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STRUCTURAL CHARACTERIZATION OF THE NIGERIAN SECTOR OF THE DAHOMEY BASIN USING GEOPOTENTIAL FIELD ATTRIBUTES

A PAPER PRESENTED

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ABSTRACT

The structural dispositions of the Nigerian sector of the Dahomey Basin have been investigated using attributes of geomagnetic and gravimetric fields. Aeromagnetic anomalies were reduced to the equator to improve the correspondence of the anomalies with the causative bodies. The residual, upward continued, Analytic signal, tilt and horizontal derivatives, and pseudogravity transformation of geopotential attributes and forward models of both geomagnetic and gravimetric anomalies were computed to accentuate geological features including regional faults and fracture network, basement block pattern and depth to magnetic basement. The results show that the basement of the Dahomey Basin ranges from continental to oceanic crust. Some shallow and deep structural lineaments show significant degree of correlation suggesting that some deep lineaments propagate to the surface. Sinistral and dextral faults were mapped. The dominant trends of structures are the NE-SW, NW-SE, N-S and E-W trends. Basement architecture is essentially of horst and graben architecture with Lagos and Badagry grabens-which straddle the coastline- showing high petroleum prospectivity in that they host significantly thick sediments. Two NE-SW deep seated regional fracture zones extending from the Atlantic Ocean demarcate the western and eastern boundary of the basin. Possible release of stress along these regional fractures may trigger trembling in the subsurface. The implication is that this region may not be totally immune to earthquakes. The geometry of the coastline; Lekki and Lagos Lagoons were suspected to have been influenced by reactivation of Pan African weak zones. Major surface features are deduced to be structurally controlled. Maximum depth to magnetic basement in parts of the graben is interpreted to be 6387 m. This study has shown the capabilities of geopotential filed attributes in imaging the structural plumbing of sedimentary basins. This knowledge will aid the understanding of the geology of the basin and its resources.

1.0 INTRODUCTION

The Benin Basin, occupying the southwestern part of Nigeria between longitude $2^0$30' and $4^0$30'E, and latitude $6^0$00' and $7^0$00'N, is considered to be one of the frontier basins in oil exploration. The Nigerian sector of the Benin Basin has been a subject of renewed exploration interests due to rejuvenated interest of the Nigerian government in increasing her crude reserve through exploration of frontier basins.

The study of basin structures is one of important economic applications of magnetic method in oil and gas exploration. Local variations in magnetic properties of crustal rocks cause anomalies in the earth's magnetic field; and geologic structures (like faults and folds) may produce small magnetic fields that distort the main magnetic field of the earth. Because basin fill typically has a much lower susceptibility than the crystalline basement (Nabighian *et al.*, 2005), and basements commonly exhibit variation in susceptibility; it is commonly possible to estimate the depth to basement and quantitatively map basement structures (Prieto and Morton, 2003). Likewise, gravity method have been used for many years to map the geometry and features of remote basins (Jacques *et al.*, 2003) where density contrast exists. Earlier work in the study area (Coker and Ejedawe, 1987) ascribed a low petroleum potential to the Benin Basin. But recent exploratory efforts in the basin have resulted into discovery of commercial oil in Aje field offshore Lagos, thus establishing the fact that the basin is a potential petroleum province (Brownfield and Charpentier, 2006). Over the past decades, magnetic and gravity methods have become prime tools for assessing the structural prospects of frontier basins, nonetheless, basin-wide geopotential study has not been carried out over this basin from the structural point of view. Previous geopotential attempts to study the basins were commonly restricted to a section of the basin (e.g Opara, 2011, Opara *et al*, 2012) and the knowledge of its structure and history has comes primarily from the numerous wells drilled to basement (Avbovbo, 1980). In this study, aeromagnetic data augmented by satellite derived gravity data were examined to understand the basin-wide structures and tectonics of the Benin Basin.

2.0 GEOLOGICAL SETTING

The Benin basin (Figure 1) is a sedimentary basin that was initiated during the Mesozoic in response to the separation of the African–South American plates and the subsequent opening of the Atlantic. The geology of the basin has been extensively discussed by various authors (Murat, 1972; Onuoha and Ofoegbu, 1988; Omatsola and Adegoke,1981, etc). Principal basement structures in the Benin Basin are those associated with Early Cretaceous rifting and are dominated by normal faults bounding a series of linked half-grabens. Several workers have worked on the stratigraphic framework of the Benin basin (Adediran and Adegoke, 1977; Nton *et al*, 2006). Cretaceous sequence in the Eastern Benin Basin began with the Abeokuta Group, which is made up of three formations namely; the Ise, Afowo and Araromi Formations. The Ise Formation unconformably overlies the basement complex of southwestern Nigeria and consists of conglomerates and grits. Overlying the Ise Formation is the Afowo Formation, which consists of coarse to medium grained sandstones. The Araromi Formation overlies the Afowo Formation and it is composed of fine to medium grained sandstone, shales, siltstone with interbedded limestone, marl and lignite (Omatsola and Adegoke,1981). The Ewekoro Formation, an extensive limestone body overlies Araromi Formation. Overlying the Ewekoro Formation is the Akinbo Formation, which is made up of shale and clayey sequence. The claystones are concretionary and are predominantly kaolinite. Oshosun Formation overlies the Akinbo Formation and consists of greenish – grey clay and shale with interbeds of sandstones. The Ilaro Formation overlies conformably the Oshosun Formation and consists of massive, yellowish, poorly consolidated, cross-bedded sandstones. Capping the sequence is the Coastal Plain Sands (Jones and Hockey, 1964) and consists of poorly sorted sands with lenses of clays.

3.0 METHODOLOGY

Aeromagnetic datasets of different vintages processed into a uniform grid of constant terrain clearance of 1000 m with 1000 m line spacing over the study area were employed for the structural characterization of the Benin Basin. Where the resolution permits, interpretation of coarse satellite derived gravity data was employed to complement the aeromagnetic data. The total magnetic intensity (TMI) map was reduced to the equator (RTE) to locate anomalies directly over their geological sources. Regional-residual isolation was accomplished using upward continuation approach of Blakely (1995) which showed that residuals can be derived by analytically continuing aeromagnetic data to a slightly higher surface and subtracting that from the original data. Different crustal types were mapped on the basis of density distribution using Analytic signal (MacLeod *et al,* 1993) attribute of satellite derived gravity. Analytic signal is often effective at highlighting geologically meaningful and subtle local anomalies (MacLeod *et al,* 1993). Surface, shallow and deep seated lineaments were mapped from lineament and TMI maps respectively. The lineaments were analyzed and classified geo-statistically according to their spatial and directional attributes using Rosette diagrams. Vertical derivatives (Milligan and Gunn, 1997), which calculate the vertical rate of change in the TMI signal was used to identify the fault systems. Pseudogravity transformation (using Poisson's relation between gravity and magnetic fields and under the assumption that the magnetic anomalies are caused by induction) of the upward continued TMI data was executed to image the subsurface structures. Under the assumption that the basement is magnetized uniformly by induction, the pseudo-gravity field can be attributed to the basement topography (Lakshmi and Babu, 2002). All deep seated structures were investigated using upward continued version of the TMI grid. Tilt derivative filtering (Miller and Singh, 1994) of TMI and decompensated satellite derived gravity maps was employed in basement contact and regional structure mapping. Tilt derivative is based on the ratio of the horizontal gradient and the total vertical gradient potential field grids. Source Parameter Imaging (SPI) method of Thurston and Smith (1997) was employed for depth computation. Structural features in the gridded data were highlighted with artificial illumination from the northeast direction. Joint forward modeling of aeromagnetic and satellite derived gravity data was employed to simulate a geological model of subsurface of the study area on the platform of GM-SYS.

4.0 RESULTS AND DISCUSSIONS

4.1 Magnetic signature of the study area

The TMI response of the study area (Figure 2) is characterized by anomalies of varying intensity (-117 to 173 nT), wavelength and trends implying different sources, depths, compositions as well as tectonic character. The residual TMI (Figure 3) reveals short wavelength anomalies that are concealed in the original map (Figure 2) by the long wavelength anomalies. The anomalies exhibit essentially steep magnetic boundaries implying vertical to steeply dipping walls of the basement blocks.

4.2 Crustal Rock Distribution

Analytic signal of upward continued (3 km) gravimetric data (Figure 4) illustrates E-W regional trend that grades from gravimetric low to high anomaly from the onshore north to offshore south respectively. This grading reveals gradual transition of the crustal rocks from continental to oceanic composition in which oceanic crust density is higher than the continental crust's. The gravimetric maximum in the far offshore depicts the high density oceanic crust. This variation is viewed to be associated with crustal compositional changes. Cycles of siliciclastic sedimentation in the Niger Delta have been observed to prograde over the oceanic crust into the Gulf of Guinea (Stacher, 1995). Thus, the crustal types in the study area changes from low density continental onshore to high density oceanic crust offshore.

4.3 Structural Lineaments

The surface lineaments map of the study area (Figure 5) shows NE-SW, NW-SE N-S and E-W (inset) to be the dominant trends. The lineament map obtained from the horizontal gradient of the tilt derivative of the residual aeromagnetic map (Figure 6A) features lineaments that originated from shallow sources. Rosette diagram of the shallow lineaments (Figure 6B) indicates four major lineament trends -, NE-SW, NW-SE, N-S and E-W - that characterize the shallow subsurface. The interpreted deep lineaments strikes in NE-SW, NW-SE and E-W directions (Figure 6C). Oluyide (1988) recognized the principal lineaments directions in the Nigerian basement complex as N-S, NNE-SSW, NE-SW, NNW-SSE and NW-SE and to a lesser extent, the E-W- which are rather localized. Sinistral and dextral faults with NE-SW, NW-SE and E-W were identified in the study area (Figure 7). The fault generation could not be established due to lack of overprinting relationship. Limited recognition of the E-W trends has been attributed healing by quartzo-feldspathic in- fillings (Oluyide, 1988). The NE-SW trend is similar to the oceanic fracture zones' that extended into the study area from the Atlantic Ocean. These predominant structure trends conform to Pan-African structural pattern (Kaki *et al* 2013). The E-W trend has been identified as the oldest (Oluyide, 1988) while the NE-SW and NW-SE are viewed as conjugate set in southwestern Nigerian which occurred under generally E-W trending, maximum compressive stress and have been interpreted to result from transcurrent movements (Okonkwo, 2001). Reduced number of lineaments at the southwestern area may be due to depth increase which hinder imaging of the deep lineaments. Spatial correlation of some shallow and deep lineaments (Figure 6A) suggest that some of the deep lineaments propagate to the surface.

4.4 Basin geometry

The Analytic signal of the TMI upward continued to 10 km (Figure 8) shows rock magnetization distribution in the study area. Low magnetization at the center of the study area is interpreted as presence of thick non magnetic sedimentary rock within the Lagos metropolis. This area corresponds to the 'Benin Basin proper' of Coker and Ejedawe (1987) characterized by drop in basement floor. The eastern and western parts are dominated by high magnetization values indicating presence of crystalline rock at the shallow depth, hence thin sedimentary accumulation. Badagry area is characterized by narrow belt of intermediate magnetization viewed as significant region of sediment accumulation. This map therefore revealed that the basement beneath the basin is not topographically flat, but characterized by a large basement depression flanked by basement highs (Omatsola and Adegoke, 1980). This observation thus imposed a horst and graben architecture on the basin geometry. The graben is viewed as zones of significant sediment accumulation where hydrocarbon exploration could be focused.

4.5 Deep seated structures

The most interesting features of the horizontal derivative of the pseudo-gravity image of TMI upward continued (10km) in Figure 8 are the two regional pseudogravity high extending through the eastern and western sides of study area in NE-SW direction. The eastern high indicates was interpreted as Okitipupa ridge (horst) (Omatsola and Adegoke, 1980) and is widely believed to be formed by structures associated with the onshore extension of the Chain fracture zone (Emery *et al* 1975, Coker and Ejedawe, 1987). Eagles and Konig (2008) and Moulin *et al* (2010) viewed fracture zones to be associated with the opening of Equatorial Atlantic starting in the Late Jurassic and continuing into the Cretaceous. The Okitipupa ridge correspond to the Benin hinge line of Murat (1972) which forms the boundary between the Benin Basin and the Niger Delta. The fracture zones were observed to have subdivided the continental margin along the West Coast of equatorial Africa into individual basins (Tuttle *et al,* 1999). The Tilt derivative map of upward continued (10 km) TMI data (Figure 9) shows amplitudes that range from -1.5707 to +1.5707 radians (-pi/2 to +pi/2) in agreement with Fairhead *et al.,* (2004) and Verduzco *et al.* (2004). The peak tilt response represents the basement block contacts in the area. The tilt derivative attribute revealed that the study area is highly segmented into block pattern and therefore portrayed the degree of tectonic activity the area has witnessed. These basement block contacts appear to have influenced the configuration of Lagos and Lekki Lagoons and certain parts of the coastline (Figure 10), suggesting that the surface geometry of the Lagoon and part of the coastline are structurally controlled. Structures recognized in the study area will play a major role in migration and entrapment of hydrocarbons and localization of other resources in this area.

4.6 Depth to Magnetic Basement

Magnetic basement depth map derived from SPI (Figure 11) shows alternation of basement high and low from east to west. There are two major basement depressions that run NE-SW and NW-SE in the western and central areas named Badagry and Lagos graben respectively. The depressions are separated by a basement uplift signifying horst and graben configuration. The maximum depth attained in the area is 6387 m. This is in agreement with Opara (2011) which estimated depth of 6039 m to the basement in the eastern part of the basin. However, Coker and Ejedawe (1987) believed the maximum depth to basement is about 2700m around the Nigerian-Benin border. On the other hand, seismic and bore hole data showed that sedimentary fill within the basin is more than 3500 m thick (Kaki *et al*, 2012).

4.7 Forward Modeling

Cross-sections constructed through the study area via joint forward modeling of the magnetic and satellite derived gravity profiles are shown in Figure 12. The major sedimentary units of the study area were lumped together as one and were assigned zero magnetic susceptibilities. In these profiles A-A', B-B' and C-C', the potential field response was accounted for by variation in depth (~0.2- 5 km), magnetic susceptibility (0.033 to 0.050 SI) and density (2642 to 2701kg/m^3) of crystalline basement. The W- E transect (profiles A-A' and B-B') in Figures 13A & B sufficiently imaged the horst and graben configuration of the basement with Lagos Graben and Okitipupa ridge being the prominent. Omatsola and Adegoke (1981) had recognized a number of horst and graben sectioned by N-S and NE-SW trending faults from a number of wells drilled to basement along the coastline. while the N-S transect (profile C-C') in Figure 13C revealed that the basement generally slopes from north to south. The N-S section of Billman, (1992) imaged a regional southerly tilt of the basement which was attributed to series of narrow step faulted basement blocks aligned parallel to the coastline (Coker and Ejedawe, 1987). Model results therefore bring forth the significance of potential field responses in imaging basement depth and architecture.

5.0 Conclusion

This study demonstrated the significance of geopotential field attributes in imaging basinal structures that will serve as the foundation for subsequent detail exploratory works. The basement of the Dahomey basin grades from continental to oceanic crust. Spatial correlation of some interpreted shallow and deep lineaments provided evidence of possible structural connectivity between shallow and deep structures. Major surface features were deduced to be structurally controlled and the basement underlying the Dahomey basin is of rugose horst and graben architecture. Lagos and Badagry grabens are zones of significant sedimentary thickness with possible hydrocarbon prospectivity.

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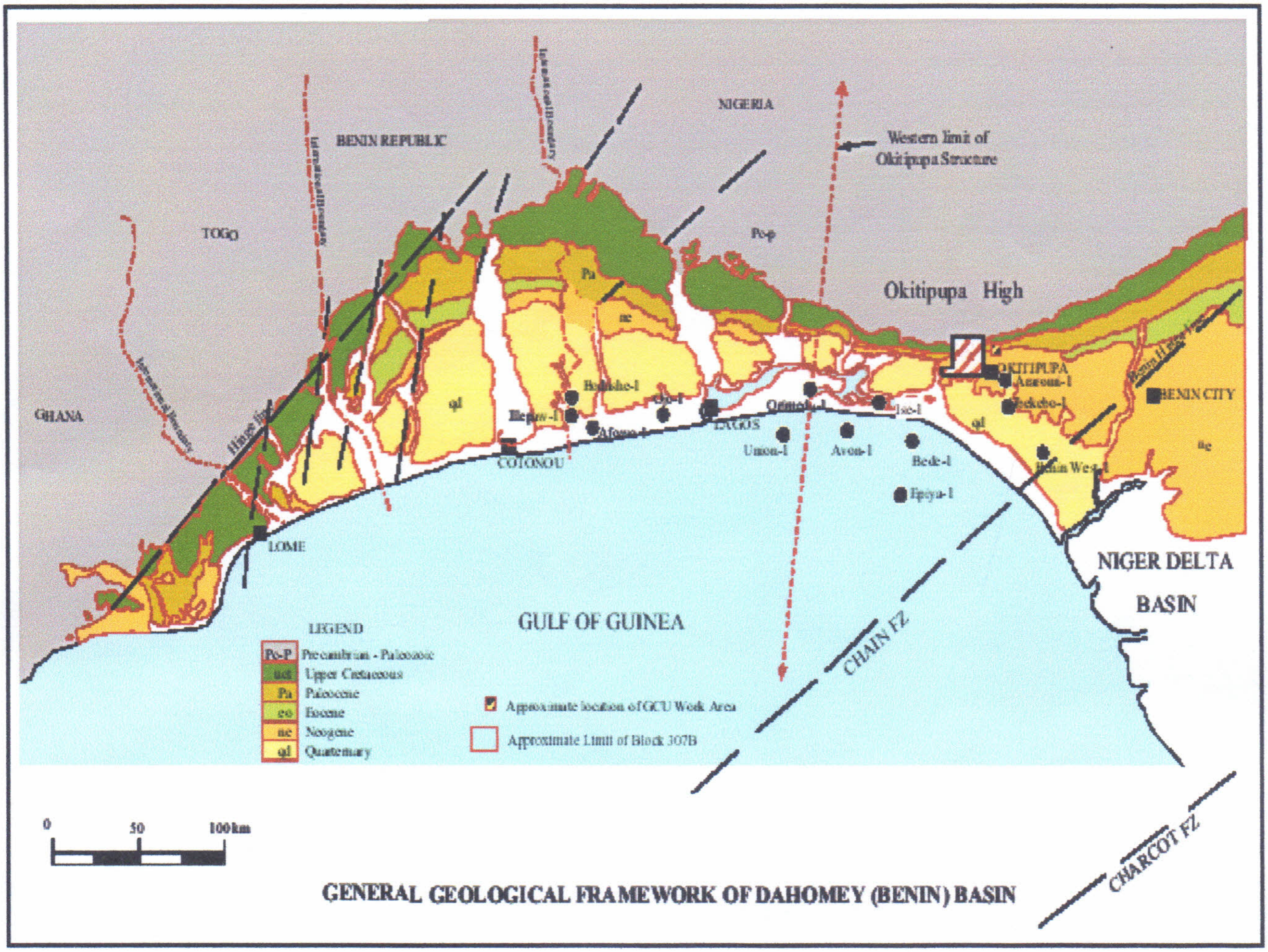


Figure 1: General Geological Framework of the Dahomey Basin. (Modified from Bilman, 1992).

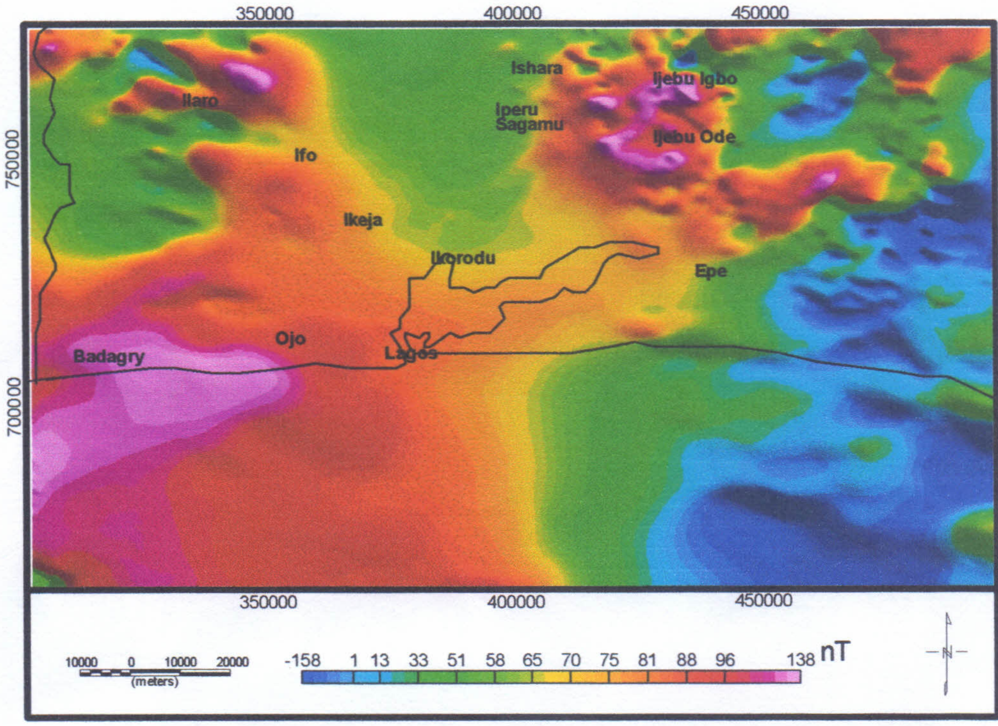


Figure 2: Reduced to the Equator Map of the Total Intensity Map of the Study Area

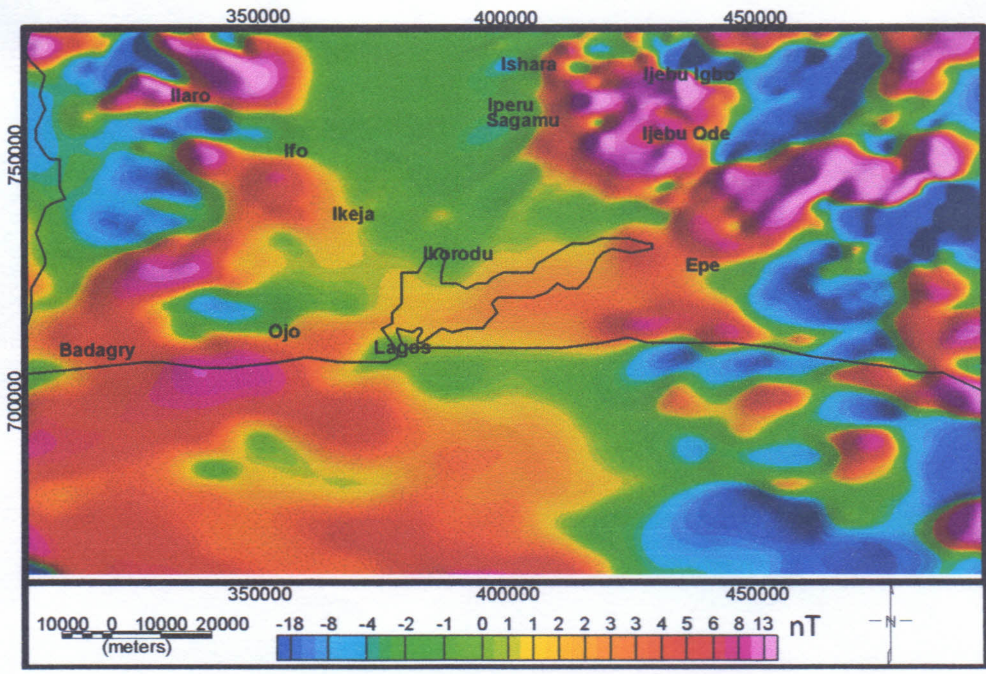


Figure 3: Resiual Aeromagnetic Map of the Study Area

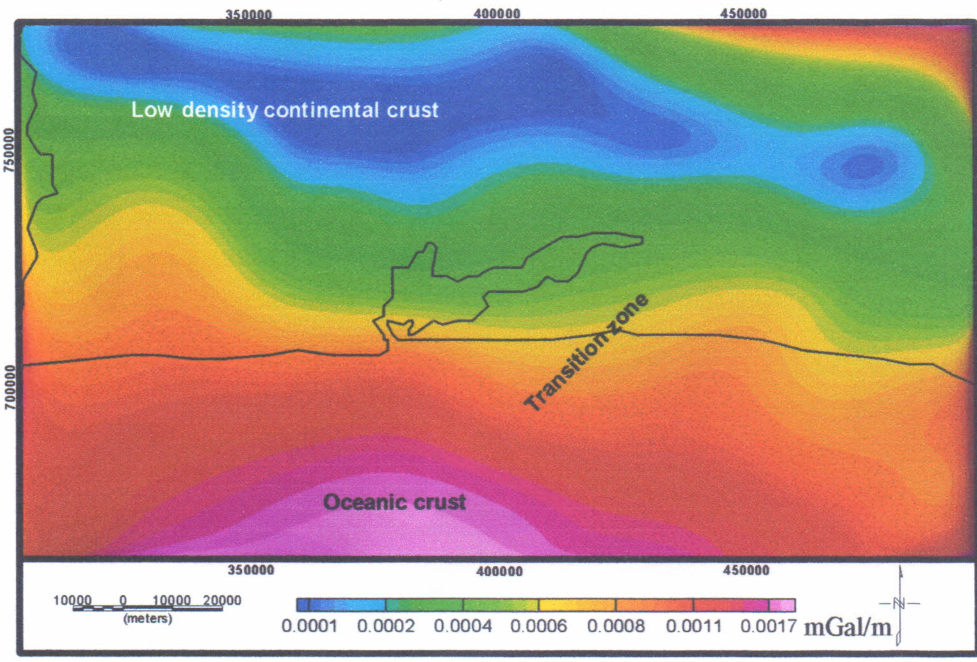


Figure 4: Analytic Signal of Upward Continued (3km) Gravimetric Anomaly

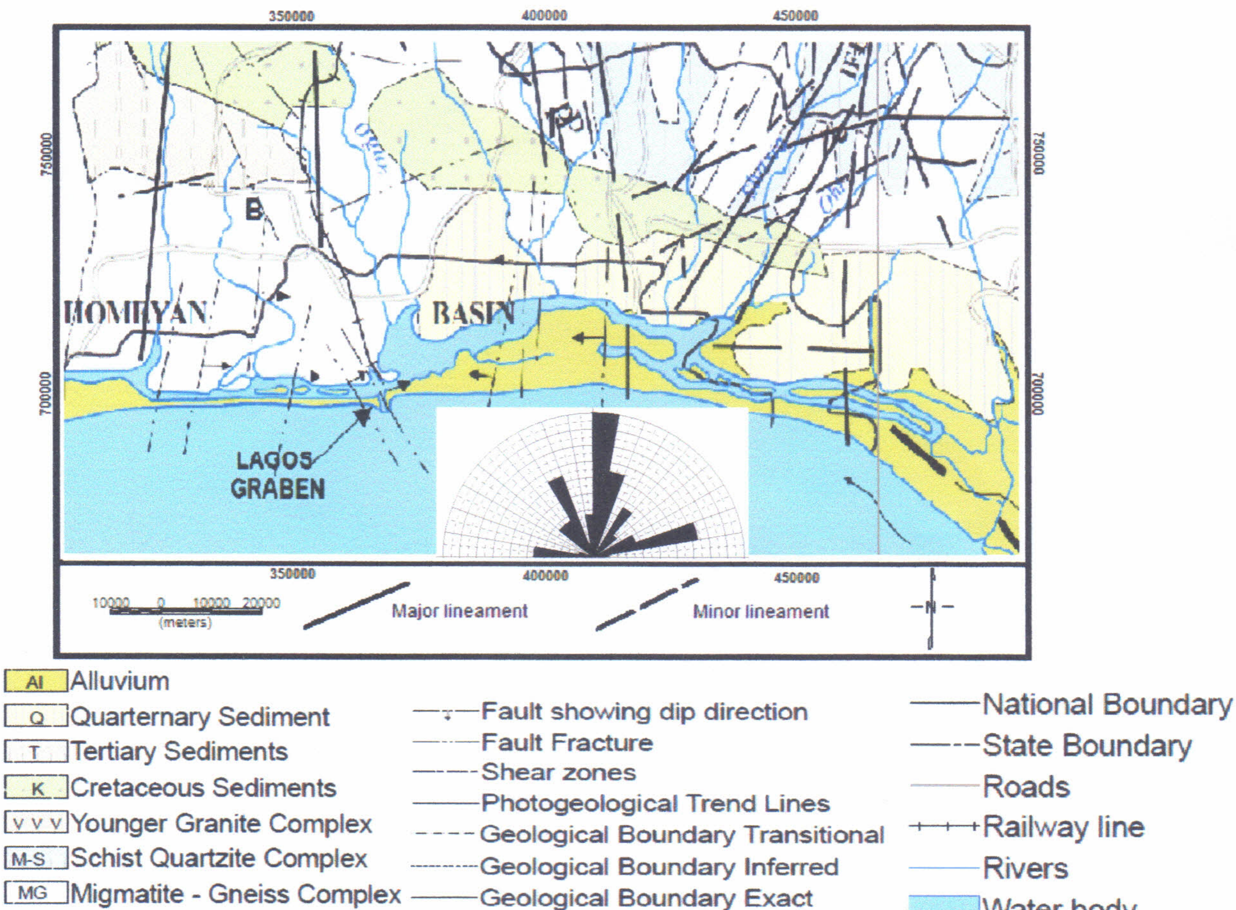


Figure 5: Surface Lineament Map (Geological Survey of Nigeria Agency)

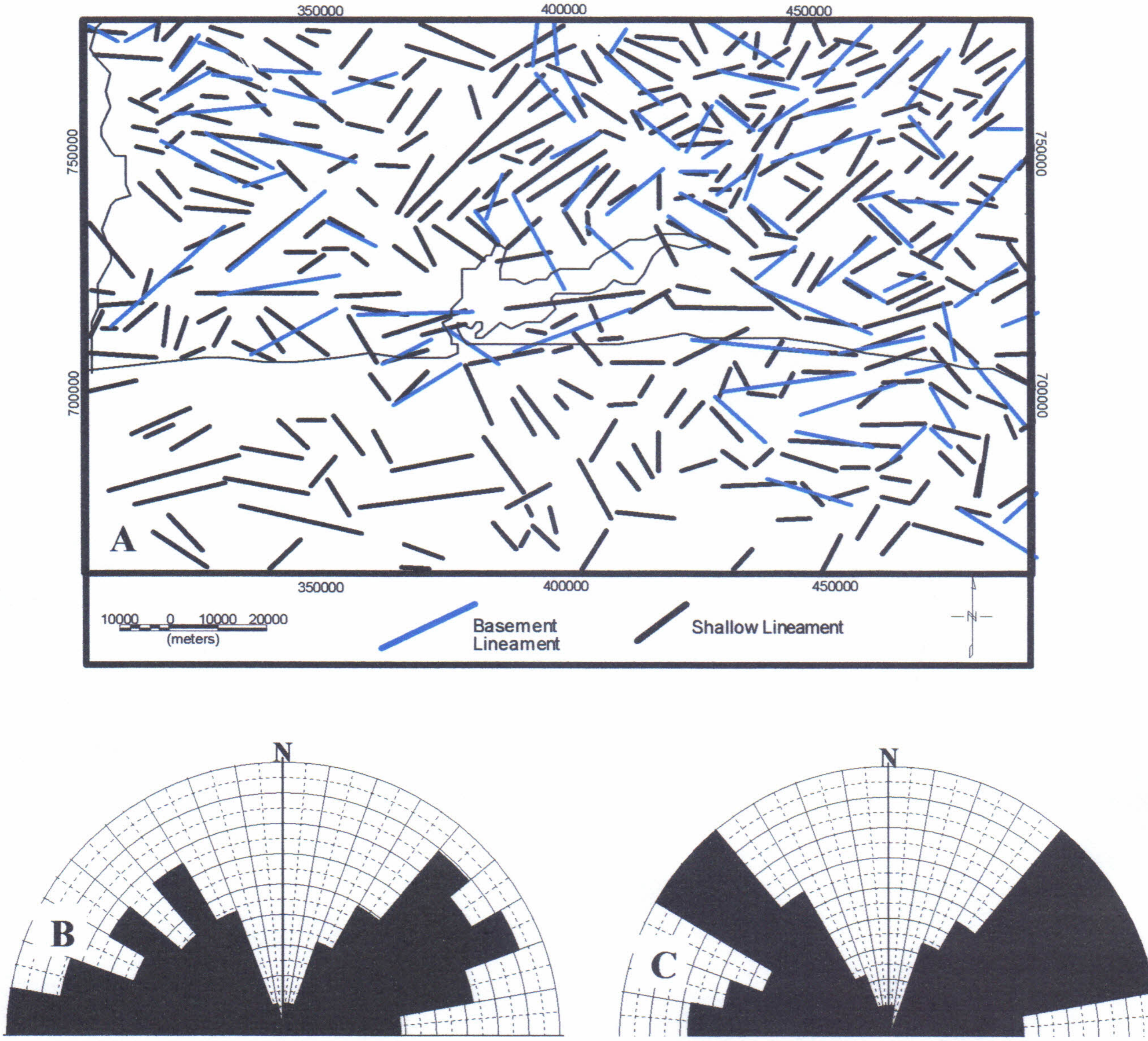


Figure 6: (A) Superposition of Shallow and Deep Lineaments derived from tilt derivatives residual and upward continued (5km) TMI data. B and C are rosette diagrams showing the dominant trends of shallow and deep lineaments respectively.

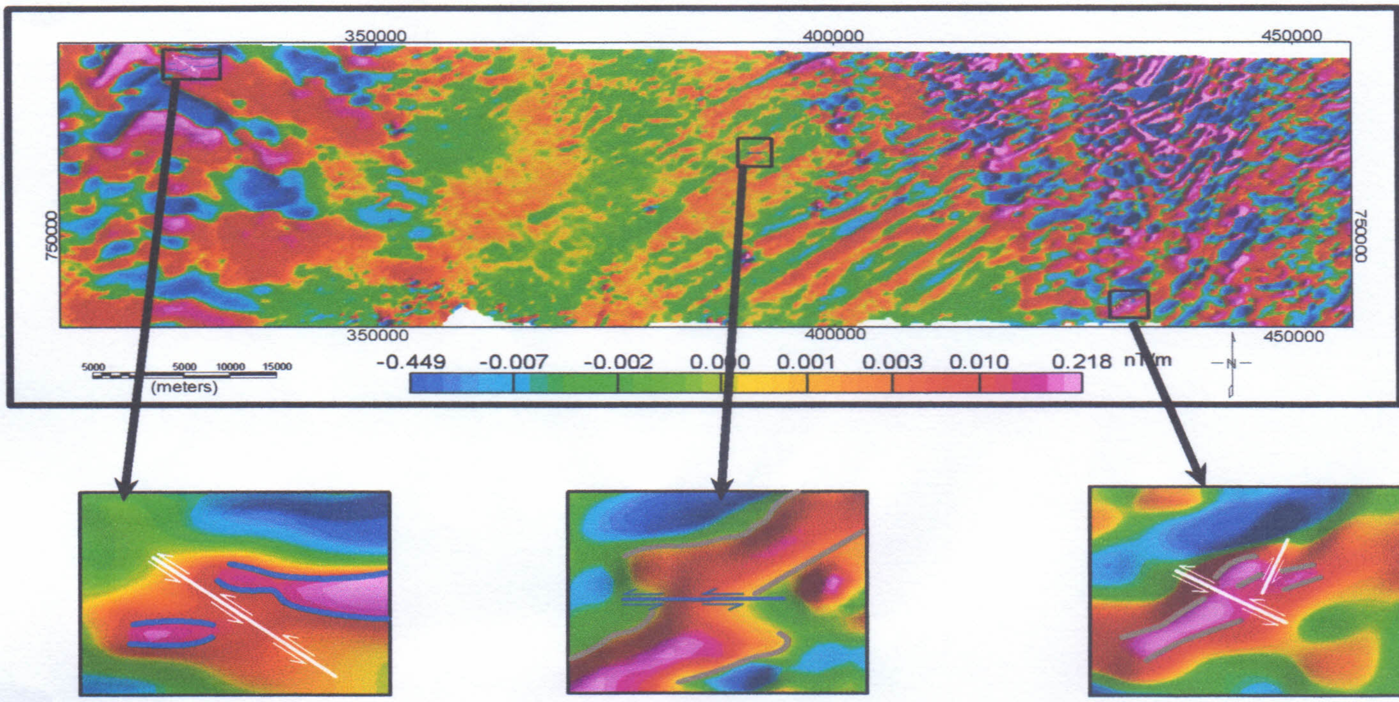


Figure 7: First vertical derivative of the High Resolution part of the TMI data showing the mapped faults in the study area

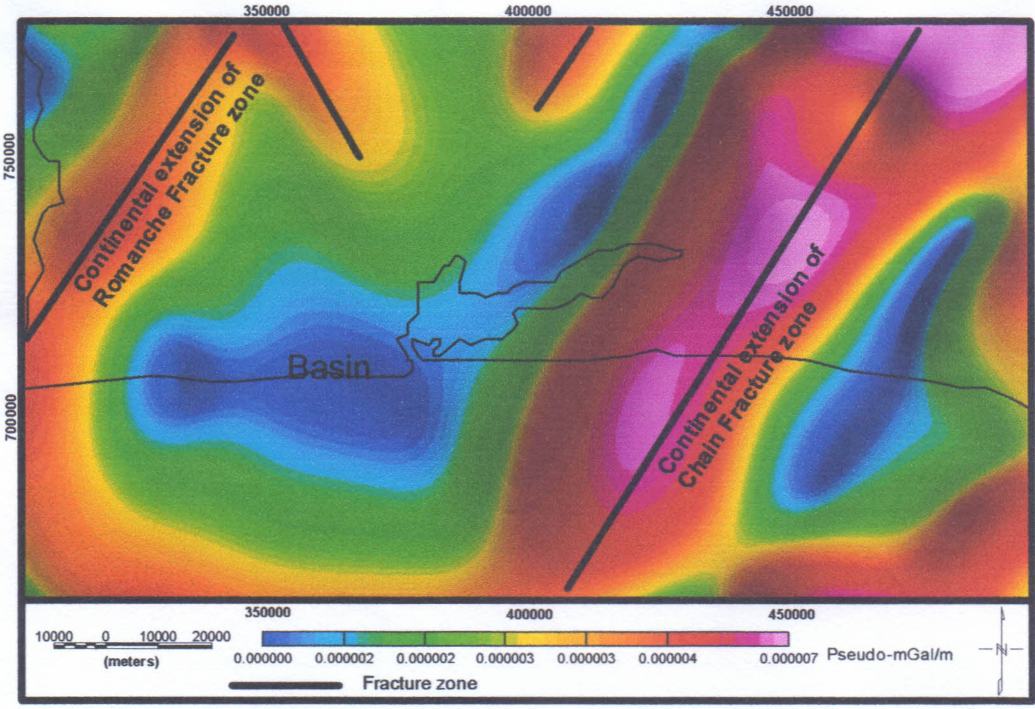


Figure 8: Horizontal derivative of pseudo-gravity map upward continued to 10 km

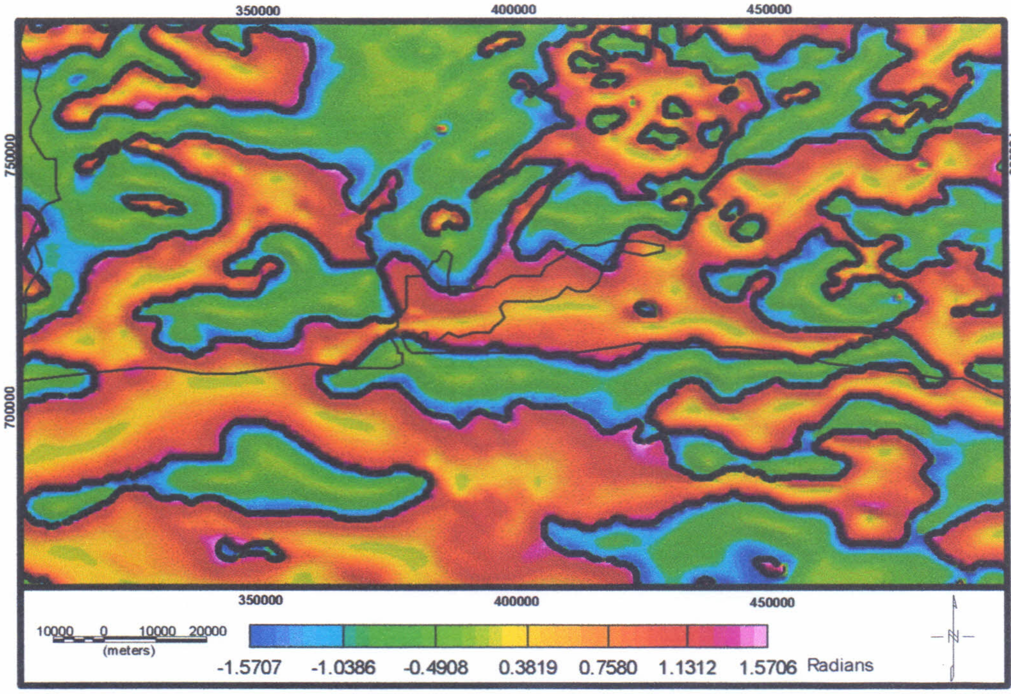


Figure 9: Tilt derivative map of upward continued (10km) aeromagnetic data showing basement block contacts

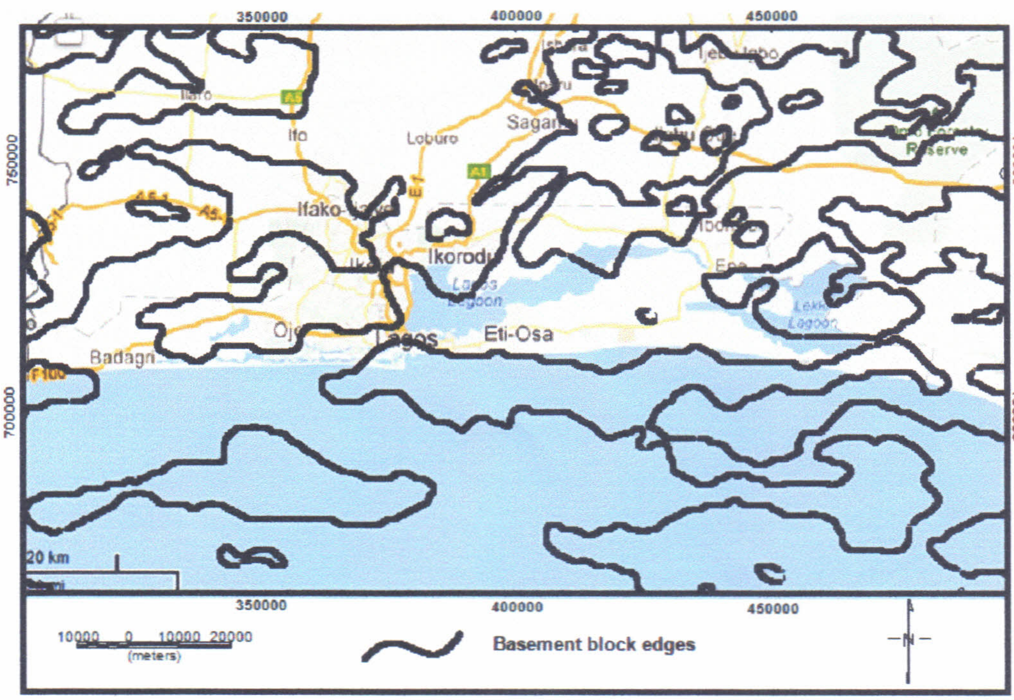


Figure 10: Basement Block Contacts Superimposed on the Geographic Map

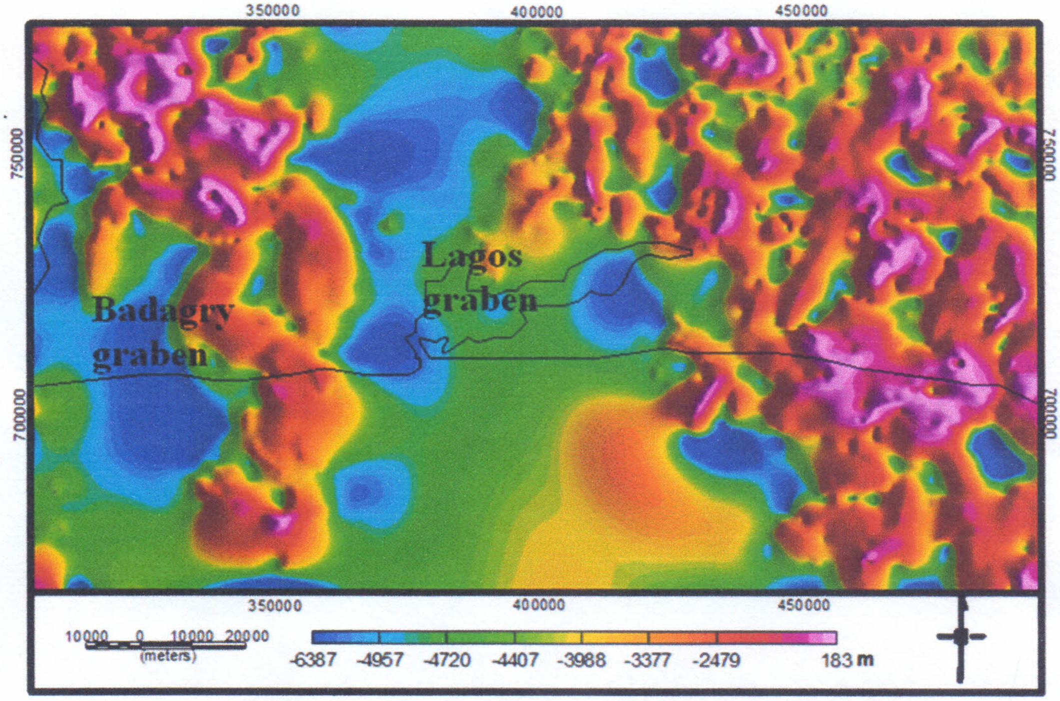


Figure 11: Depth to magnetic Basement derived through SPI Method.

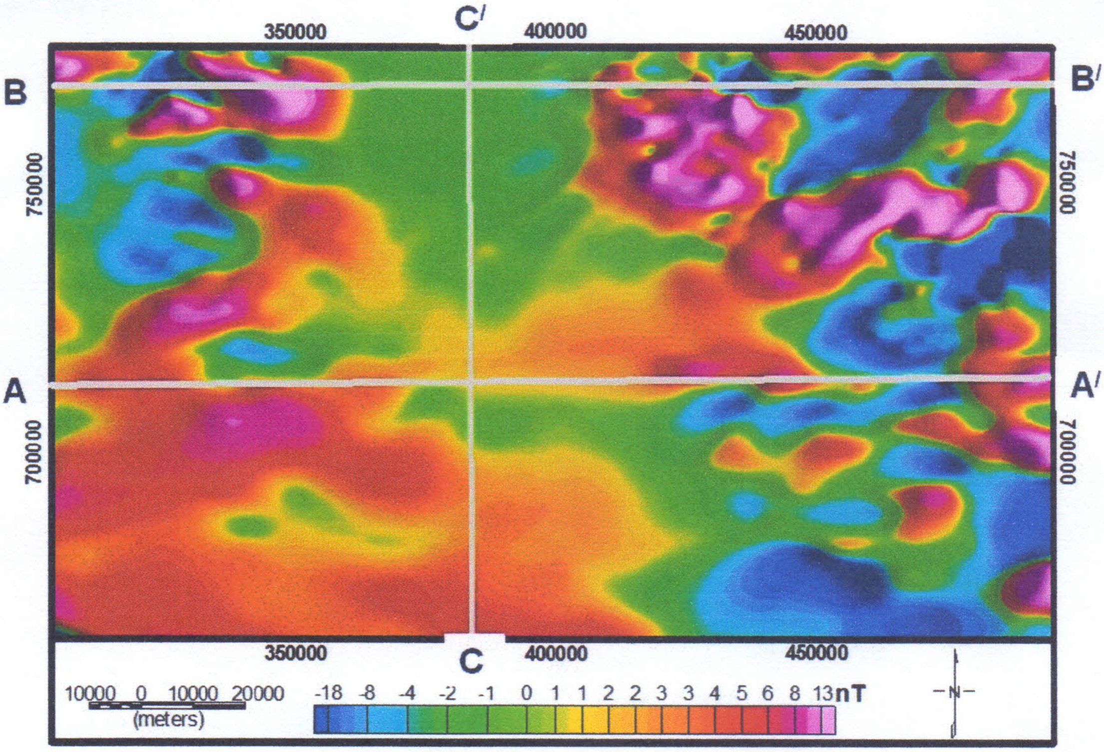
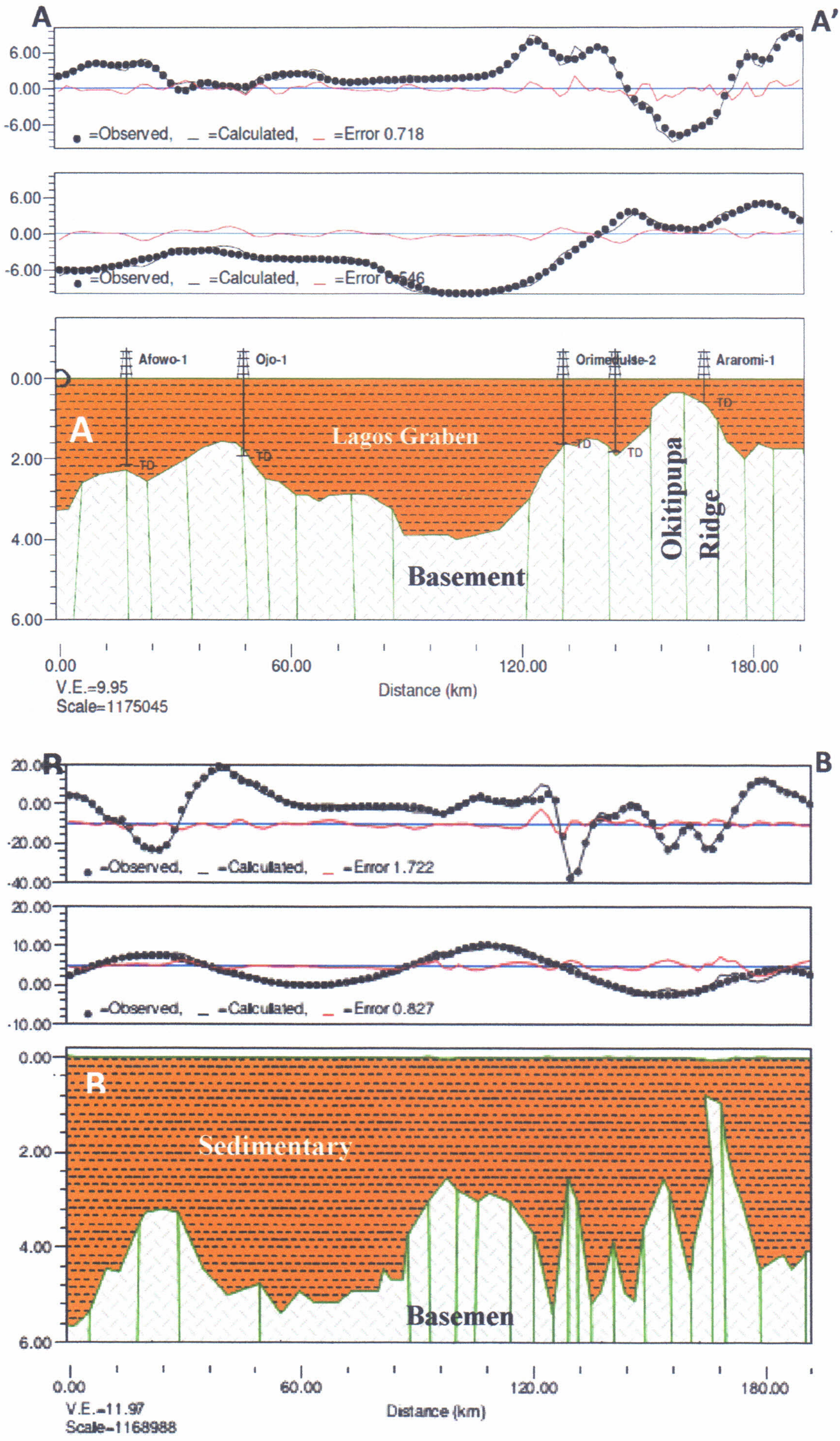


Figure 12: Residual map showing the locations of the modeled profiles A - A' to C – C'


A
A'
6.00
0.00
-6.00
=Observed, _ =Calculated, _ =Error 0.718
6.00
0.00
-6.00
=Observed, _ =Calculated, _ =Error 0.546
Afowo-1
Ojo-1
Orimedu-2
Araromi-1
TD
Lagos Graben
Okitipupa Ridge
Basement
0.00
2.00
4.00
6.00
0.00
60.00
120.00
180.00
V.E.=9.95
Scale=1175045
Distance (km)
B
20.00
0.00
-20.00
-40.00
=Observed, _ =Calculated, _ =Error 1.722
20.00
10.00
0.00
-10.00
=Observed, _ =Calculated, _ =Error 0.827
Sedimentary
Basemen
0.00
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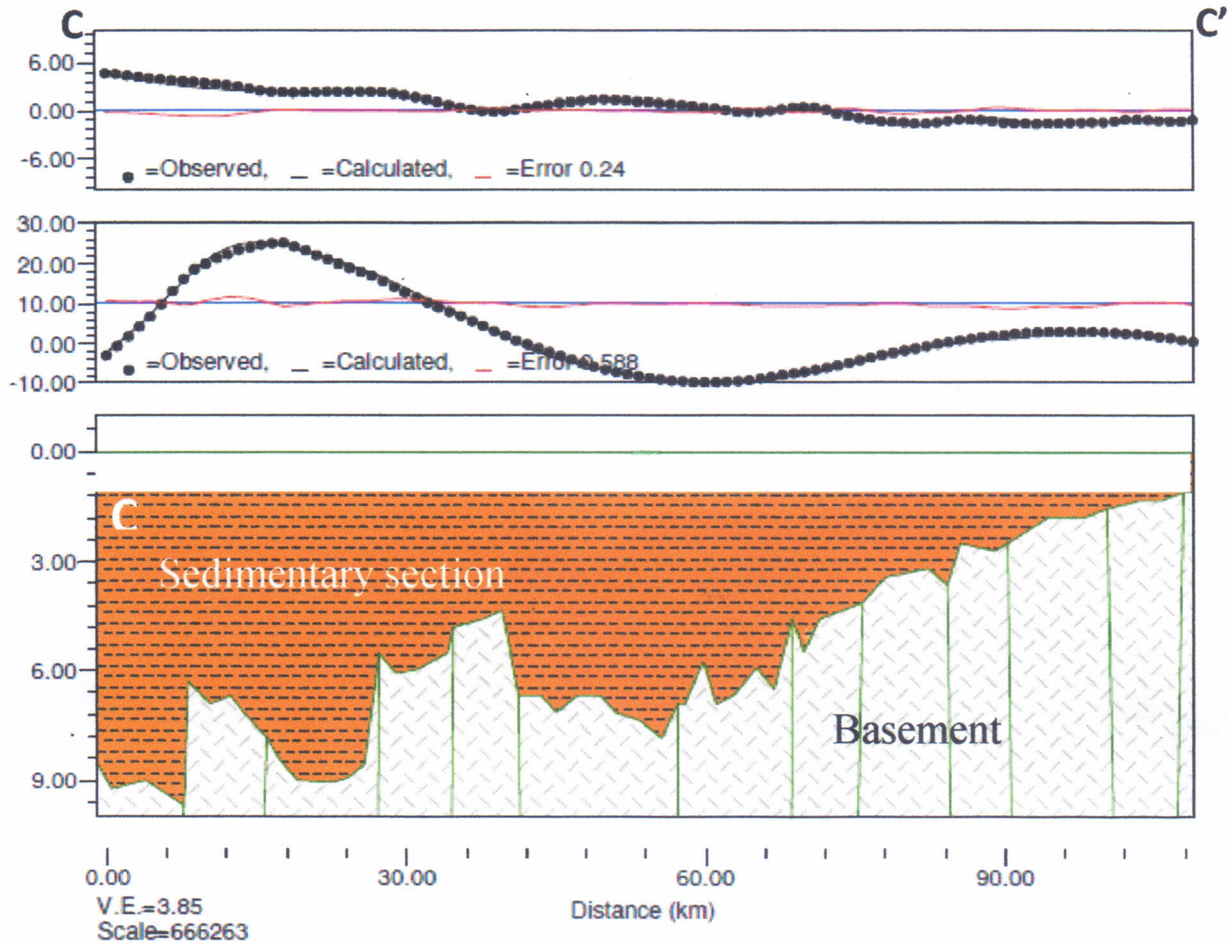

Figure 13: (A) W-E joint cross-sectional forward model across the coastline (B) W-E joint cross-sectional forward model across the northern part of the study area (C) S-N joint cross-sectional forward model through the study area