CHARACTERISATION OF TECTONIC LINEAMENTS IN THE CENTRAL EQUATORIAL ATLANTIC REGION OF AFRICA USING BOUGUER ANOMALY GRAVITY DATA

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ABSTRACT

3-D standard Euler deconvolution analysis was carried out on Bouguer anomaly gravity data for configuration definition and approximate depth estimate of tectonic lineaments in the central portion of the Equatorial Atlantic African region. Based on many trials for the most appropriate deconvolution parameters, the best Structural Index and Window Size adopted were 1.0 and 10 respectively and depth solutions were obtained to the depth of 45,000 m. Although, shallow crustal lineaments could not be mapped due to the resolution of the data (5' x 5' grid), good solution clusters of mid-range and deeper lineaments were obtained. The Euler solution clusters showed a largely curvi-linear trend and predicted vertical crustal movement along these lineaments (curvi-lineaments) at deep depths. It also predicted the existence of a micro-basin within the Niger Delta in Agbor region. The lineament networks comprised of major lineament frames to which the minor lineaments were appended and were observed to enter into the continent from the oceanic region mainly through the Chain, Charcot and the Fernando Po Fracture zones which were already established fracture zones within the Equatorial Atlantic Oceanic region. The major lineaments were oriented in the NE-SW direction while the minor lineaments had orientations ranging from ENE-WSW, NW-SE, to approximately NNW-SSE. Volcanism was also noted to be closely associated with the mapped lineaments. The study concluded that the study area was largely sheared and severely traversed by the extension of the Equatorial Atlantic rift system whose development was precursor to the opening of the Equatorial Atlantic Ocean.

Keywords: Euler Deconvolution, Tectonic Lineaments, Rift, Asthenosphere, Isostatic Adjustment.

INTRODUCTION

Regional tectonism has been a very enigmatic research area especially as it relates to the understanding of the making and breaking of continental plates (Meert and Torsvik, 2003; Ngako and Njonfang, 2011). Over the years, while the attempt to study plates' tectonism holistically had resulted in the identification and sequential relation of the major processes believed to be associated with the making and breaking of continents and the formation of ocean basins (Wilson, 1966; Weckmann, 2012), there are still uncertainties, gaps and unexplained misfits that remain conspicuous (Moulin *et al.,* 2010), with tectonic conditions in different mega-tectonic environments also known to vary significantly (Ziegler and Cloetingh, 2004). With this realisation, it has become pertinent to study different tectonic settings individually in order to understand the processes and regimes associated with their evolution.

The central portion of the African Equatorial Atlantic region has been of great economic and tectonic significance. It is the region where the oil-rich Niger Delta province is located. It is also within the region where the Equatorial Atlantic Ocean opened-up, leading to the complete breaking away of the South-American plate from the African plate. While this region remains a good setting for the study of tectonic forces that were at play when the Equatorial Atlantic Ocean opened-up, it has only been thoroughly explored and studied for economic reasons around the Niger Delta province.

Tectonic studies have hardly been undertaken beyond the Niger Delta and observations were neither reconciled with notable events in adjacent provinces nor applied to draw holistic trans-provincial inferences for the purpose of understanding crustal plates' dynamics and lithospheric responses. Consequently, the knowledge of tectonic evolution of the region over recent geologic years has been meagre and there has also been no scientific prediction about the outlook of the region in years to come. In a quest to comprehend the tectonic events that had contributed to the evolution of the present day central portion of the Equatorial Atlantic African region, the region was explored for lineaments which are often expressions of crustal weaknesses and deformation. Lineaments often include, rift boundaries, fractures (faults and joints), geologic contacts, and even fissures and could be regional-scaled.

Regional-scaled lineaments (especially fracture systems and rifts) are often believed to have tectonic implications (Gabrielsen *et al.,* 2002; Ziegler and Cloetingh, 2004) as they are brought about either by tensional forces (as in the case of rifts) or compressional forces or a combination of both, and could define boundaries of crustal plates. Lineaments are also known to be capable of adequately defining suspected rifted margins (Batayneh *et al.,* 2012; Mitchell, 2015).

In this study, the configuration of prominent lineaments in the central portion of the Equatorial Atlantic African region was defined from regional scaled gravity data, their approximate depths were estimated and the behaviour of these structures were studied from the crust down to the upper mantle. The lineaments were mapped from offshore to deep within the continent and their tectonic importance in the opening of the Equatorial Atlantic Ocean and formation of the adjacent inland sedimentary basins studied from Euler Deconvolution analysis.

The choice of the Euler Deconvolution approach to characterise the regional lineaments is to give not only their orientation but also their depth estimates in addition, an operation which is not possible with aerial photographs and satellite imageries that have commonly been used in the mapping of lineaments. In tectonism, adequate characterisation of regional lineaments should include the estimation of their depths for the purpose of determining if they are confined to the crust or transcend to the asthenosphere in addition to determining their linear extents and orientations.

The Study Area

The study area in this research work is designated as "the Central Portion of the Equatorial Atlantic African region". It spans between the Equator (0^{o}N) to Latitude 10.0^{o}N and between Longitudes 3.0^{o}E and 15.0^{o}E (Fig. 1). The area consists of both oceanic and continental regions with the elevation ranging from -4,200 m to 4,000 m. The eastern region is an upland having a peak elevation of about 4,000 m (Mt. Cameroon), the southwestern region is the oceanic section having a peak bathymetry of about -4,200 m (at the extreme southwestern end), the central region is the coastal sedimentary lowland region which is approximately at sea level, and the northwestern and the northcentral areas are areas of moderate and high elevation respectively. The average elevation for the mountains and plateau found within the region is about 1,500 m approximately (Fig. 2).

Tectonic Settings of the Study Area

The study area is a very important region tectonically because it was the last portion to finally give way (giving way in the Albian-Aptian period) as the South America broke away from Africa (Pletsch *et al.,* 2001). It has a good history of rifting, shearing and volcanism and include cratonic regions, mobile belts, rifted passive margins and regions of active magmatism and volcanic lines (Elsheikh *et al.*, 2014).

Figure 3 shows the boundaries of some tectonic provinces in the study area. The area covered in this research study includes the Niger Delta region, the Benue Trough, the Niger Trough, the South Western Basement Complex and part of the North Central Basement Complex (all in Nigeria), the Cameroon Volcanic Line (CVL) and the Adamawa Uplift (Cameroon), the Central Africa Shear Zone (Ngaoundere Rift) in Cameroon and the Gabon-Cameroon Shield.

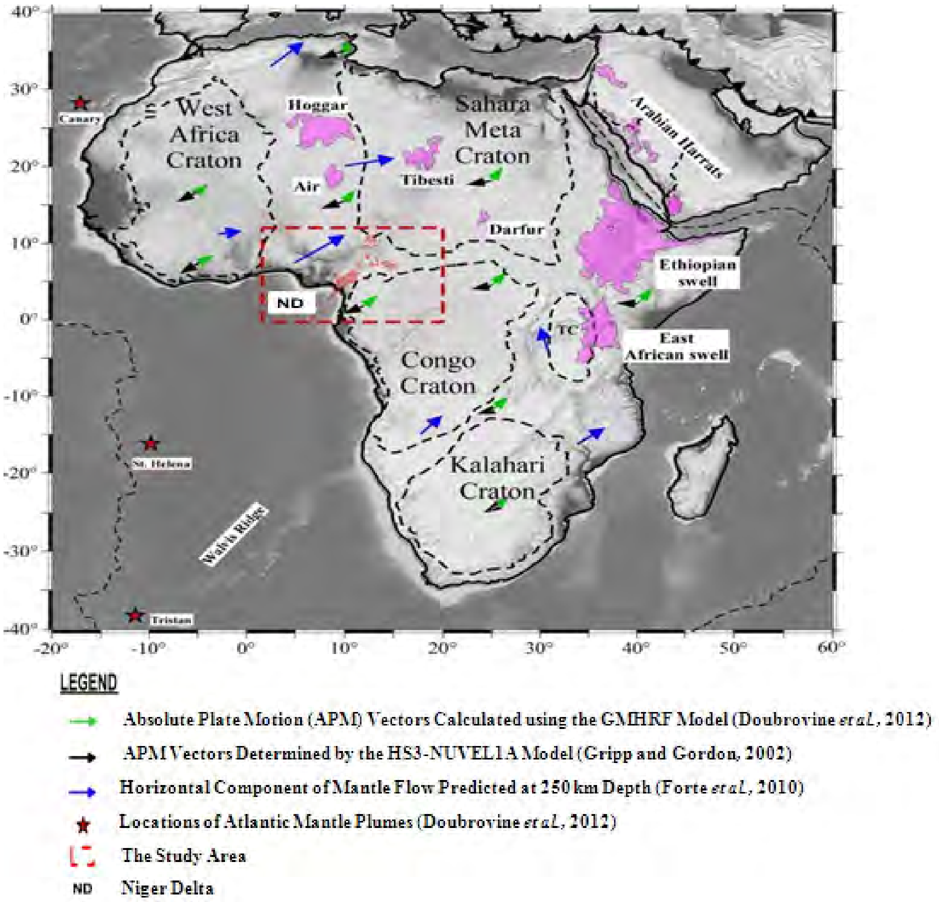

Figure 1: Map of Africa Showing the Study Area and Major Intraplate Volcanic Centres and Cratons (Modified After Abdelsalam *et al.*, 2011)

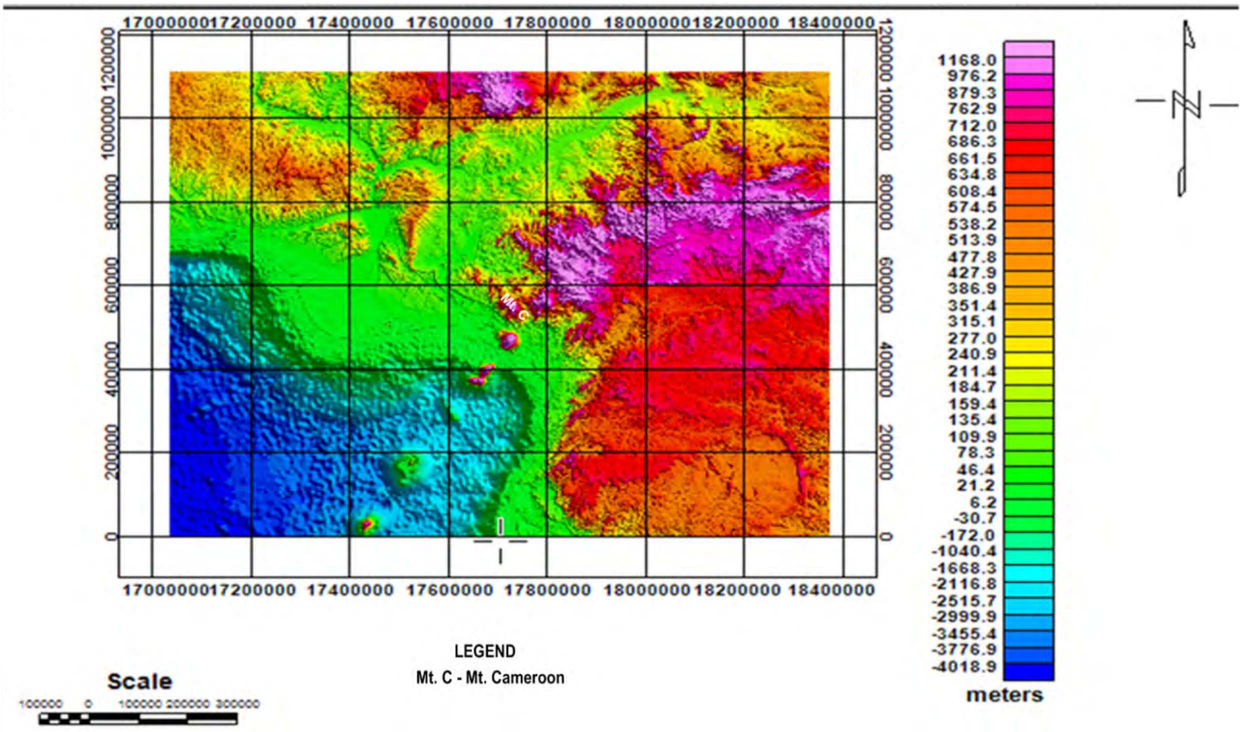

Figure 2: Topography/Bathymetry Map of the Study Area (coordinates in WGS-metres) – Generated from Scripps Institution of Oceanography's Topography/Bathymetry Point Data for the Region

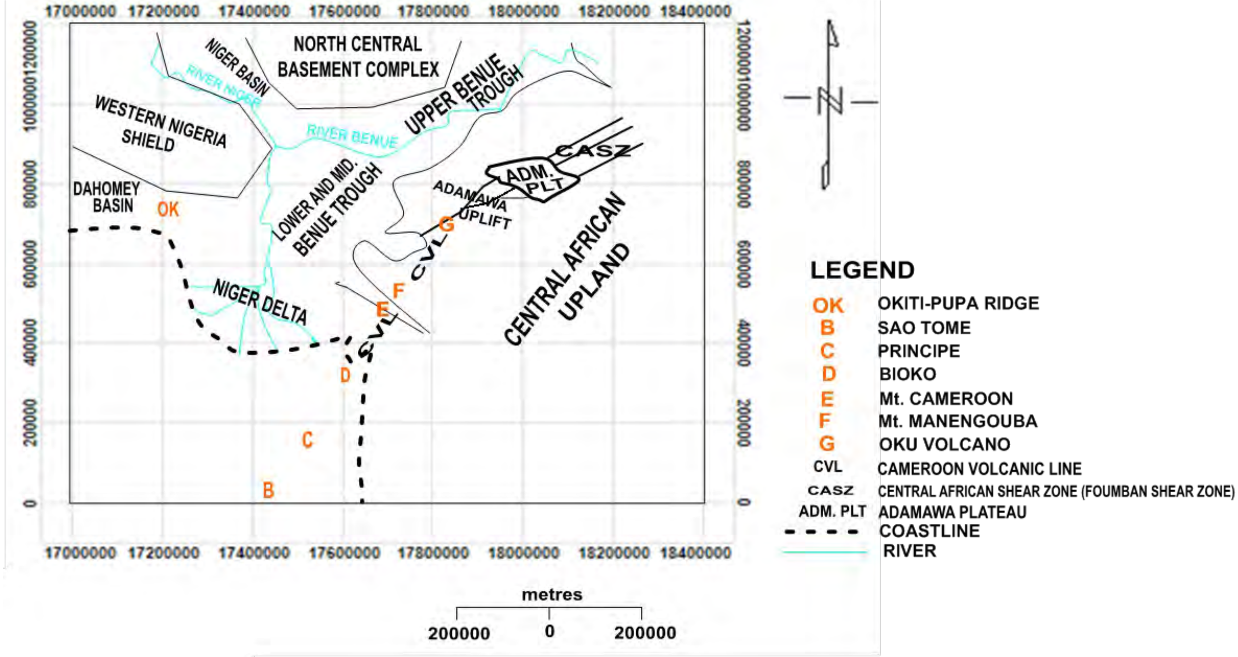

Figure 3: Map Showing some Tectonic Provinces within the Study Area and their boundaries

Aside the Cameroon Volcanic Line (designated as B, C, D, E, F and G in Figure 3) which is a line of volcano extending for about 1,600 km from the Atlantic Ocean deep into the continent and terminating around the Biu plateau (Djomani *et al.,* 1995), another major tectonic structure in the area is the Benue Trough which is a Mesozoic rift basin that starts from the northeastern edge of the Niger Delta and extends transversely as a deep furrow within the Nigerian shield to the southern limit of the Chad Basin. It forms part of the West African Mezosoic bifurcating rift system which connects other continental rifts in the interior of West African republics of Chad and Niger (Machens, 1973; Burke and Dewey, 1974). It is believed to have a length of about 1000 km and a maximum width of about 300 km (Nwajide, 1990) and has been considered to be an aulacogen (Hoffman *et al.*, 1974; Olade, 1975; Petters, 1978).

According to Osazuwa (1978), three notable events had happened in the Benue Trough which were rifting caused by the separation of South America from Africa, volcanism marked by the axial gravity high along the trough due to the presence of volcanic rocks under the sediments and folding (or compression) represented by gravity low flanking the axial gravity high.

The Niger Trough is another striking intracratonic feature within the study area. The basin is delimited in the Northeast and Southwest by the basement complex while it merges with Anambra Basin in the Southeast and Sokoto Basin in the Northwest in sedimentary fills comprising post orogenic molasse facies and a few thin unfolded marine sediments (Adeleye, 1974). Based on interpretation of gravity data, Ojo and Ajakaiye (1976) favoured the Isotatic Subsidence Hypothesis but concluded that a rifting origin could not be totally ruled out because the gravity effect of the shallow structural features may have obliterated the effect of deeper features.

There is also the The Western Nigeria (Benin-Nigeria) shield consisting of the Nigerian Basement Complex which is situated within a Pan-African mobile zone extending between the West African Craton in the west and the Gabon-Congo Craton in the southeast.

Nigeria lies in the central part of the Gondwana portion of the Pangean Supercontinent and remained a fairly resistant region to denudation (Doust and Omatsola, 1990). The Western Nigeria (Benin-Nigeria) shield is part of the ancient rocks of the African shield. The Adamawa uplift (in Cameroon) falls within the study area as well. This is a volcanic dome in Central Cameroon formed during the Tertiary together with other African volcanic uplifts such as the East African plateau, and is underlain by Precambrian basement rocks, remobilised by the Pan-African episode (600 – 500 Ma) and uplifted (1 km) relative to the surrounding area. These rocks, mainly schists and gneisses, intruded by granites and diorites, are cut by faults of the Central African Shear Zone (CASZ) (Nnange *et al.,* 2000). The Adamawa uplift comprises of the Adamawa Plateau, the Oku Massif, Mount Bambouto and the Manengouba mountain. The study area also covers the Central African Shear Zone (CASZ) and the Gabon-Cameroon Shield (in the region of the Central African Upland). The Central African Shear Zone is a Megashear zone in Africa extending over about 200 km from Sudan to Cameroon (Ngako *et al.,* 2008). It was believed to be formed during the Pan-African cycle (600 ± 100 Ma) during which important tectonic movements occurred giving rise to the Megashear zones in Africa (Ngako *et al.,* 2008).

MATERIALS AND METHODS

Data Description

The datasets used for this study are 5 x 5 minute grid terrestrial Bouguer anomaly gravity data from the GETECH's Africa Gravity Project and 1 x 1 minute grid satellite altimetry derived Topographic-Bathymetric data made available by Scripps Institution of Oceanography, University of California, San Diego, USA. Gravity data were preferred for this study because, unlike magnetic method, the gravity method can image beyond the Curie depth. The resolution of the Bouguer anomaly data equals ~9,295 m by 9,295 m in ground unit and that of the topography/bathymetry data equals 1,859 m by 1,841 m in ground unit. This implies that the datasets can at best be used only for regional studies.

The Coordinate System Adopted

The data were acquired in the geographic coordinate system but were converted to a universally uniform WGS-metre coordinate system for compatibility with the processing software and easy location of features and distances in metres.

Method of Data Processing: The 3-D Standard Euler Deconvolution Technique

3-D standard Euler deconvolution technique was carried out on the Bouguer anomaly data for lineament trend analysis and depth estimates. The 3-D Standard Euler deconvolution technique is the sole technique utilised in this study due to the fact that no deep seismic data with good coverage are available in the study area.

The study took advantage of the fact that Euler deconvolution is both a boundary finding and depth estimation technique as it is capable of providing automatic estimates of source location and depth (Oyeniyi *et al.,* 2016).

Euler deconvolution is commonly employed in potential field data interpretation because it requires only a little prior knowledge about the source geometry, and more importantly, it requires no information about the magnetization vector in the case of magnetics (Thompson, 1982; Reid *et al.*, 1990). The 3-D standard Euler deconvolution technique is based on solving Euler's homogeneity equation (Eq. 1) (Reid *et al.*, 1990):

$$(x - x_0)\frac{\partial T}{\partial x} + (y - y_0)\frac{\partial T}{\partial y} + (z - z_0)\frac{\partial T}{\partial z} = \eta(\beta - T) \qquad (1)$$

which can be re-written as:

$$x\frac{\partial T}{\partial x} + y\frac{\partial T}{\partial y} + z\frac{\partial T}{\partial z} + \eta T = x_0\frac{\partial T}{\partial x} + y_0\frac{\partial T}{\partial y} + z_0\frac{\partial T}{\partial z} + \eta\beta \qquad (2)$$

where β is the regional value of the potential field and x_0, y_0, z_0 defines the position of the source, which produces the total potential field T measured at (x, y, z), η is the so-called structural index. In Euler deconvolution η is a homogeneity factor relating the potential field and its gradient components to the location of the source. By changing η, the geometry and depth of the potential field sources can be estimated. Poor choice of η can cause a diffuse solution of source locations and serious biases in depth estimation (Thompson, 1982; Reid *et al.*, 1990).

Since gravity fields due to structures like regional scaled lineaments (e.g. contacts and some faults) are likely not to be strictly homogeneous, Euler deconvolution depth estimates will at best be an approximation in such cases. However, they can be found useful in cases where there are sparse deep seismic data such as the study area (Reid and FitzGerald, 2003). Also, in Euler deconvolution, for each position of the moving window, an over-estimated system of linear equations is solved for the position and depth of the sources (Thompson, 1982; Reid *et al.*, 1990). Hence, the choice of the right window in relation to the data grid interval becomes important.

This study utilised Geosoft's Oasis Montaj^{TM} software for processing the data. The software adopts the algorithm published by Reid *et al.* (1990) and requires carefully choosing the right grid interval, window size and structural index.

The Grid Size, Window Size, Structural Index and Minimum-Maximum Depth Imaged

The resolution of the Bouguer anomaly gravity data is 5 x 5 minute. This is equal to a grid size of 9,295 m x 9,295 m. As has been established from simulations and empirical testing, minimum depths obtainable are usually about the same as the grid interval while maximum depths are usually about twice the window size (Reid *et al.,* 1990; Reid and FitzGerald, 2003).

Geosoft's Oasis Montaj^{TM} software allows window size to be varied between 3 and 20. The best window size obtained for this study is 10. Thus, the window size is equivalent to 92.950 km x 92.950 km. Twice this window size will give 185.900 km x 185.900 km.

Therefore, we can roughly estimate the minimum depth that can be imaged from the data as ~9.3 km and the maximum as ~185.900 km. Lineaments that can be found within this depth range can be classified as mid-ranged continental structures (lineaments) and deeper lithospheric structures (lineaments), hence good representation of the lithospheric lineaments. However, to ensure the credibility of the depth estimates especially for deeper depths, the maximum distance (depth) accepted was limited to 45 km because from previous studies, crustal thickness rarely exceeded 39 km in the region (Elsheikh *et al.,* 2014; Balogun, 2015).

In the study of the configuration of regional scaled lineaments (such as contacts, fractures and faults) whose gravity field are likely not to be strictly homogeneous, the right structural index has to be established by testing of different structural indices. Indices ranging from 0 to 2 were tested and the structural index that yielded the best solution was 1.

It should be noted that depth estimates from Euler deconvolution for lineaments of considerable depth extent can at best be an approximation (Reid and FitzGerald, 2003).

RESULTS AND INTERPRETATION

The Bouguer Anomaly Map

The Bouguer anomaly map generated from the Bouguer anomaly data is shown in Figure 4. Bouguer anomaly values ranged between -121 and +229 mGal. The map typifies an area having both oceanic and continental crustal regions. The Atlantic Ocean region of the southwestern portion of the study area is characterised by negative Bouguer anomaly values (with values ranging from -80 to 0 mGal), the eastern region which is purely a continental area is also characterised by negative Bouguer anomaly values though with greater amplitude (-30 to -100 mGal), the central western region corresponds with the oceanic crust of the Niger Delta and has positive anomaly values which ranged between +10 and +50 mGal while the northwestern section has a combination of moderately positive and negative Bouguer anomaly values. The Bouguer anomaly map shows a combination of elongated and circular positive Bouguer anomalies and also a combination of elongated and circular negative Bouguer anomalies. The circular positive Bouguer anomalies are characteristic of the oceanic section of the Cameroon Volcanic Line while the circular negative Bouguer anomalies are characteristic of the Minna Batholith and the Younger Granite Province of Jos. The dominant orientations of the elongated Bouguer anomalies are the ESE-WNW, NE-SW and E-W orientations.

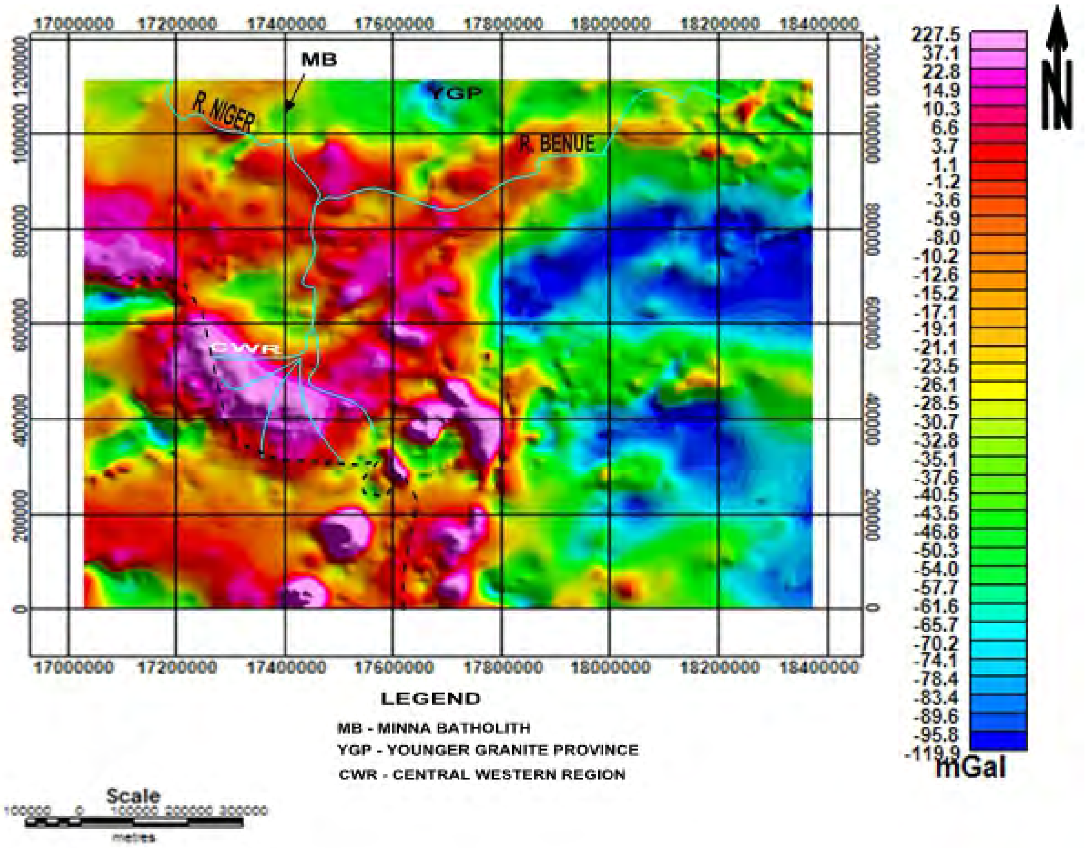

Figure 4: Bouguer Anomaly Map of the Study Area

The Euler Deconvolution Analysis

The result of the analysis of 3-D Euler Deconvolution for the Bouguer anomaly data is presented as colour-range symbol maps in Figures 5(a) and 5(b). Depths solutions were obtained up to the depth of 45,000 m.

Colour range symbol map was super-imposed on the Bouguer anomaly gravity map in Figure 5(c) in order to correlate the trends of the Euler solution clusters with some of the major anomalies. Good conformity of the clusters with the Bouguer anomaly patterns was observed. Figure 5(d) is the 3-D Euler solution map showing isolated solutions of depths between 10,000 – 30,000 m and Figure 5(e) is the solution map showing isolated solutions of depths between 30,000 - 45,000 m.

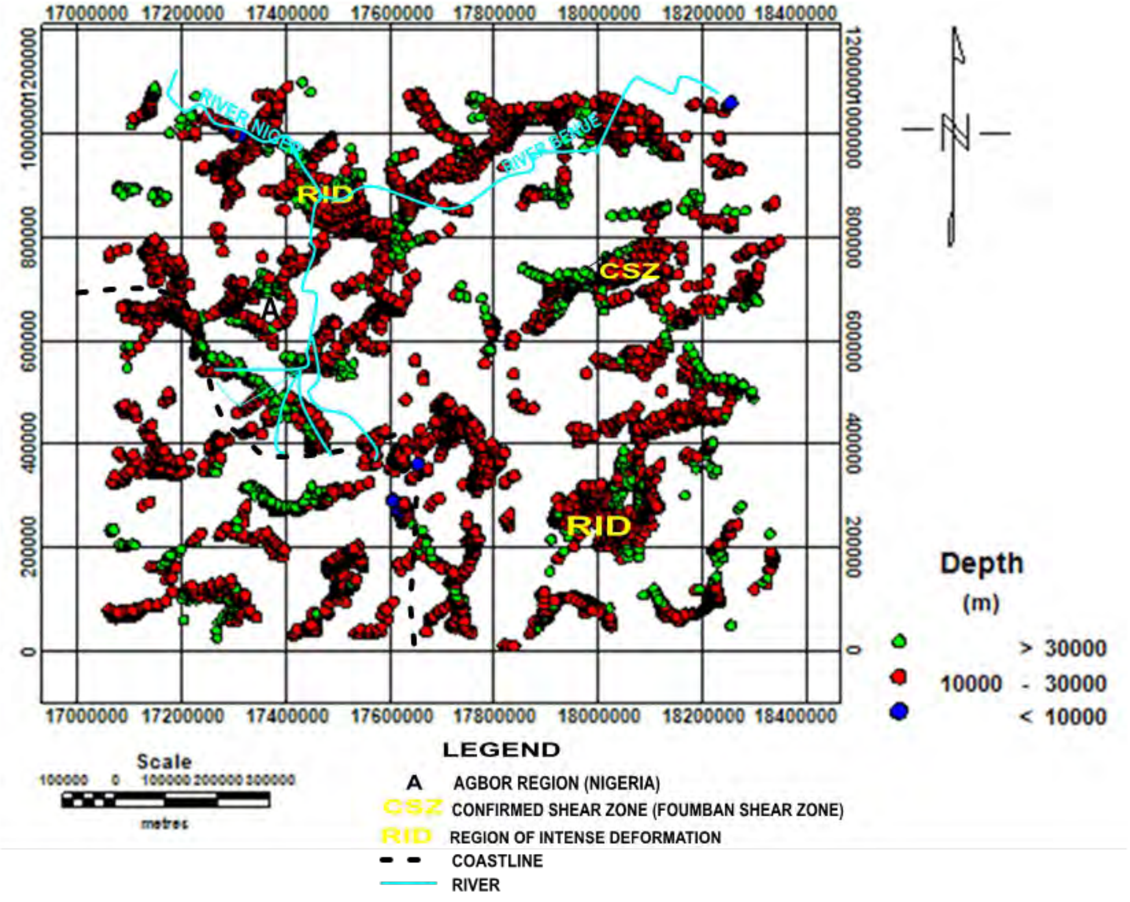

Figure 5(a): Colour Range Symbol Map of the Euler Solutions

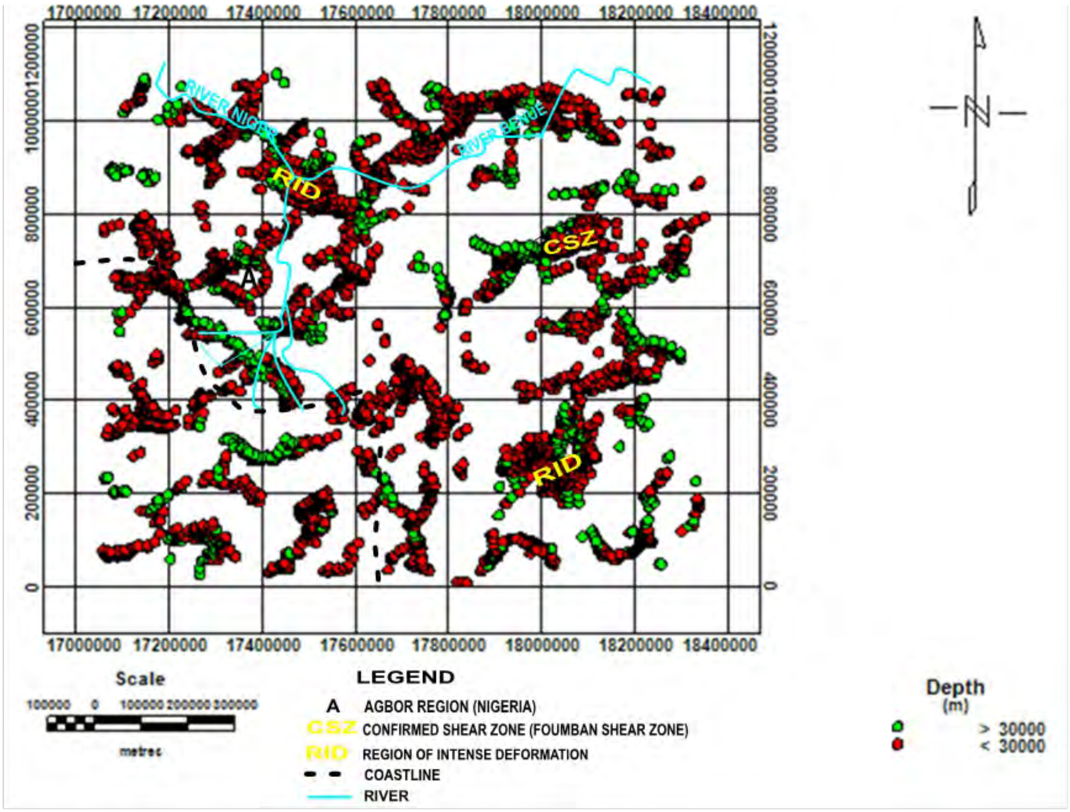

Figure 5(b): Colour Range Symbol Map of the Euler Solutions: depth classified as greater than or less than 30,000 m

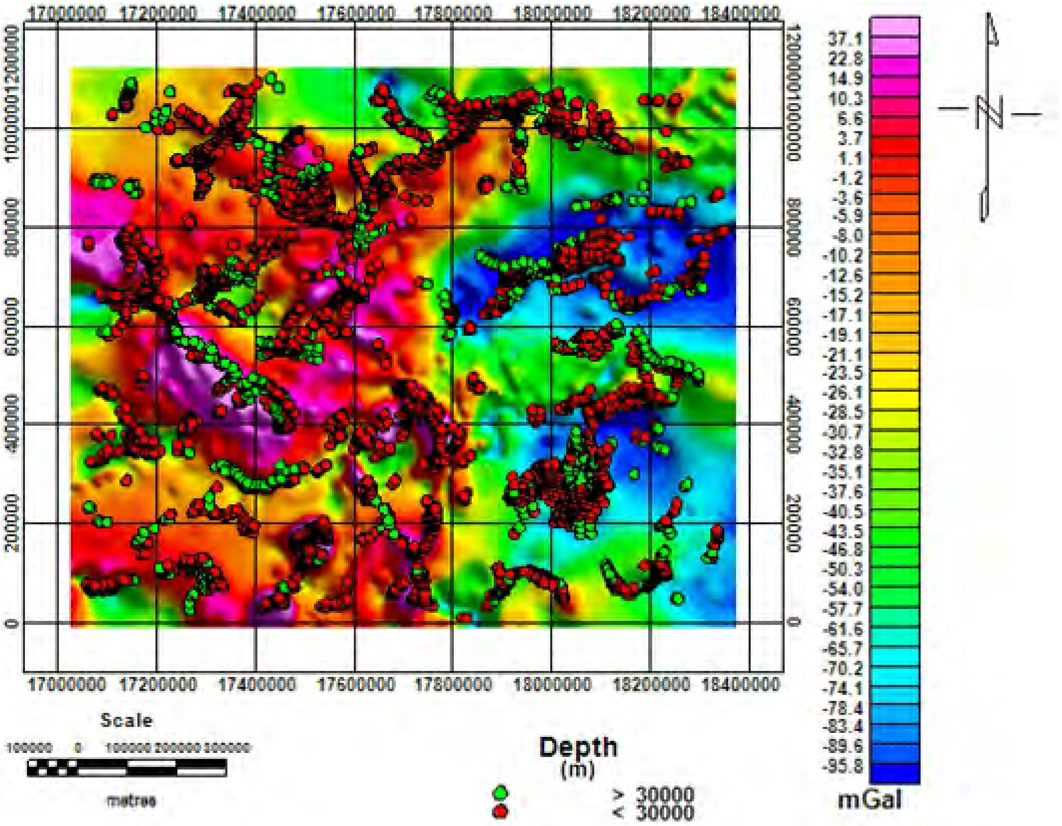

Figure 5(c): Colour Range Symbol Map Super-imposed on the Bouguer anomaly gravity map

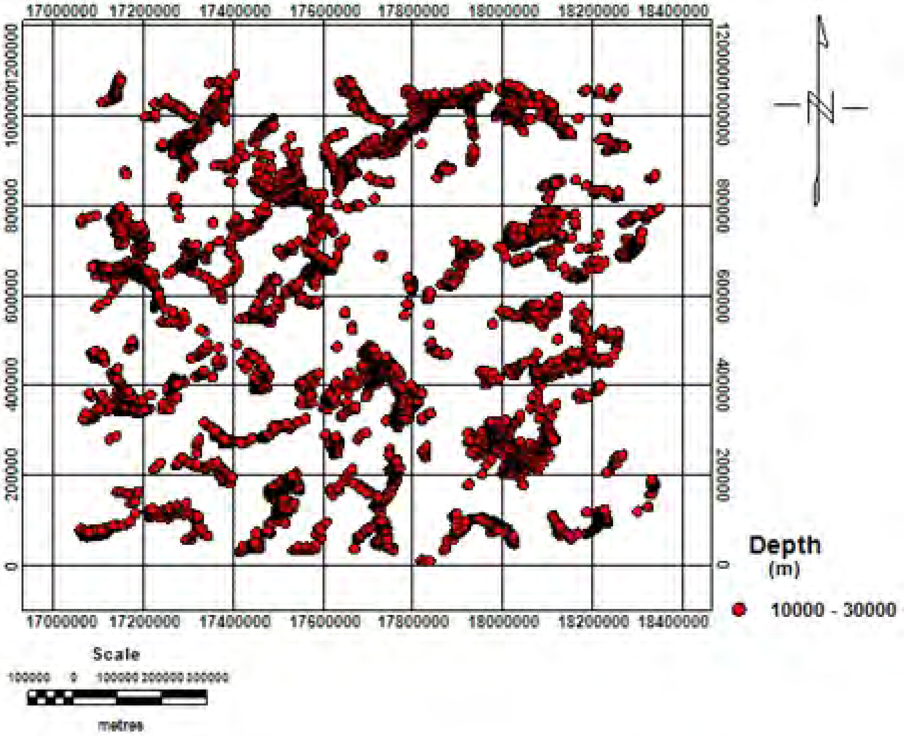

Figure 5(d): 3-D Euler Solution Map Showing Isolated Solutions at Depths between 10,000 and 30,000 m

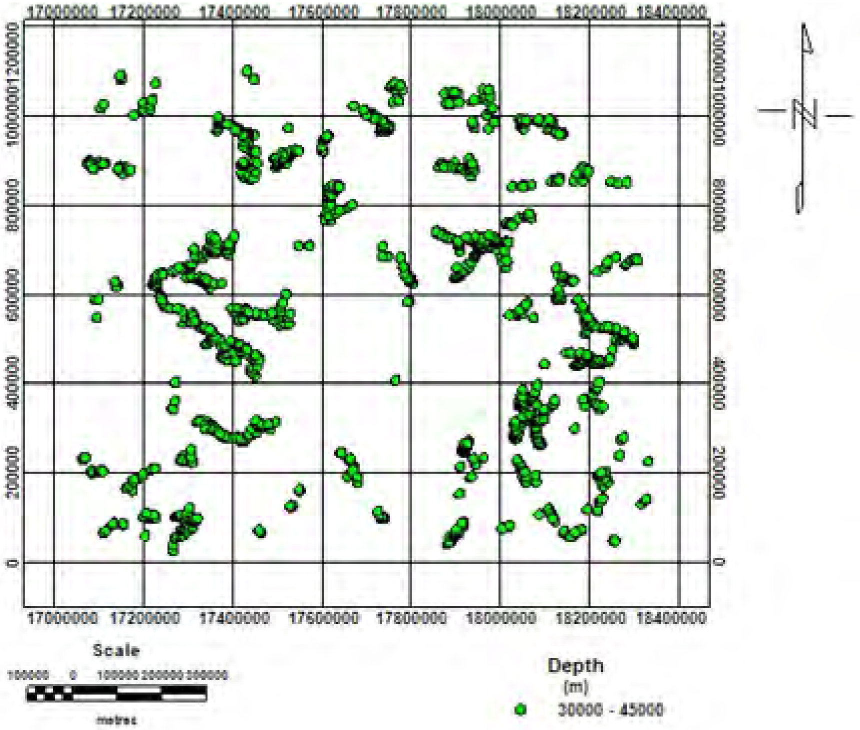

Figure 5(e): 3-D Euler Solution Map Showing Isolated Solutions at Depths between 30,000 and 45,000 m

In Figure 5(a), the blue, red and green points define solutions for depths that range from 0 to 10,000 m; 10,000 to 30,000 m and depth greater than 30,000 m (i.e. 30,000 to 45,000 m) respectively. In Figure 5(b) depth classification was based on whether the depth of a mapped lineament is within the upper 30,000 m or transcends deeper within the lithosphere (i.e. has a depth greater than 30,000 m). The trends shown by the Euler deconvolution solutions can be said to be well defined. These trends are largely curvilinear.

In Figures 6(a) and 6(b), the lineaments were picked out by thin lines. Figure 6(a) showed the fully picked lineaments comprising of the major and minor ones while only the major ones were presented in Figure 6(b). Figures 6(c) and 6(d) are the rose diagrams depicting the orientations of the lineaments presented in Figures 6(a) and 6(b) respectively. A map generated for the study area which classified the region based on how the major lineaments traversed it and segmented it into rifted provinces was shown in Figure 7 and finally, a superimposed tectonic and lineament map of the study region was presented in Figure 8.

DISCUSSION OF RESULT

Figures 5(a) and 5(b) are colour range symbol maps of the study area. Due to the resolution of the data (~9,300 m x 9,300 m), solutions whose depth estimate is less than 10,000 m were not resolved. Hence, oceanic crustal lineaments (which should have been depicted within shallow cluster ranges of between 0 and 10,000 m) could not be mapped. However, good solution clusters of mid-range continental crustal lineaments (i.e. from 10,000 m to 30,000 m) and deeper lineaments (clusters of solutions greater than 30,000 m) were obtained.

Crustal thickness studies in the study area have shown that depth to the Mohorovicic discontinuity ranged between 33–39 km (Elsheikh *et al.,* 2014; Balogun, 2015). It was on this basis that lineaments were re-classified as crust confined lineaments (lineaments with depth not greater than 30,000 m) and deeper lithospheric lineaments (lineaments with depth greater than 30,000 m).

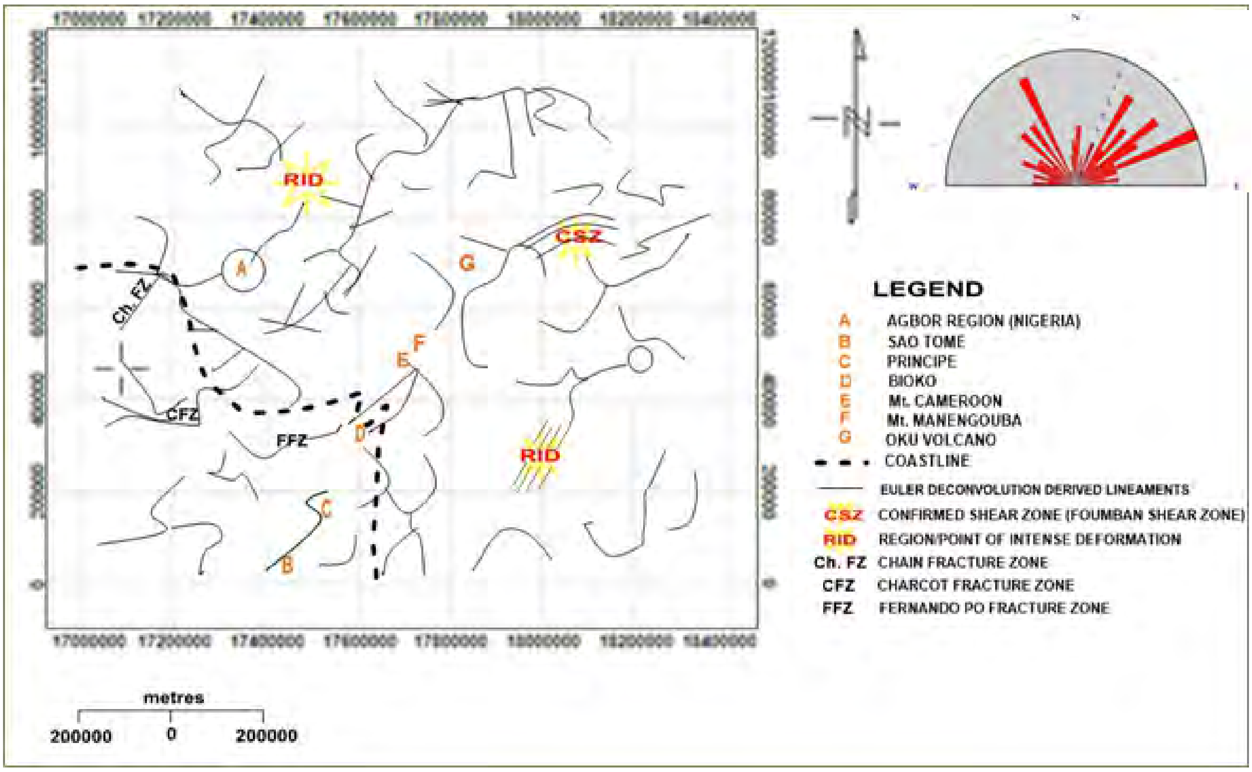

Figure 6(a): Map of the Fully Picked Lineaments Derived from Euler Solutions for the Study Area

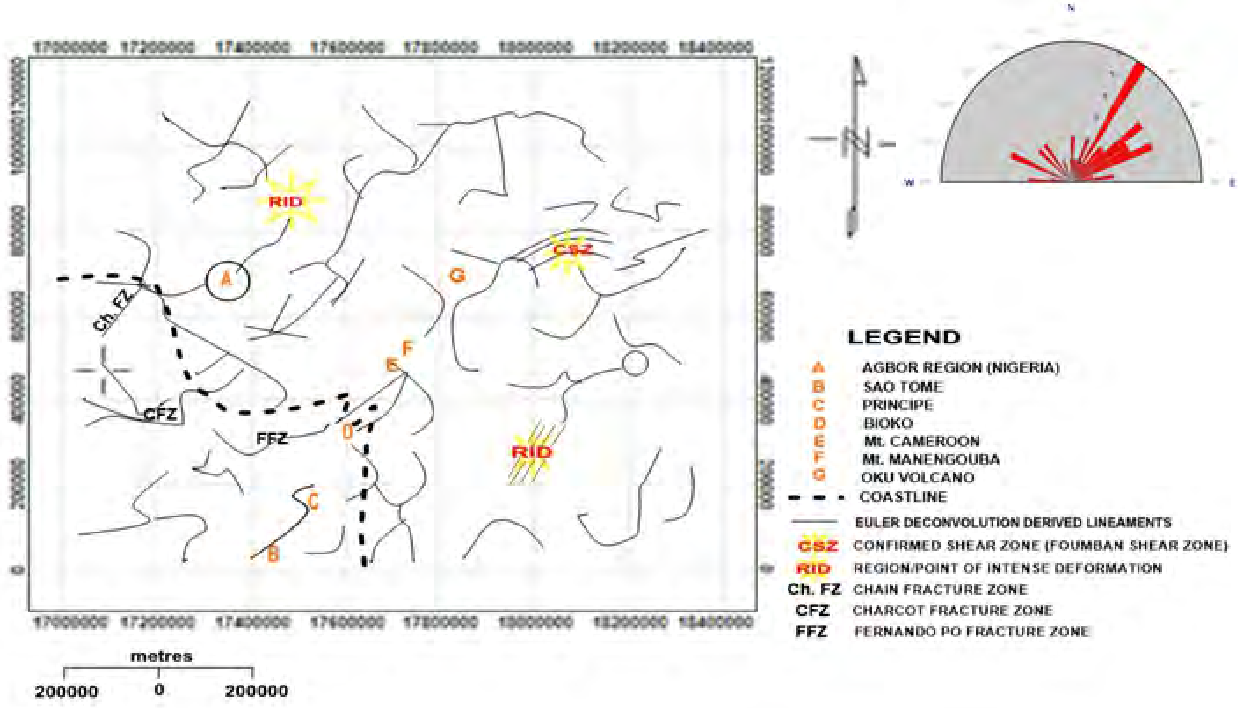

Figure 6(b): Map of Major Lineaments Derived from Euler Solutions for the Study Area

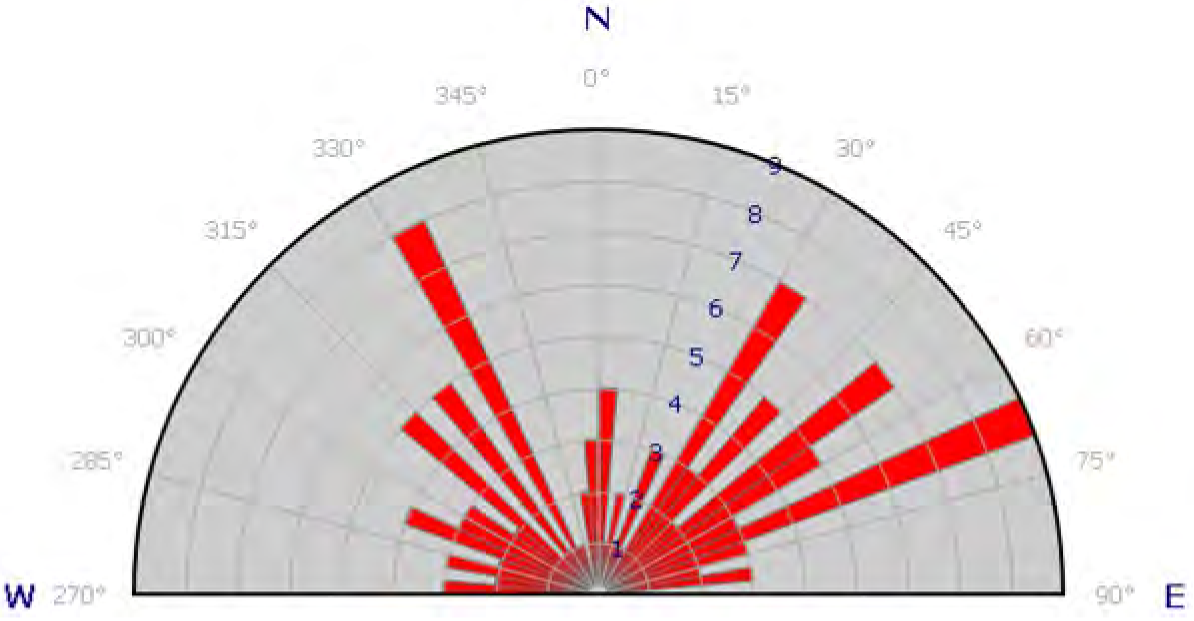

Figure 6(c): Rose Diagram showing the Orientations of the Fully Picked Lineaments Derived from Euler Solutions for the Study Area

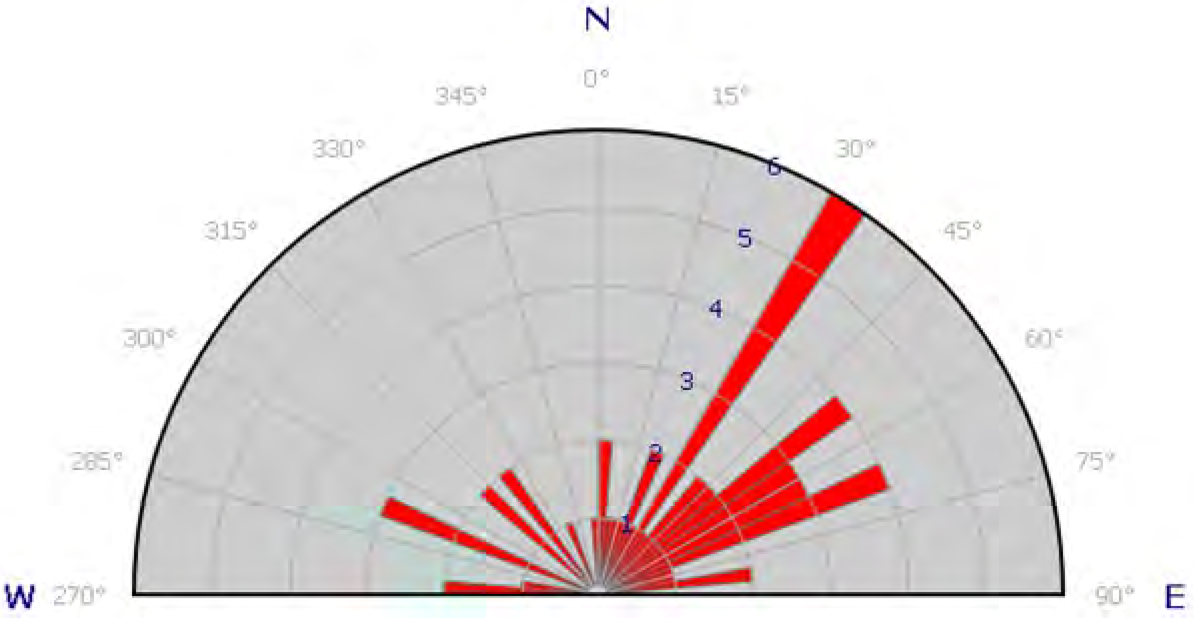

Figure 6(d): Rose Diagram showing the Orientations of the Major Lineaments Derived from Euler Solutions for the Study Area

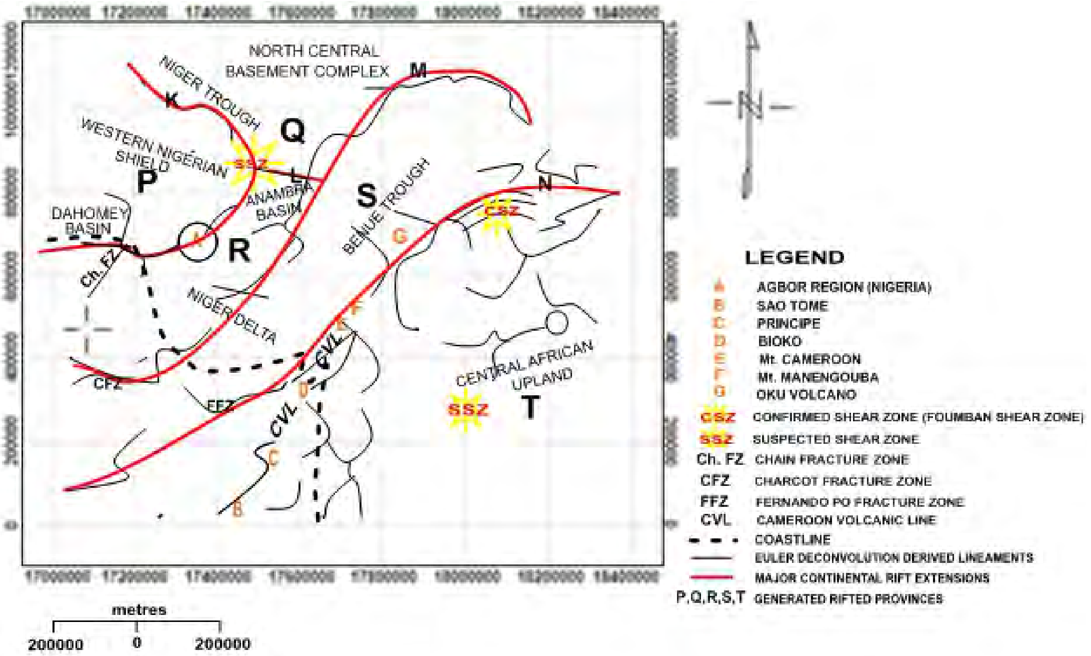

Figure 7: Map Showing the Rifted Provinces Realised from the Major Lineament Patterns

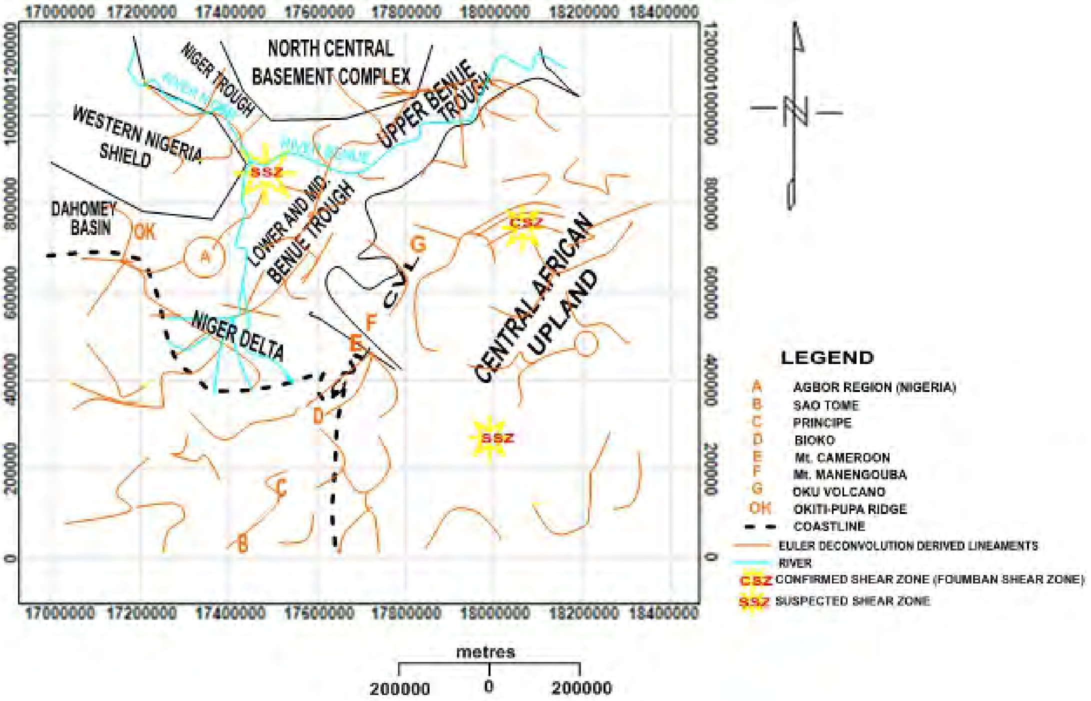

Figure 8: Super-imposed Tectonic and Lineament Map of the Study Area

Figure 5(e) shows the Euler deconvolution solution clusters at depth beyond 30,000 m (i.e. 30,000 – 45,000 m). The relative sparseness of clusters in this depth range is probably an indication that the upper mantle is approached as the upper mantle region is expected to be more ductile relative to the crust, hence, less prone to being markedly affected by tensional and compressional forces responsible for the creation of lineaments.

The non-uniformity in depth of solutions along lineaments (i.e. occurrence of patches of ordered green clusters within ordered red clusters along the same trend as seen in Figures 5(a) and 5(b)) suggests that there may have been vertical displacements along those lineaments. Since such vertical displacements are still noticeable at depth greater than 30,000 m (which is a considerable depth around the vicinity of the viscous asthenosphere), then the vertical movements may have been caused by isostatic adjustment in the region.

Also, distinctive overcrowding of Euler solution clusters were observed at three different locations on the Euler deconvolution maps (Figures 5(a) and 5(b)). This kind of signature is believed to be typical of regions of intense crustal deformation. While one of the points (the point designated as CSZ) corresponds to the region of the already established Foumban Shear Zone (in central Cameroon), the fact that one of the two remaining overcrowded cluster points (the northwestern point) coincides with the confluence region of Rivers Niger Benue and the other (the southeastern point) corresponding to the region of the "Affele – Kye – Ntem Thalweg" around the Cameroon-Gabon boundary corroborate the fact that they could actually be regions of intense crustal deformation.

A Suspected Micro-basin in the Western Niger Delta Region

A closed set of well-defined Euler solution clusters seem to appear to be conspicuously defining a very small region (designated as "A") in the central western region of the study area in the Euler colour range symbol maps shown in Figures 5(a) and (5b). The region enclosed by the said Euler solution clusters is likely to be a micro-basin having its center around "Ekum Osadegbe town (17336100mE, 683300mN i.e. 6.03°E, 6.15°N)" within the Agbor region of Delta State, Nigeria in the western section of the Niger Delta (Figures 5(a) and 5(b); Figures 6(a) and 6(b)).

The idea of a micro-basin created by isostatic subsidence occurring due to the inevitable lithospheric adjustment following the separation of the South American plate from the African plate is a more plausible explanation for the creation of the suspected micro-basin region whose boundary has been defined by the closed set of the Euler Solutions. The observation that mid-range and deep Euler solution clusters were superimposed (superimposed ordered red and green Euler clusters) along at the boundary trend could be a pointer to vertical movement event along the boundary at depth, hence isostatic adjustment. The fact that the Bouguer anomaly over the suspected micro-basin is anomalously negative (Figure 5(c)) whereas the Bouguer anomaly associated with the volcanic expressions in the genetically related, neighbouring Benue Trough is positive, giving rise to an axial gravity high within the Benue Trough as observed by Osazuwa (1978), could be a justification in favour of the idea of a micro-basin over the idea of a volcanic intrusion. The estimated area of coverage of the suspected micro-basin is about 6,570 km^2 if the micro-basin were approximated as being circular in shape.

The Lineaments and their Tectonic Implications.

The lineaments that characterise the study area are segmented curvilinear trends that form some chain-like networks across the entire region (Figures 6(a) and 6(b)). The wide coverage, density and deep depth-reach (as have been established from the Euler depth solutions) of the lineaments across the study area make the region a shear zone.

The lineament networks comprise of major lineament (curvi-lineament) frames to which minor lineaments are appended. The major lineament frames are almost parallel at their southern ends in the south-western region of the study area but deviates as they approach the northern region (Figures 6(b) and 7). The major lineaments are oriented mostly in the NE-SW direction (Figure 6(d)). The appended lineaments have orientations ranging from ENE-WSW, NW-SE, to approximately NNW-SSE (Figure 6(c)).

The lineament networks were observed to enter into the continent from the oceanic region mainly through the Chain, Charcot and the Fernando Po Fracture Zones (Figures 6(b) and 7) which are already established fracture zones within the Equatorial Atlantic oceanic region (Genik, 1992; Samaila and Likkason, 2013) and terminate deep into the continent. This suggest that the lineament networks may have been related to the Equatorial Atlantic fracture systems (rift) which preceded the opening of the Equatorial Atlantic ocean and are therefore extensions of the rifts from which the

Equatorial Atlantic ocean opened. Presently, these continental rift extensions are noted to have become boundaries of inland sedimentary basins such as the Niger Basin, the Anambra Basin, the Niger Delta and the Benue Trough.

It was also noted that volcanism was closely associated with the mapped lineaments in the study area as volcanic island and mountains (Sao-Tome, Principe, Bioko, Mt. Cameroon, Mt. Manengouba and Oku Volcano) were observed to be either located at the terminal end of the mapped lineaments or enclosed by them (Figures 6(a) and 6(b)). This indicates that there were moderately intense volcanic activities during the rifting stage. This kind of rift-related magmatic activity have often been noted to be associated with upward-doming of the rift zone (Doust and Omatsola, 1990; Ziegler and Cloetingh, 2004). This would then explain the formation of the two prominent domes, the Adamawa Uplift (comprising of the Adamawa Plateau, the Oku Massif, mount Bambouto and Manengouba Mountain) located around the rifted region of the Foumban Shear zone and the Sanaga Fault zone and the Nigerian Younger Granite Ring Complexes which are both raised by over 1,000 m (Nnange *et al.,* 2000; Balogun, 2015) above the surrounding in the study area.

The noted association of the volcanoes with the mapped lineaments could also be an indication that the volcanoes exploited for their emplacement weaknesses in the crust due to crustal extension which is usually precursor to rifting and/or already established lineaments due to crustal rupturing. The fact that the islands of Sao Tome and Principe are located along the same lineament (Figures 6(a) and 6(b)) could be an indication that they both exploited the same channel of crustal weakness for their emplacement.

Based on the major continental rift K, L, M and N identified, the study area was classified into rifted provinces designated as Provinces P, Q, R, S and T (Figure 7). Province P is the region to the far west bounded by the rift K. It covers the entire Western Nigerian Shield and the Nigerian section of the Dahomey Basin. Province Q is the segment bounded to the north by rifts K, L and M. It covers the Niger Basin (Bida Basin) and part of the North Central Basement Complex of Nigeria. Province R is the segment bounded to the south by rifts K, L and M. It covers the Anambra Basin and the western portion of the Niger Delta. Province S is the strip bounded by rifts M and N. The northern part forms majority of the Benue Trough while the southern part forms the eastern section of the Niger Delta. There seems to be no structural demarcation between the Benue Trough and the Niger Delta in this strip. This corroborates the proposition of Balogun (2015) who suggested from mantle density analysis of the region that the Benue Trough is the north-eastern extension of the Niger Delta.

Province T is the segment to the east of rift N. The region is known as the Central African Upland and it is a transition environment into the Congo craton.

It can be observed from the superimposed tectonic and lineament maps (Figure 8) that the major lineaments define exactly or approximately major tectonic, geological and physical features in the study area. It can also be observed that the drainage pattern along Rivers Niger and Benue, to a good extent, was influenced by the lineament network.

CONCLUSION

The study area is a sheared zone that was severely traversed by the extension of the Equatorial Atlantic rift system whose development was precursor to the opening of the Equatorial Atlantic Ocean.

The tectonic settings of the area typifies the Atlantic-type rift system where in the early phases of rifting, large areas around future zones of crustal separation were affected by tensional stresses, giving rise to the development of graben (basin) systems from rifts. Over time, the rifting activity concentrated on the zone of future crustal separation, with tectonic activity decreasing and ultimately ceasing in the adjacent graben systems. Upon crustal separation, the diverging continental margins and the "unsuccessful" intra-continental branches of the respective rift system became tectonically inactive though the rift could be reactivated during subsequent tectonic cycles.

The presence of vertical displacements observable in the vicinity of the asthenosphere (as observed in figures 5(a) and 5(b)) suggest that isostatic adjustment (subsidence) had taken place over time in the region. The close association of some lineaments with volcanoes and volcanic islands suggests that the volcanoes exploited the crustal weakness for their emplacement.

It was also concluded that the major lineaments found in the study area define exactly or approximately the major tectonic, geological and physical features in the study area and that the flow of the Niger and Benue rivers are highly structurally controlled by the lineaments present in the region.

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