using Hanning method. Smoothening filter was applied to attenuate extreme values or spikes. The eventual results were validated with well depths.

Upon scrutinising the depth solutions with well depth data, the solutions were discovered to be generally too deep. In order to reduce the average depths, an high pass filter was used to remove signals with wavelengths longer than 100 km from the gravity data (Reid et al. 2014). This involved applying the Gaussian Residual filter, with a cut-off wavelength of 100 m. The solutions obtained afterwards are generally more reasonable, although they are still deeper than they should be within the basement terrain, north of the study area.

4. Results and interpretations

The qualitative interpretation of the Bouguer anomaly data permits the discrimination of the geologic terrain, based on variation in rock density, sizes and relative depth. These are observed on the grid maps as variations in amplitude attributes and dominant wavelengths. The mapping of geologic zones, geologic contacts, lineaments, basement topography and basin architecture are done quantitatively.

4.1. Bouguer anomaly distribution

The Bouguer anomaly distribution across the study area is presented in Figure 3. The map indicates the anomaly values range from 77 to 210 mGal, with the values decreasing from west to east. The study area is divided along a north–south boundary around longitude 670,000 m into eastern and western parts. The western part has a relatively higher Bouguer anomaly values (>140 mGal) than the eastern part (<135 mGal). The western half shows anomaly values increasing from north to south, with the values exceeding 155 mGal in the southwest where the Dahomey Basin is located. The eastern half, however, shows a decrease in anomaly values from north to south, with the southeast part, where the Niger Delta Basin is located, dominated by values less than 127 mGal.

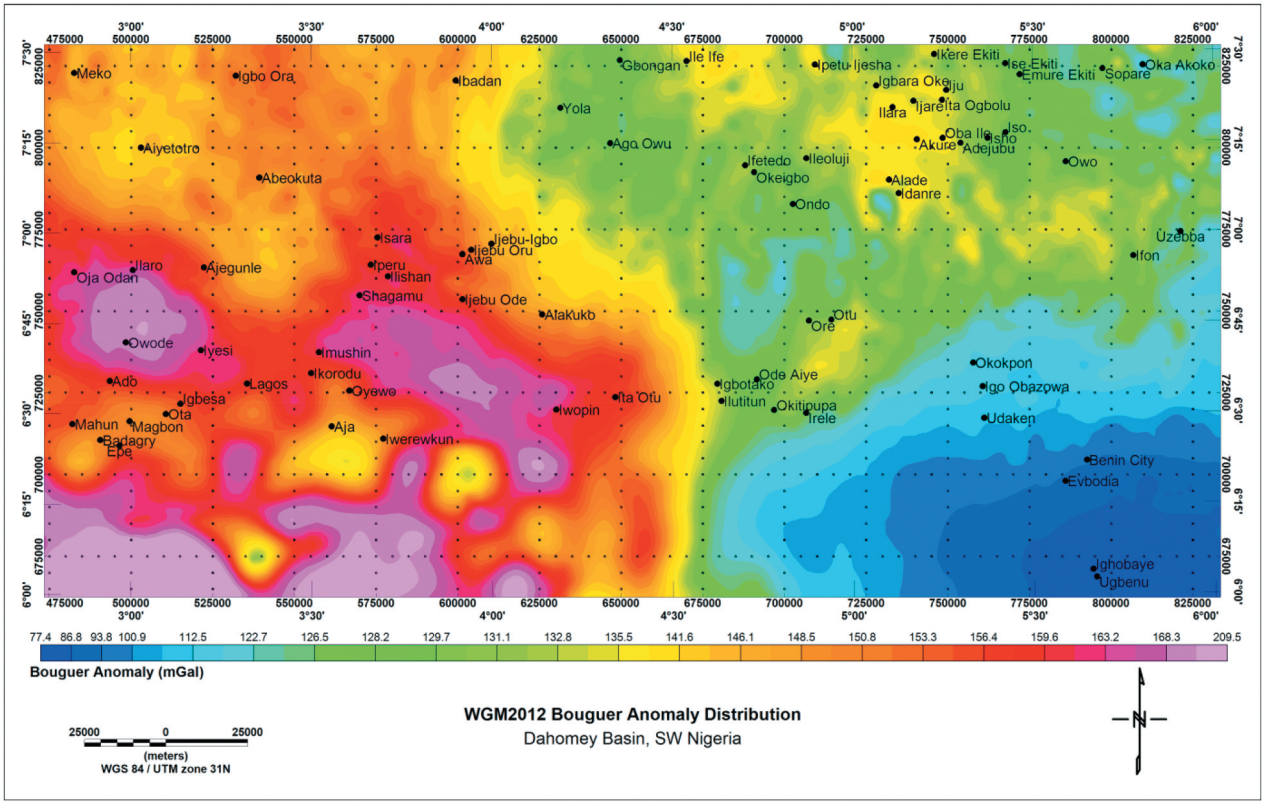

Figure 3. Bouguer anomaly distribution.

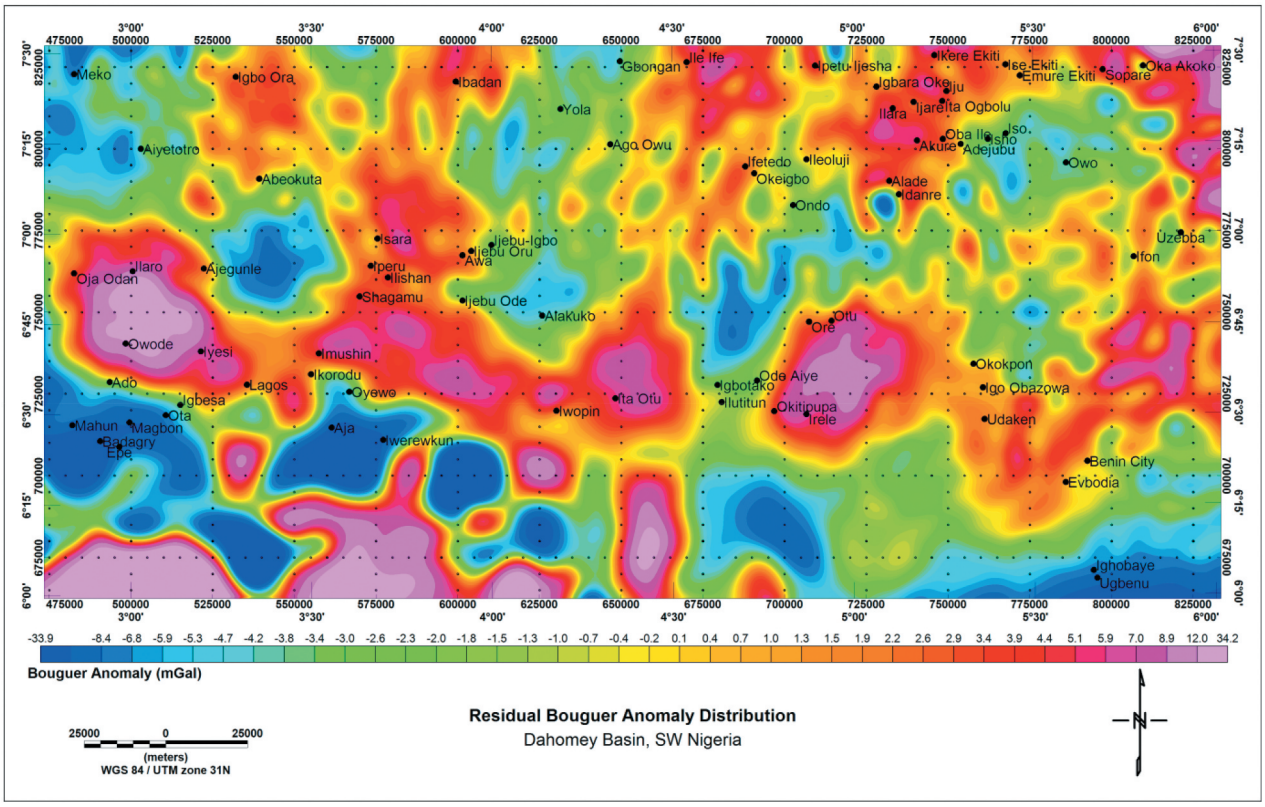

Figure 4. Residual Bouguer anomaly distribution.

4.2. *Residual Bouguer anomaly distribution*

The residual Bouguer anomaly distribution is presented in Figure 4. The map displays a wide variation in Bouguer anomaly values, with the values ranging from −34 to 34 mGal. The distribution of the anomalies depicts the division of the study area into basement terrain in the north and sedimentary terrain in the south. The basement terrain displays anomalies of

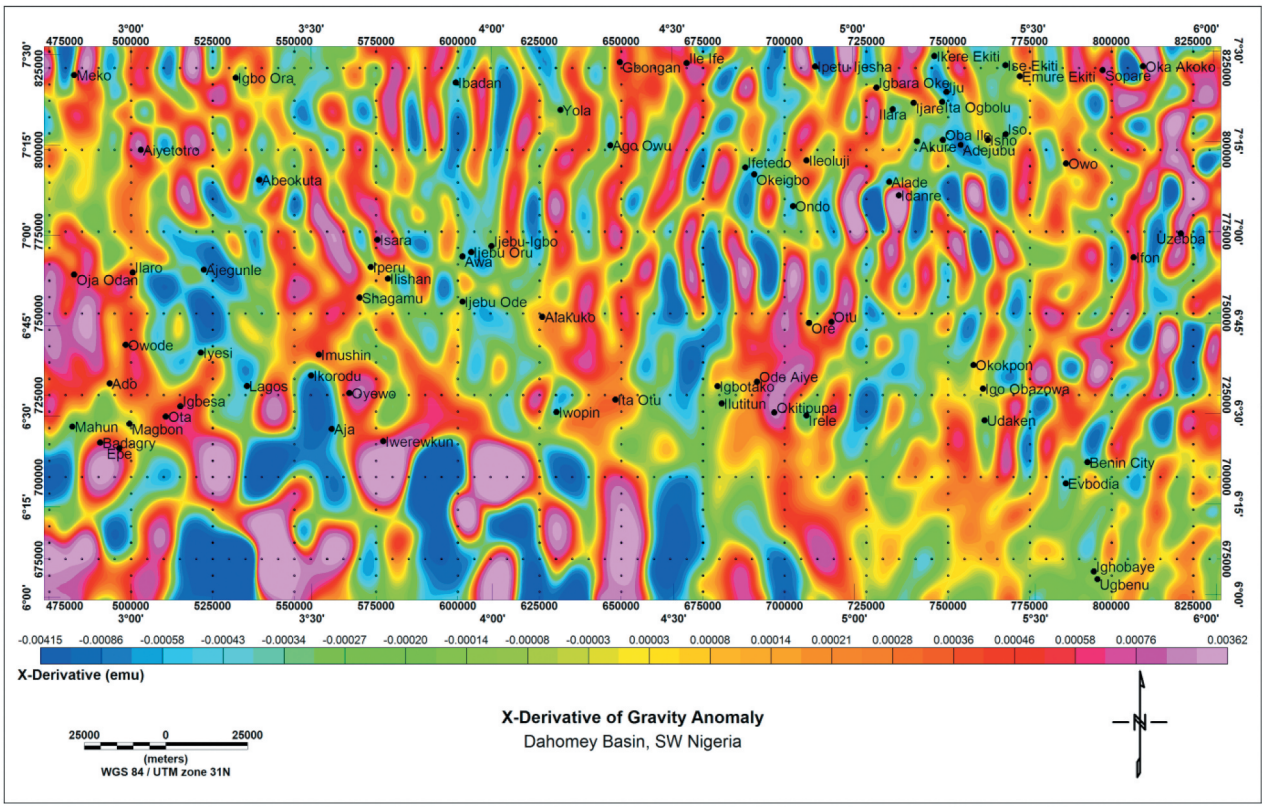

Figure 5. X-derivative of gravity anomaly.

relatively shorter wavelengths, with the values ranging from −10 to 10 mGal. The sedimentary terrain is dominated by anomalies of relatively long wavelengths and wide amplitude range of −34 to 34 mGal, with the Dahomey Basin in the southwest exhibiting a high-density contrast. The west–east trending anomaly zone (2–25 mGal) in the middle of the map corresponds to the basement/sedimentary transition zone of the study area.

4.3. Horizontal derivatives distribution of Bouguer anomaly

The horizontal derivatives maps are presented in Figures 5–7 and they serve the purpose of amplifying structured anomalies, which permits mapping of contacts, ridges and lineaments. The x-derivative map (Figure 5) vividly shows the general north–south trend of the basement rocks. The elongated features are mostly well defined within the basement terrain in the north and less developed in the sedimentary terrain in the south. The positive anomalies in the north of the study area mostly terminate within the basement/sedimentary transition zone. The prominent NE-SW trending positive anomalies in the central and eastern parts, corresponds to areas, previously identified in previous works to be dominated by regional fractures, such as the Ifewara-Zungeru fault and the Chain Fracture Zone (Oluyide and Udoh 1989; Ola and Olabode 2018).

The y-derivative map (Figure 6) shows the general east–west trend that is typical of y-derivative maps. The south–west Nigeria basement terrain rocks basically trend north–south, thus the prominent NNE-SSW trending ridge-like features in the southern and north-central areas of the map are typical of the basement terrain. The NE-SW trending positive anomaly within the south-central of the map around Okitipupa and Irele, correspond to the area defined by the Okitipupa ridge (Omatsola and Adegoke 1981; Coker et al. 1983; Ola and Olabode 2018). The prominent east-west trending region of negative anomalies (< −0.0003 emu) extending from around Oja-Odan/Ilaro to Ore/Otu possibly correspond to the areas defined as the shallow basement transition zone (Osinowo and Olayinka 2013).

The total horizontal derivatives map (Figure 7) produce results similar to that of the x-derivative, thereby confirming the general north–south trend of the basement structures. The total horizontal derivative map also displays high anomaly contrast within the Dahomey Basin in the southwestern part of the study area, as was the case on the x and y derivative maps. The trace of the Dahomey Basin boundary can thus be established from the three horizontal derivatives map, extending from the western edge of the map at around latitude 780,000 m, through Iwopin, to the southern edge around longitude 710,000 m.

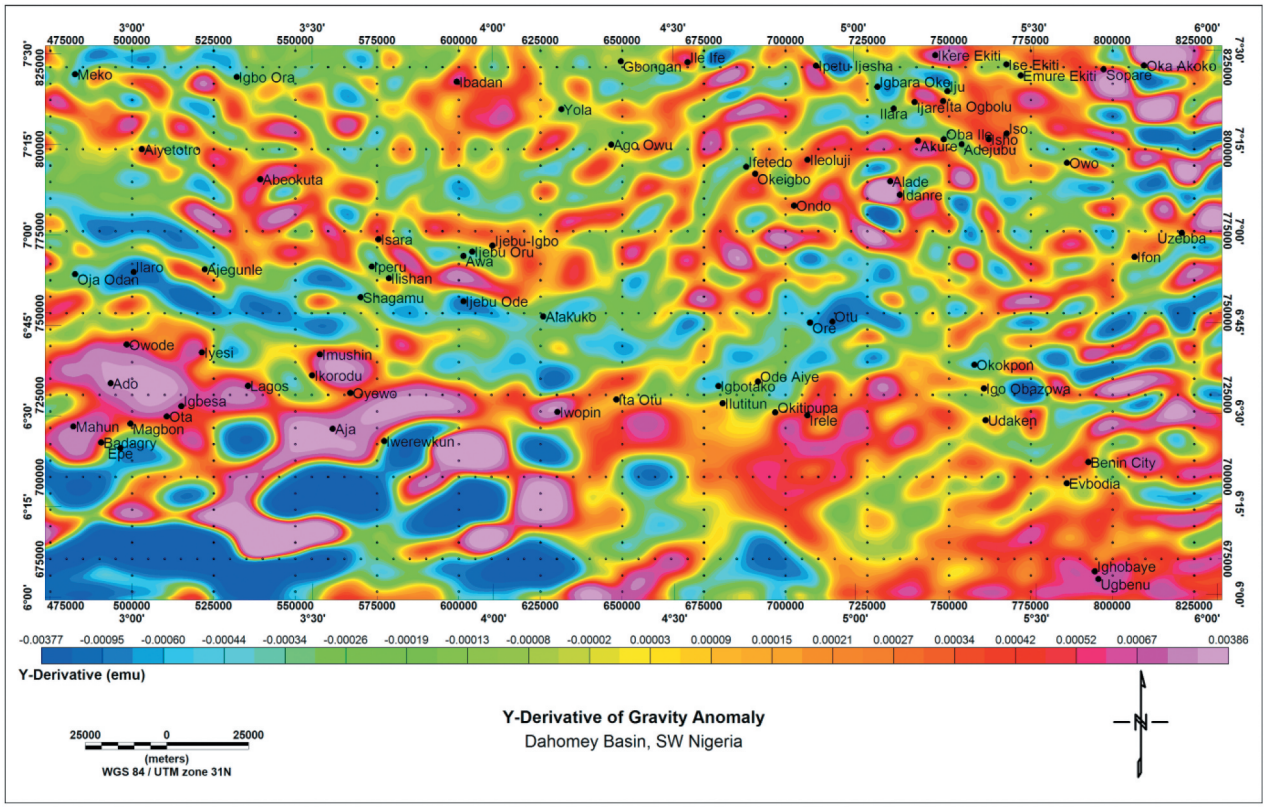

Figure 6. Y-derivative of gravity anomaly.

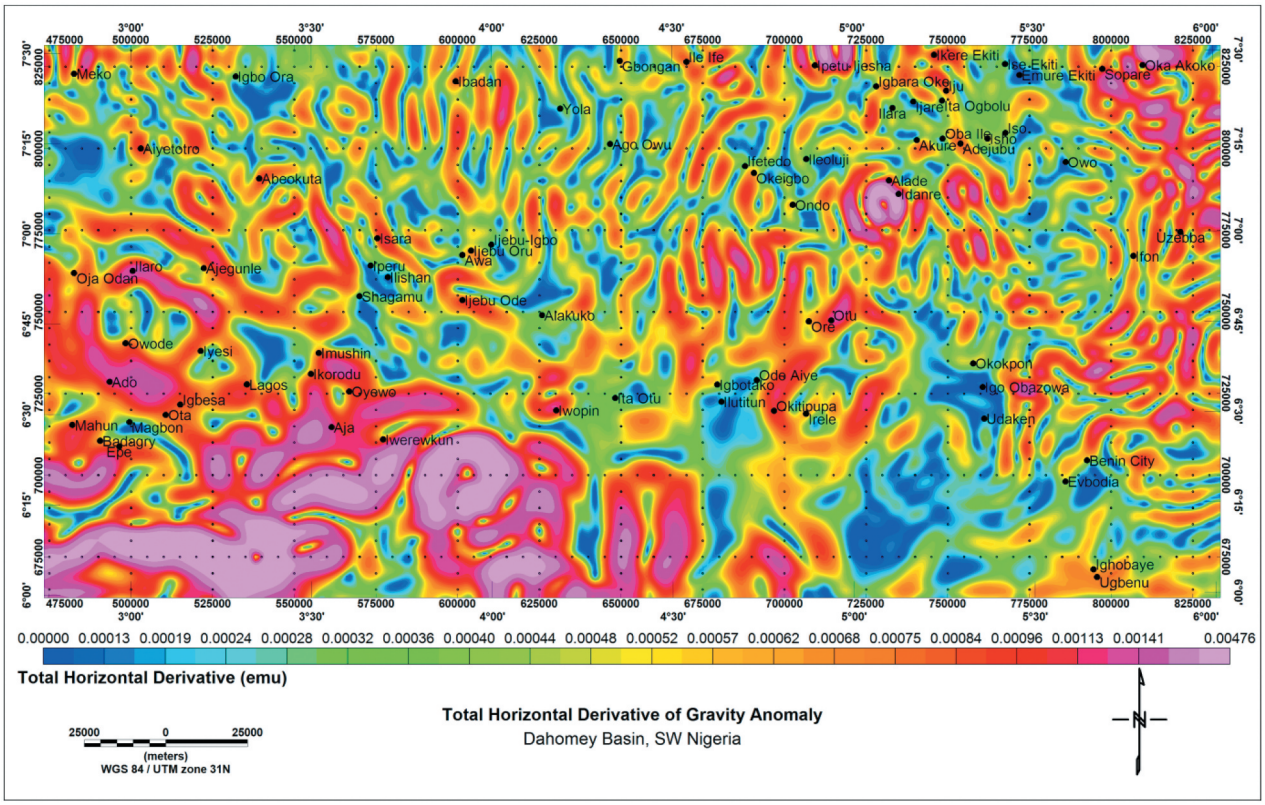

Figure 7. Total horizontal derivative of gravity anomaly.

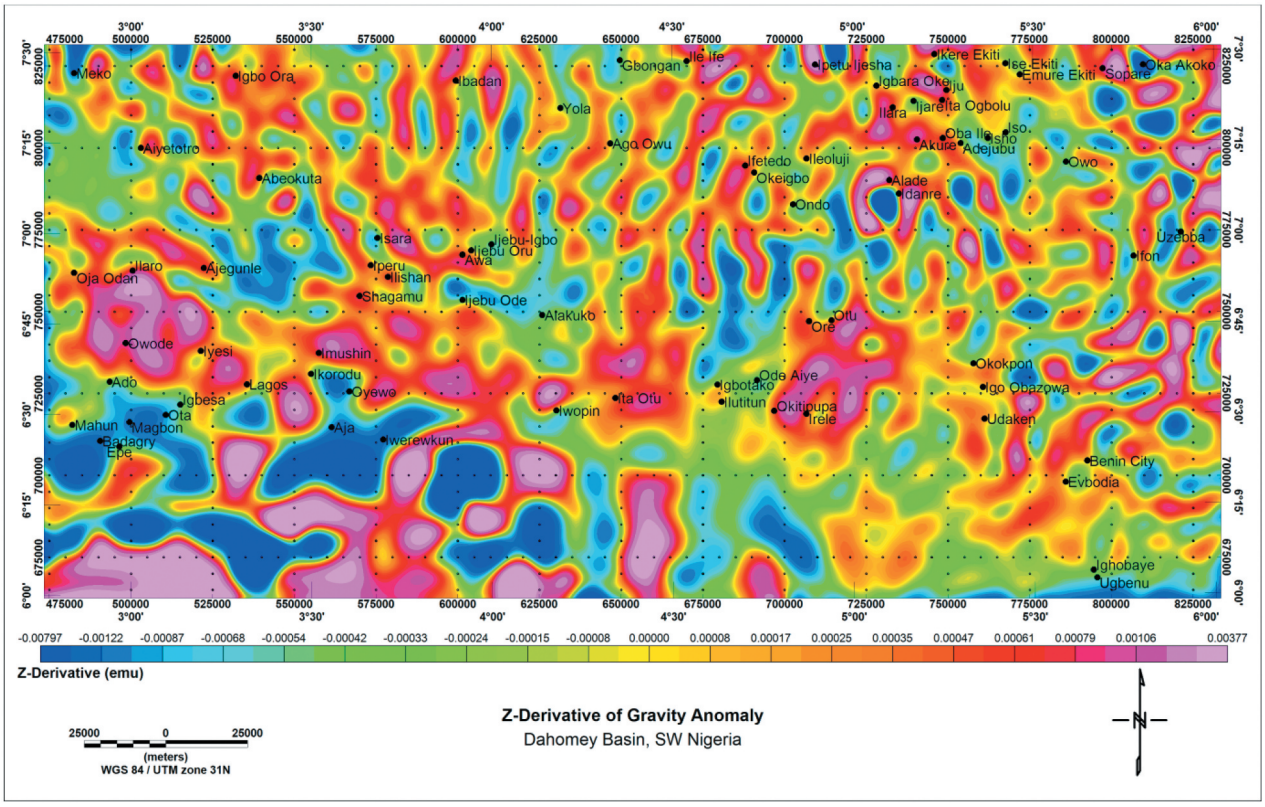

Figure 8. Z-derivative of the gravity anomaly.

4.4. Vertical (Z) derivative distribution of the Bouguer anomaly

The z-derivative map is presented in Figure 8 and the result appears similar to that of x and total horizontal derivative. The basement terrain in the north of the study area presents predominantly north-south trending features. The approximate orientations however vary from NW-SE to NE-SW across the map, which is also observed on the horizontal derivative maps, although relatively less obvious. The earlier interpreted regional fractures coincide with the NE-SW trending positive anomaly (>0.0004 emu) extending from Ile-Ife to Ita-Otu, and the NE-SW trending positive anomaly (>0.0007 emu), extending from latitude 825,000, through Ifon and terminating around Evbodia, south of the map.

4.5. Tilt derivative of the Bouguer anomaly data

The tilt derivative (Figure 9) produces a similar result to the vertical derivative. The anomalies are however narrower, with improved amplitude contrast and continuous tracing of subsurface discontinuities, thereby offering a significant advantage over the vertical derivative in edge detection (Reeves 2005; Dentith and Mudge 2014; Isles and Rankin 2018). The general north–south trend and the changing orientations of the basement structures are also visible, albeit more vividly. The earlier interpreted regional fractures can also be observed running NE-SW through the central and south-eastern parts of the map.

4.6. Analytic signal of the gravity anomaly data

The analytic signal grid (Figure 10) is apt at discriminating geobodies (Roest et al. 1992; Li 2006) and thus able to discriminate between the basement and sedimentary terrains, and to also separate the Dahomey Basin from the Niger Delta Basin. The basement terrain is dominated by short-wavelength anomalies indicating shallow source bodies, while deeper causative bodies are responsible for the long wavelength dominating the sedimentary terrain. The Dahomey Basin, in the south-west is dominated by anomalies > 0.0014 emu, while a transitional region of 0.0007 to 0.0012 emu anomalies around longitude 700,000 m, separates it from the Niger Delta Basin, with anomalies < 0.0007 emu.

4.7. CET lineament analysis of gravity data

The result of CET lineament extraction overlain on the gravity data is presented in Figure 11. The traces generally trend in the north–south direction, but some, especially in the southern areas trend east-west. The lineaments in the basement terrain trend approximately NNE-SSW. Dominant NNE-SSW trending traces occupy the region surrounding the interpreted regional fracture that runs through the middle of the study area and the Chain Fracture Zone dominated parts in the eastern ends of the map. The NW-SE trending lineaments

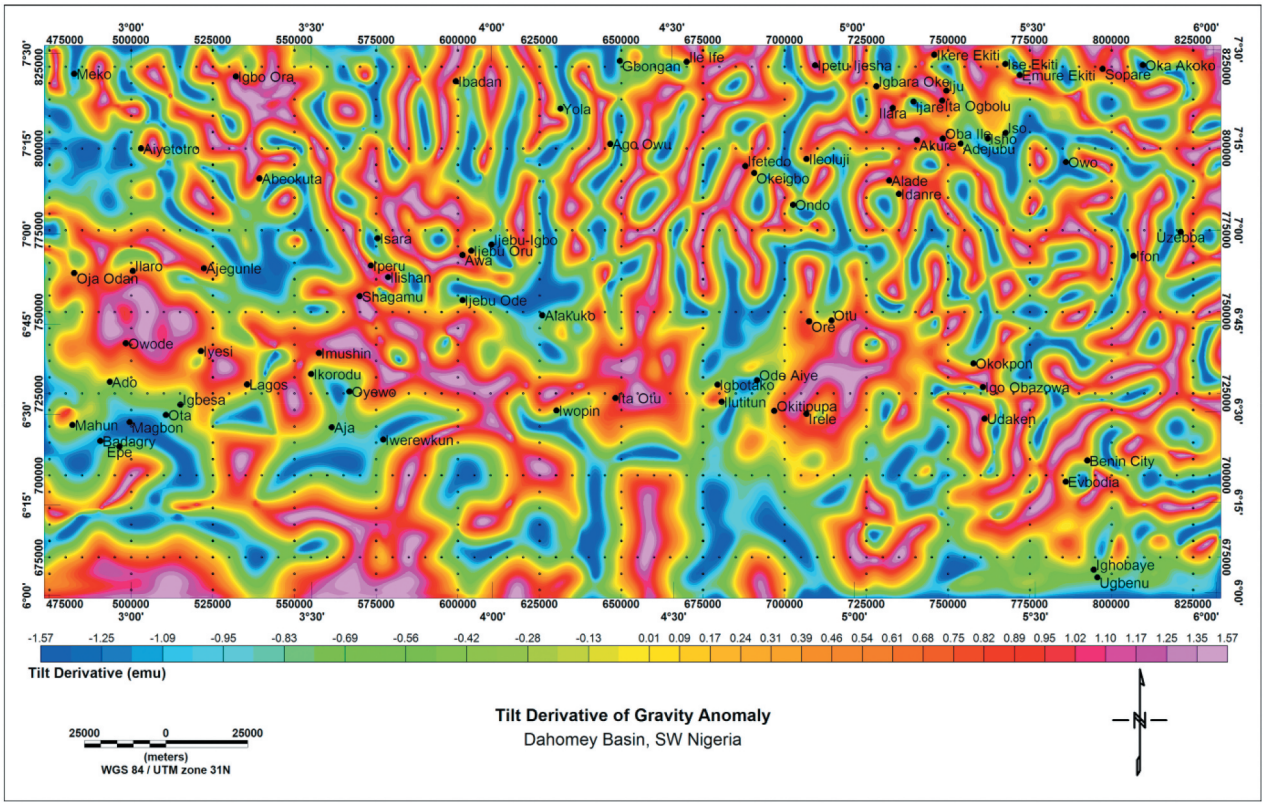

Figure 9. Tilt derivative of gravity anomaly.

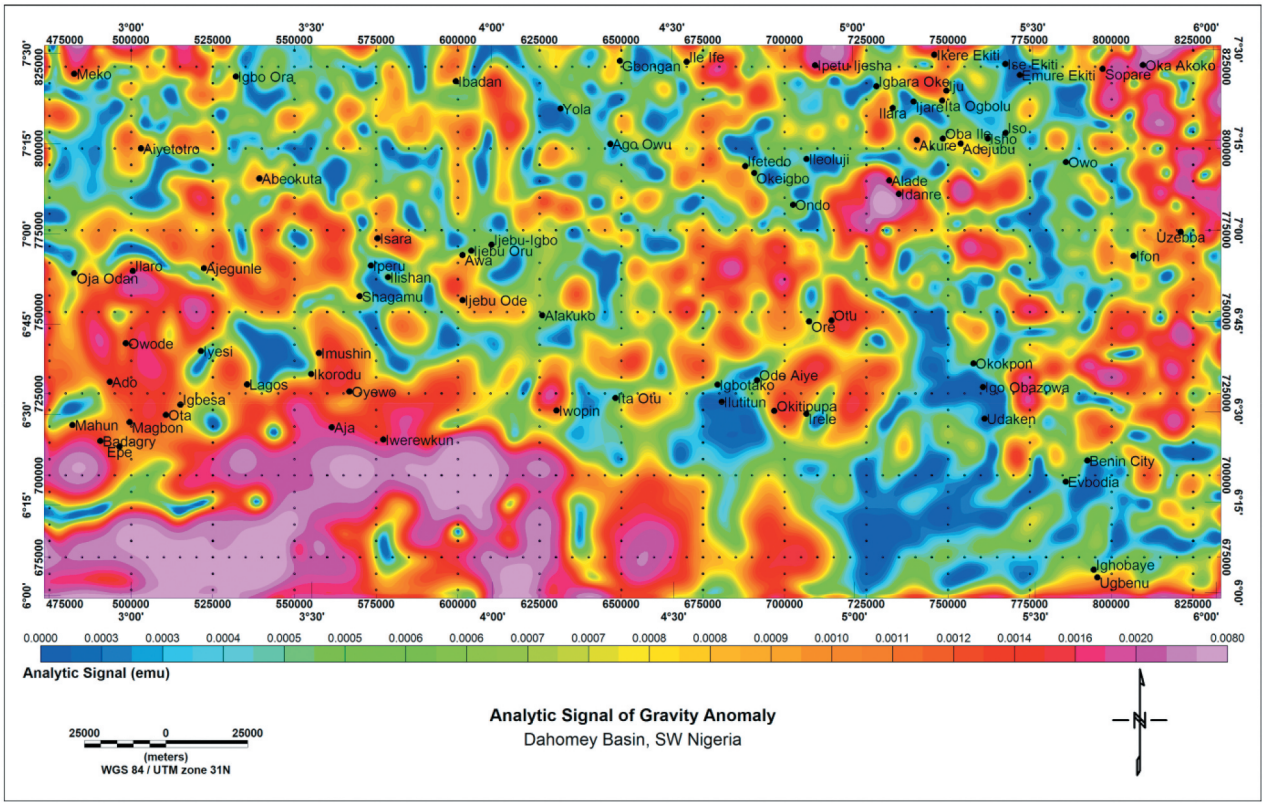

Figure 10. Analytic signal distribution of the gravity data.

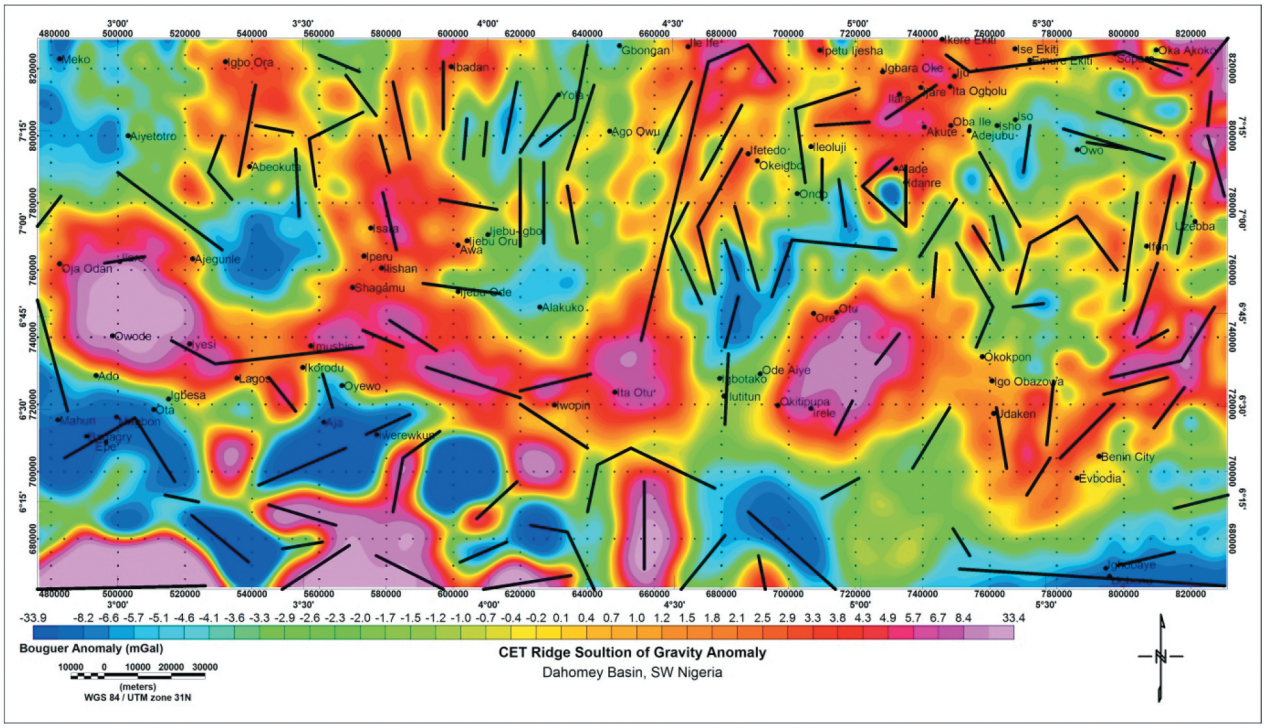

Figure 11. CET ridge solution overlaid on the gravity data.

in the western to south-central part of the study area appear to carve out the Dahomey Basin. Inside the basin, the traces are numerous, with varying orientations, but most of them trend approximately NNE-SSW as it is the case with most of the basement terrain.

4.8. Basement topography from gravity data

The Euler depth solutions are presented as zone coloured plots in Figure 12. Depths to basement range from <1500 m to >10,000 m, with the values increasing from north to south. The distribution of the

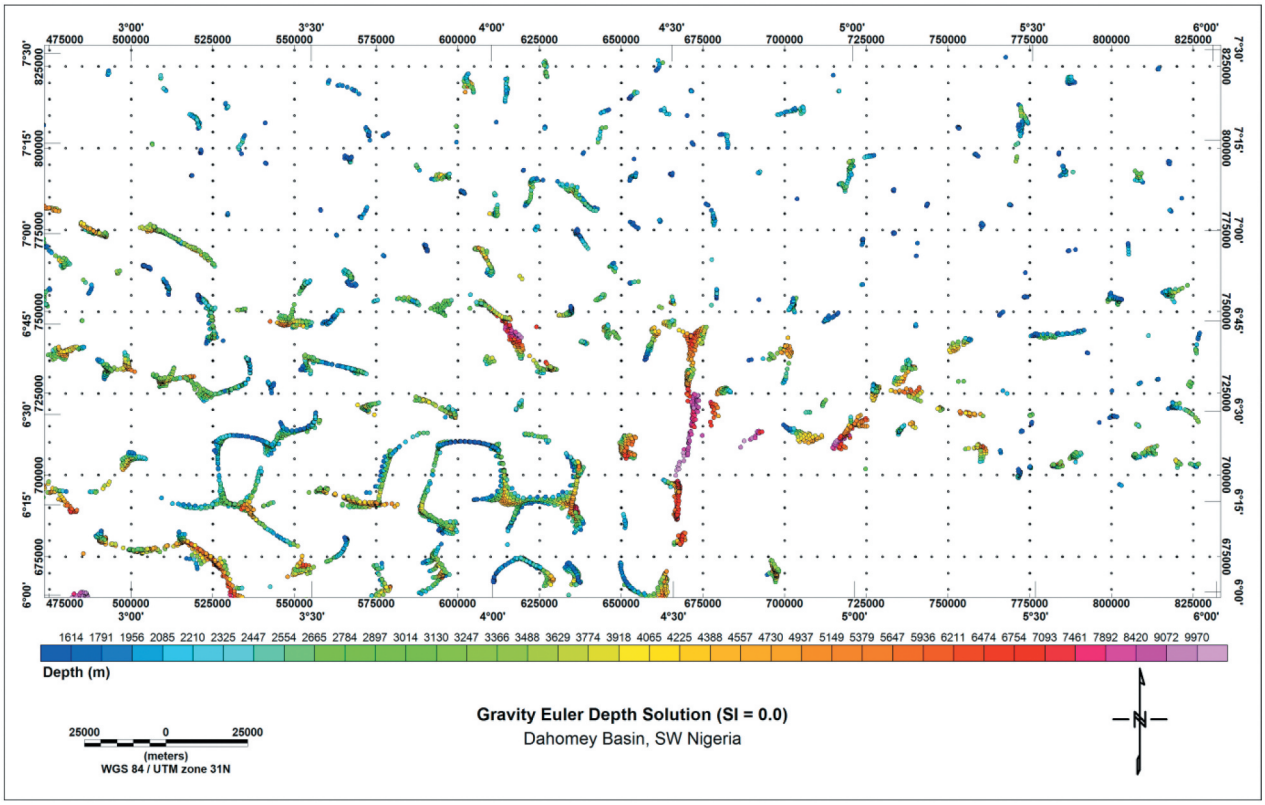

Figure 12. Total gravity field basement depth solution plots.

plots reveals a division of the study area into three geologic zones. These include the basement terrain in the north, the Dahomey Basin in the southwest and the Niger Delta in the southeast. Depths to basement in the basement terrain are less than 2000 m, while depth values in the sedimentary terrain (Dahomey and Niger Delta Basins) exceed 5000 m. The basement topography, generated after topographic correction

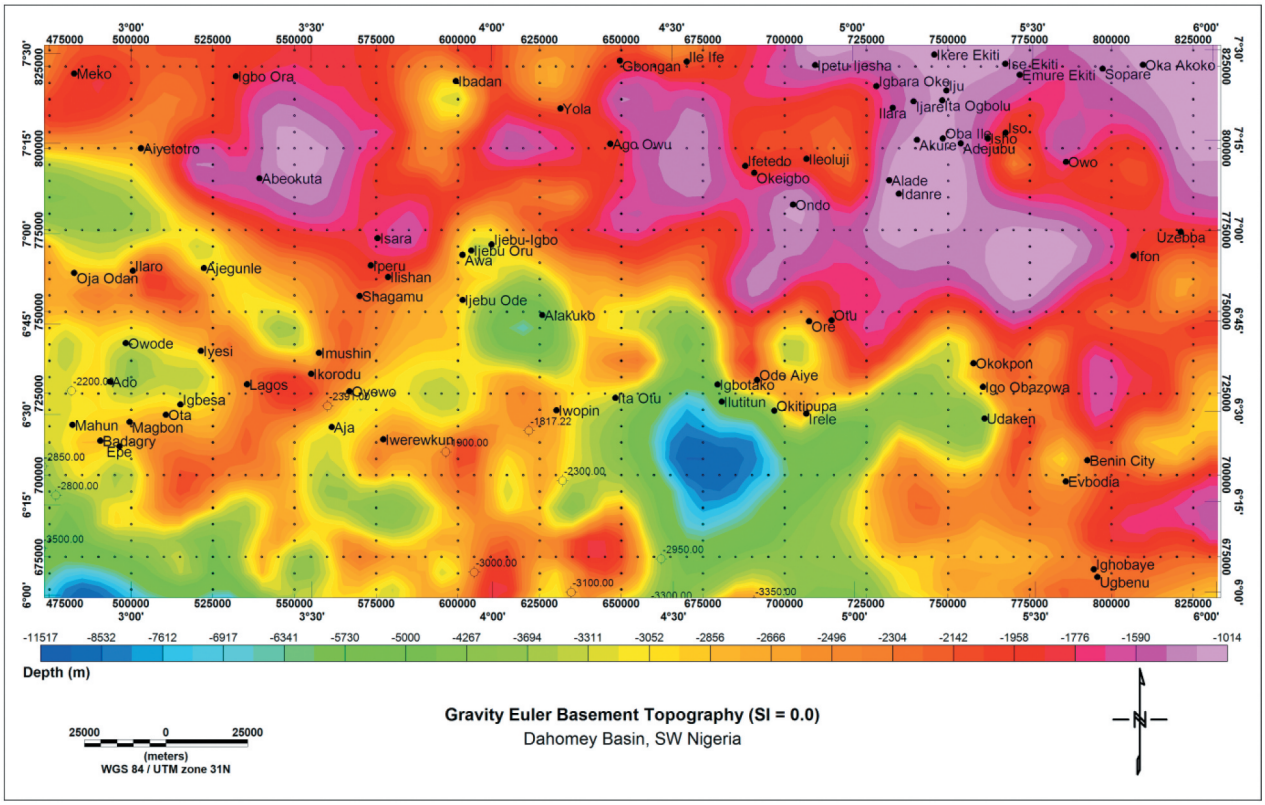

Figure 13. Total gravity field basement topography.

of the Euler depth solutions and 2D gridding is presented in Figure 13. The map displays the Dahomey Basin in the southwest as the deepest part (>3500 m) of the study area, while the Niger Delta Basin in the southeast appears as the shallowest part (<3000 m) of the sedimentary terrain.

The depth to basement solutions generated from the residual anomaly data is presented in Figure 14.

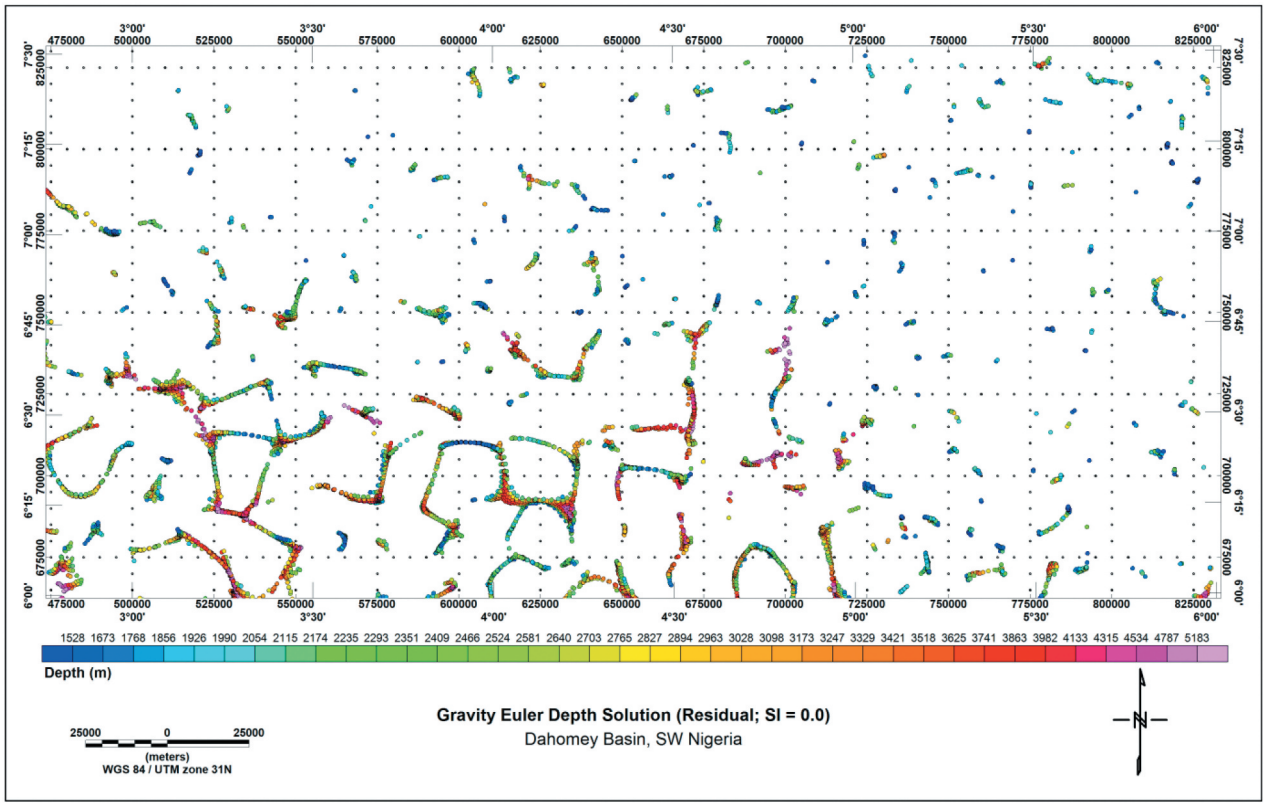

Figure 14. Residual gravity field basement depth solution plots.

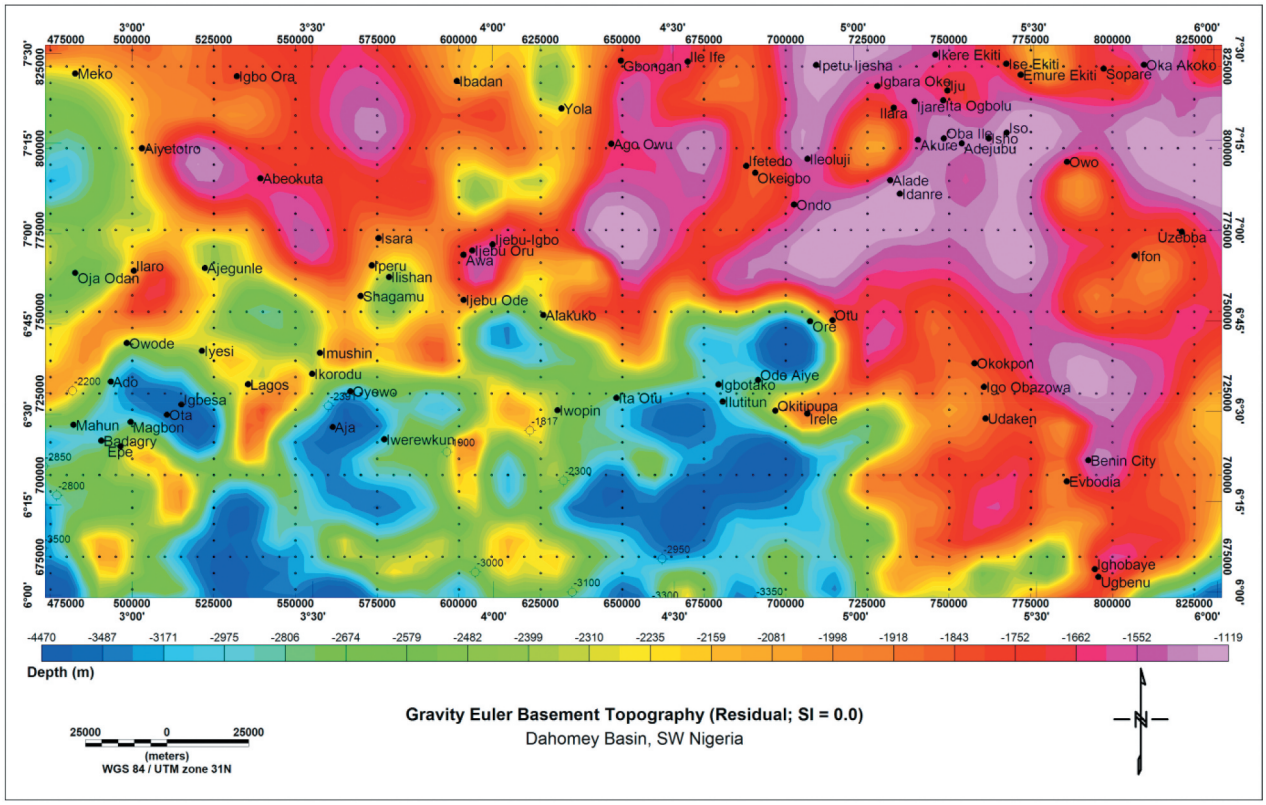

Figure 15. Residual gravity field basement topography.

This was done with the hope of better resolving relatively shallow depths (<5 km), as depth distributions in the northern and southeastern parts are unreasonable (Reid et al. 2014). The residual anomaly depths distributions show a range of <1500 m to >5000 m, with the values also increasing from north to south. However, the basement terrain, north of the study area still show depth values of up to 2000 m, while the Niger Delta Basin also show depth values of less than 2500 m. The Dahomey Basin in the southwest still appear as the deepest part of the study area, with its average depths of <3000 to >5000 m agreeing with what was obtained initially (Figure 12). The residual gravity basement topography (Figure 15) also agrees with what was obtained initially (Figure 13). Depths to basement in the Dahomey Basin (−2500 to −4500 m) are within expected range, while depth values in the basement terrain (>1000 m) and Niger Delta Basin (<2500 m) remain unreasonable.

4.9. Discussion of the results

Processing and analyses of the gravity data enabled discrimination of the study area into two primary geologic zones; namely the basement terrain in the northern half of the study area and the sedimentary terrain in the southern half of the study area. The northern areas contain shallow basement rocks, which often exist as outcrops, while the sedimentary terrain, south of the study area constitutes part of the Nigerian coastal basins (Adediran et al. 1991; Obaje 2009). Anomaly enhancements, through computation of derivatives and analytic signals, further enable division of the sedimentary terrain into the Dahomey Basin, in the southwest part of the study area and Niger Delta Basin in the southeast part of the study area (Avbovbo, 1980; Whiteman 1982; NGSA 2005; Obaje 2009), with a region of relatively smooth anomaly gradient separating the two.

The general north–south trend of the basement structures agrees with observations reported in various works (Opara et al. 2012; Oladele et al. 2015), although some lineament features are sub-parallel to discordant. However, while the varying orientation of the lineaments points to the highly fractured nature of the geologic terrain of southwest Nigeria (Osinowo and Olayinka 2013), the trend filtering and lineament results does not properly delineate the regional fractures that dominate the subsurface terrain. The regional Iwaraja-Zungeru fracture (Oluyide and Udoh 1989; Oladele et al. 2015) can nonetheless be identified, running through the middle of the study area.

The Euler depth solutions produced contrasting depth estimates between the basement terrain in the north of the study area and the sedimentary terrain, south of the study area. The basement topography in the north of the study area is relatively even, with the values varying from 1000 to 2000 m. The sedimentary terrain, south of the study area, however depicts an undulating basement topography, with the basement depths varying widely (<2000 to >5000 m) in the west–east direction. The increasing depth to basement from north to south and from east to west implies that the south-west is the deepest part of the study area, with basement depths exceeding 3000 m on the average.

The result obtained in the southwestern part of the study area agrees to some extent with previously reported values from magnetic and seismic works (Avbovbo, 1980; Brownfield and Charpentier 2006; Osinowo and Olayinka 2013), while the results obtained in the northern (>1000 m) and southeastern (<2500 m) parts does not agree with any previously published work, as depths in the basement terrain have been estimated to be less than 500 m, while depths in the Niger Delta in the southeastern part of the study area is well above 3000 m (Whiteman 1982; Brownfield and Charpentier 2006; Osinowo and Olayinka 2012; Osinowo et al. 2014). However, the relatively shallow Okitipupa Ridge separating the Dahomey Basin from the Niger Delta (Okosun 1998) could not be mapped with certainty, as the south-central part of the study area around which the basement uplift is expected to be found appear to be one of the deepest parts of the sedimentary terrain, although the western edge and outline of the ridge is visible in Figures 12, 14 and 15.

The unreasonably depth estimates in the basement terrain, north of the study area is due to over-estimation, while under-estimation is responsible for the unreasonably shallow depths in the Niger Delta Basin, south-east of the study area. Over-estimation of basement depth in the northern part of the study area can be attributed to domination of the gravity data by long wavelength regional anomalies of deep depths (Sobh et al. 2019) and due to the fact that the original grid spacing in the gravity data is about 3600 m. Re-gridding the raw data to 1000 m, does not appreciably improve the resolving capability of the data (Reid et al. 2012), as depth solutions obtained were mostly greater 1500 m. In addition, attempt to remove the long wavelengths (>100 km) from the data does not produce reasonable improvements.

The under-estimation of basement depths in the Niger Delta Basin is somewhat confusing as depth values in this part of the study area were expected to be much greater than 2500 m, due to reasons discussed above and previously reported depths. The maximum expected depth for the southeast part of the study area, which covers the western part of the Niger Delta was 10 km. However, the deep depth values (>2500 m) obtained during Euler deconvolution were mostly greater than 10 km, have high relative errors (>15%) and far from the centre of the moving window, so they

had to be rejected. This explains why depth solutions in this area are sparsely distributed (Figures 12 and 14), and probably why 2D gridding produce even shallower basement depth distributions (Figures 13 and 15).

5. Conclusion

Characterisation of the study area into basement and sedimentary terrains was initially apparent from the wavelength and amplitude variation of Bouguer anomaly. The basement terrain is dominated by positive anomalies, with short wavelengths, while the sedimentary terrain exhibit high anomaly contrasts, with long wavelengths. Additional distinction of the south-western Dahomey Basin from the south-eastern Niger Delta was made possible with calculation of derivatives. The sedimentary terrain exhibits relatively low gradients, while the basement terrain displays relatively high gradients. Lineament analyses reveal that the subsurface basement is highly fractured, with the structures trending in varying directions, although with a general north–south orientation. Results of depth estimates established that depths to basement increase from north to south, with depth values exceeding 3000 m in the Dahomey Basin. This implies that the Dahomey Basin contains the minimum 3000 m thickness of sedimentary depositions, necessary for hydrocarbon formation. The presence of basement fractures in varying directions; also suggest the possibility of the existence structural traps, suitable for hydrocarbon accumulation and preservation. This also suggests that the reactivation of the basement rocks could result in the formation of new fracture systems, capable of forming new trapping mechanisms that can open up new prospects for hydrocarbon exploration of the basin.

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