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Interpretation of Regional Magnetic Field Data Offshore Niger Delta Reveals Relationship between Deep Basement Architecture and Hydrocarbon Target

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Abstract

Directional horizontal derivatives, analytic signal, filtering of magnetic data sets and 3D magnetic modelling incorporating induced and remanent magnetization were performed on low resolution aeromagnetic data to unravel the basement structure and its relationship with hydrocarbon target offshore Niger Delta basin. Forward modelling of the residual magnetic data gave discrete depth values that were exploited to compile the depth to basement (thickness of the sedimentary section) map which highlighted deep depocenters, high blocks and major sedimentary fairways in the study area. The uplifted blocks created the arches while downdropped ones produced the depocenters. The depth to the basement map revealed basement paleotopography which resulted from movement along fault zones. The transformed/enhanced data revealed three potential stress regimes trending NE-SW, N-S and E-W. The NE-SW lineaments are shear zones, more dominant and indicate possible extensions within the African continent of Charcot and Chain oceanic fracture zones. The E-W lineaments are revealed not only in the enhanced maps but also in the total magnetic intensity and residual data sets because they are associated with dykes. The N-S structures are very subtle and are therefore highlighted only in the transformed data. In combination with the E-W structures they are brittle and reactivated structures associated with faults and have significant implications for the tectonic evolution of the Niger Delta and its basin extensions. The transformed data sets, depth to basement map and residual data strongly suggest that jostling of the basement blocks has influenced deposition in the Niger Delta basin. The structural highs (basement highs), basement lows (structural lows) and steep/faulted basement flanks are attractive sites for oil and gas accumulation.

Keywords: analytic, derivatives, basement, magnetic, modelling, hydrocarbon

1. Introduction

Correlation between basement features and magnetic expressions can readily be established because of the response of basement rocks to magnetic effect. From this relationship the impact on sedimentary section can be demonstrated if adequate knowledge of the regional tectonic history of the area is known and if modern tools for data analyses and interpretation are applied to magnetic data. Magnetic and gravity data can be used in many ways to solve different exploration problems, depending on the geologic setting and rock parameters. Although, most think of magnetic and gravity as tools to map structure; these data can be analyzed to provide insights to other elements of petroleum exploration and production (Johnson, 1998). Application of magnetic exploration can address such issues as where are the source rock deposited, how deep are the source rocks, how much relief is in there on the basement, where are thickest sediments, what is the influence of tectonics on deposition. Magnetic method of exploration has the potential to reveal major lineations and their relationships with more recent geologic features. It can also unravel structural grain and the presence of major structures. From regional aeromagnetic data sets, information such as tectonic frame of the upper crust can be obtained. The patterns and amplitude of anomalies reflect the depth and magnetic character of crystalline basement, the distribution and volume of intrusive and extrusive volcanic rocks and the nature of boundaries between magnetic terrains (Meyer Jr., 1998).

The application of magnetic method of geophysical exploration in sedimentary area is based on the fact that there is usually a marked difference in magnetization between the basement and that of the sedimentary section. In applying magnetic method, the data can be analyzed in different ways. In this study we used relevant transformed (enhanced) techniques and 3D forward modeling to achieve our objectives, which include the demonstration of the relationship between basement features and hydrocarbon target. This relationship is poorly understood in the Niger Delta even though it is well established in some other basin of the world. Additional objective is to demonstrate that exploration of hydrocarbon should proceed from the basement. This will contribute to basin modeling result and serve as a risk assessment for hydrocarbon exploration. One key reason is that structural analysis of the basement can advance the understanding of the overlying structures and the petroleum system for an area (Alexander, Prieto, & Radovich, 2003).

Thus, simply put, this study is to demonstrate the control on oil and gas located in the Tertiary strata of Niger Delta by the underlying Precambrian crystalline basement. We used inexpensive potential field (magnetic) data and showed that regional magnetic anomalies are sensitive to the variations of the structure and composition of the crystalline basement. Most bodies within the basement have distinctive magnitude, heterogeneity and magnetic fabric (Li & Morozov, 2006). Using regional magnetic data we unraveled structural pattern of the basement which include large structural domain, tectonic domain, magnetic lineaments and small structural domains. The large structural domain may be visible in the total intensity and residual magnetic field data but some lineaments, particularly, the subtle ones are only revealed in the transformed data. The identification and mapping of geometry, scale and nature of basement structures is critical in understanding the influence of basement during rift development, basin evolution and subsequent basin inversion (Smith & Mosley, 1993). Thus, we exploited enhanced techniques such as directional horizontal derivatives, analytic signal and traditional filtering techniques to map the subtle lineaments in the basement. Attention was paid to techniques which are amenable to studying structural features in equatorial belt. We combined Precambrian depth basement map obtained from 3D forward modeling with the enhancement techniques to identify major basement blocks, structural contrasts and basement topography. This approach proved invaluable to the geophysical information concerning the structural pattern and domain definition of the Niger Delta basin and hydrocarbon target.

Leblanc and Moris (1999) reported the correlation between residual magnetic field and majority of the hydrocarbon pools in Southern Alberta. Their findings showed that the long axis of the pool appears to be coincident with the strike of the basement- sourced magnetic signal and that pools are associated with linear and/or curvilinear magnetic lineaments, a great number of which have topographic expression. Their study also showed that Southern Alberta cross-cutting features or faulting systems are located within areas of majority of hydrocarbon pools and that hydrocarbon pools encompass areas of broad low amplitude magnetic anomalies. Jorgensen (2004) stated that small offsets in the basement structure can generate hydrocarbon traps by creating structural or stratigraphic traps in the overlying sediments. Using magnetic and gravity data he mapped basement geology and compared it to know oil and gas pool locations and used the information to show clear association between magnetic patterns and known oil and gas pools. Kreis and Kent (2000) reported basement control on sedimentation and hydrocarbon production in Southeastern Saskatchewan. Gay (1995) used residual aeromagnetics in Kansas and opined that this approach is a principal technique used in mapping basement and it is generally employed only to outline the basement fault block pattern. Successful application of basement structural analysis and the impact on overlying sediments has also been reported by Brown and Brown (1987). They concluded that the boundaries of the basement blocks which affect deposition are defined by lineaments which can be detected by the study of aeromagnetics. The ability to estimate/ interpret basement structure via magnetic depth estimates provides a more complete understanding of critical first-order basin exploration parameters (Li, 2003).

The Niger Delta (Figure 1) is situated in the Gulf of Guinea (Tuttle, Charpentier, & Brownfield, 1999). The delta has an area of 300 000km^2, sediment thickness of over 10 000km and sediment volume of 500 000km^3. The delta has only one identified petroleum system found within the Akata-Agbada Formation. The study area is bounded within latitude 3°30′-4°00′ N, longitude 6°00′-7°00′ E (offshore) and latitude 4°00′-4°30′ N, longitude 6°30′-7°00′ E [onshore] (Figure 2).

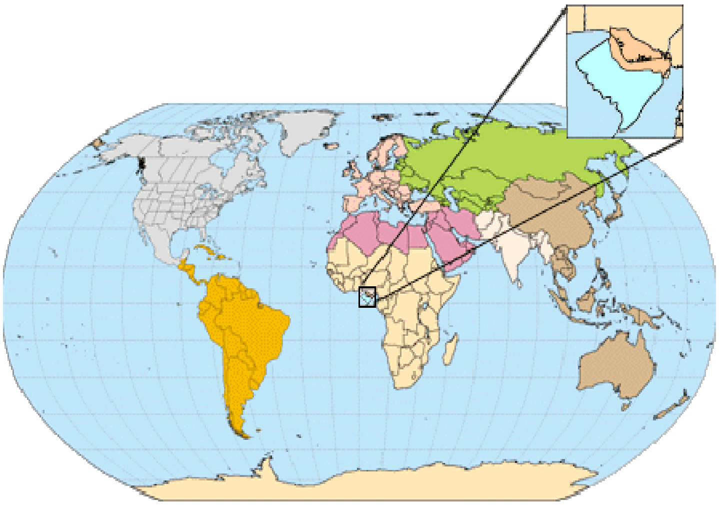


Figure 1. Location of the Niger Delta province (United States Geological Survey open file report, 1999)

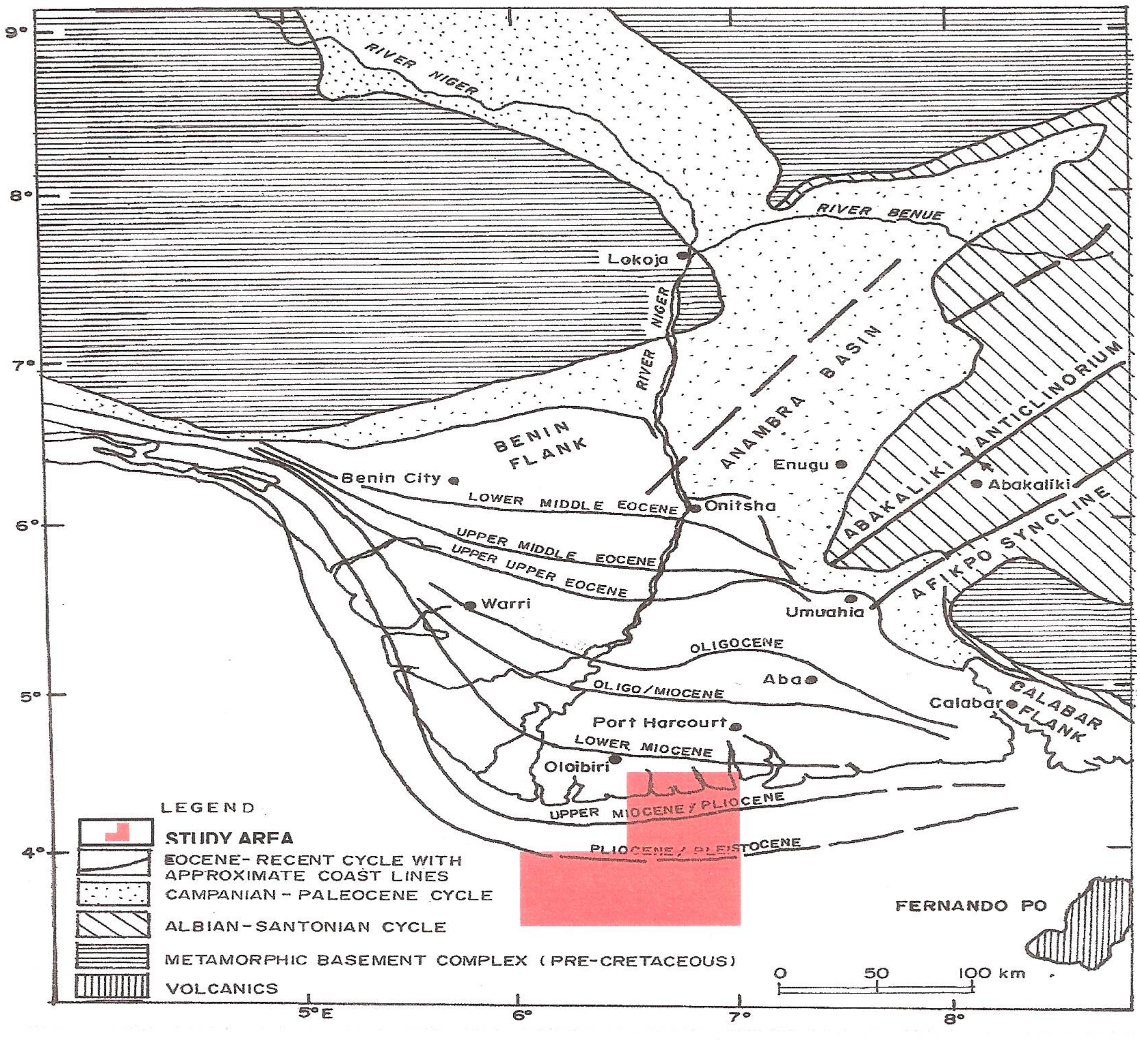


Figure 2. Generalized geological map of the Niger Delta Basin showing the study area

2. Geologic and Tectonic Setting

The Tertiary sedimentary fill of the Niger delta basin shows an overall upward and updip transition from marine prodelta shales (Akata Formation) through an alternating sand/shale paralic interval (Agbada Formation) to continental sands of Benin Formation (Ejedawe et al., 1984). The sedimentary sequence (Figure 3) was deposited in a series megasedimentary belts (depobelts) in succession in time and space with southward progradation of the delta. Evamy et al. (1978) showed that each depobelt is bounded to the north by a major structure-building fault and to the south by a change in regional dip of the delta or by a counter- regional fault. The delta is a large arcuate-type basin and the sediments reach a maximum thickness of about 12,3000 m (Hospers, 1965). The sands and sandstones of the Agbada Formation are the main hydrocarbon reservoirs.

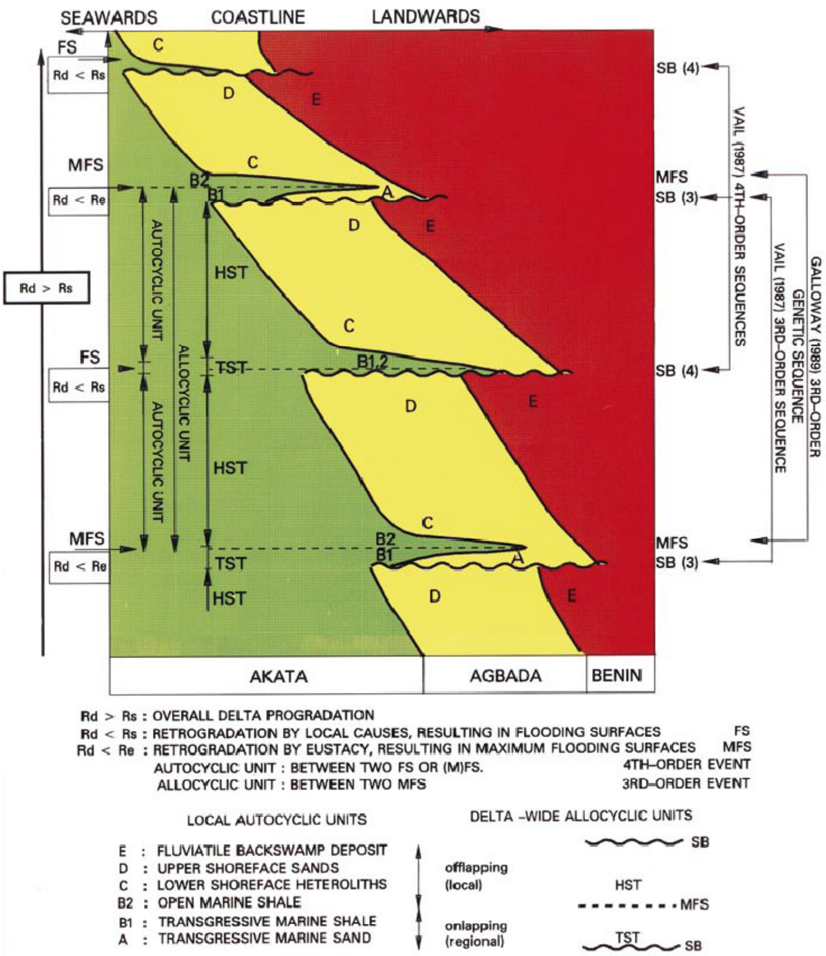


Figure 3. Mechanisms and units of delta evolution (After Reijers, 2011)

During the Cenozoic, until the Middle Miocene, the Niger Delta grew through pulses of sedimentation over an oceanward-dipping continental basement into the Gulf of Guinea; thereafter progradation took place over a landward-dipping oceanic basement (Reijers, 2011). The development of the delta has been dependent on the balance between the rate of sedimentation and subsidence. This balance and the resulting sedimentary patterns appear to have been influenced by the structural configuration and tectonics of the basement. Basement tectonics related to crustal divergence and translation during the Late Jurassic to Cretaceous continental rifting probably determined the original site of the main river and controlled the early development of the delta (Evamy etal., 1978).

The tectonic framework of the continental margin along the West Coast of equatorial Africa is controlled by Cretaceous fractures zones expressed as trenches and ridges in the deep Atlantic. The trough represents a failed arm of a rift triple junction associated with the opening of the south Atlantic (Tuttle, Charpentier, & Brownfield, 1999). In the Delta, rifting diminished altogether in the Late Cretaceous. After rifting ceased, gravity tectonics became the primary deformational process. Shale mobility induced internal deformation occurred in response to two processes. First, shale diapirs formed from loading of poorly compacted, over-pressured prodelta and delta-slope clays (Akata Formation) by the higher density delta-front sand (Agbada Formation). For any given depobelt, gravity tectonics were completed before deposition of the Benin formation and are expressed in complex structures, including shale diapirs, roll-over anticlines, collapsed growth fault crests, back-to-back features and steeply dipping closed spaced flank faults (Evamy et al., 1978). Deposition of the three formation occurred in each of the five off-lapping Siliciclastic Sedimentation Cycle that comprises the Niger Delta. One of the most conspicuous geological features of the Niger Delta is its growth fault pattern. Almost all the oil reserves are contained in rollover structures which are associated with growth -faults. These structural features are thought to have been formed by the force of gravity acting on a thick body of sediments supplied mainly by the Niger River (Webber, 1971).

3. The Regional Magnetic Field Data

The total intensity magnetic data (Figure 4) was flown at an elevation of 2500 ft (762 m) above sea level with flight line spacing of 2 km. This is therefore a low resolution data sourced from geological survey of Nigeria. The magnetic anomalies are sourced overwhelmingly from the basement. The main advantage of this data for this study is that cultural features such as railroad tracks, power transmission cables, metals from buildings, drill cores, storage tanks, steel well casings, oil pipelines and other metallic objects are not sources of anomalies in the data and therefore, cultural editing are not required. Large concentrations of cultural sources with particularly strong and pervasive magnetic fields such as cathodically protected pipelines can seriously mask the geologic information contained in aeromagnetic survey data (Philips, Saltus, & Reynolds, 1998). Gridding of the data were done at 1km interval along the flight lines which is orthogonal to the regional geologic strike. The grid spacing is tight enough to capture the anomaly details and meet the objective of this study. All the magnetic maps were plotted with potent software with the colour interval in all the figures being the convention in magnetic studies. The magnetic highs are depicted with yellows, oranges and reds while purples, blues and greens represent magnetic minima (lows). Using colours on the aeromagnetic map further accentuates the effects of visualization of the magnetic fields. The gradient zones in the total magnetic intensity field data are shear zones. The shear zones are relics of basement tectonics and are early Precambrian plate boundaries. They trend NE-SW and are principal zones of weakness in the basement and reflects edges of basement blocks.

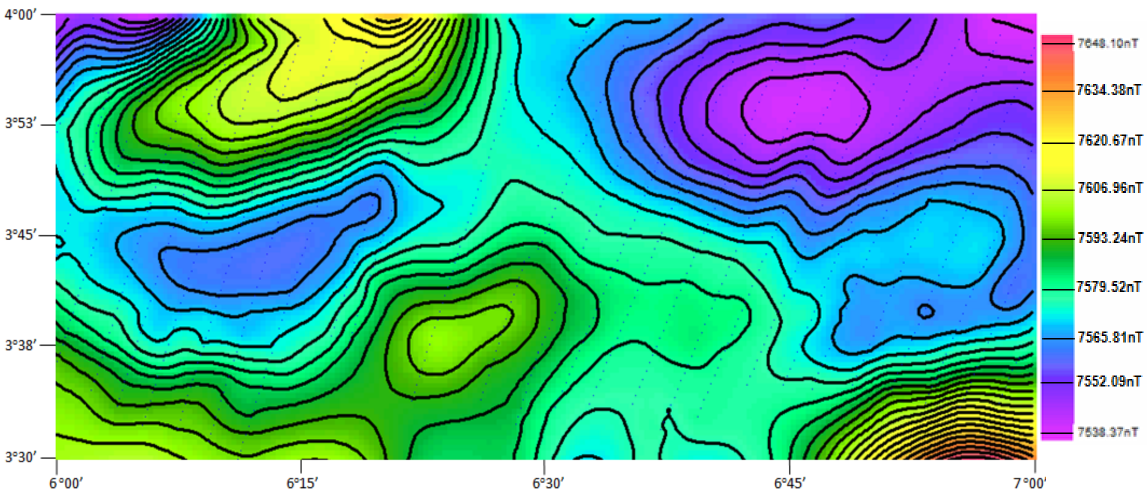


Figure 4. Total magnetic intensity data offshore Niger Delta. The gradient zones and elliptical contours reflects basement structures

The magnetic anomalies in Figure 4 are as a result of total magnetization of rock and represent the vector sum of the induced and remanent magnetizations. The induced magnetizations are produced as a result of the interaction of magnetic minerals with the Earth's magnetic field. This is contrary to the remanent magnetization which acts independently of the Earth's present field. If remanent magnetization is significantly strong and acts in the direction opposite to the present field, it can generate isolated magnetic high at low latitude and produce a magnetic low at high latitude. If the induced magnetization acts in the direction of the Earth's field it produces a magnetic low in low latitude. Experimental work on rock magnetization has made it abundantly clear that contrary to the earlier belief, presence of remanent magnetization is often the rule than the exception, in the rocks of the Earth crust and remanent magnetization associates itself with induced magnetization to orient the polarization vector of the rock mass in some arbitrary direction (Bhattacharyya, 1964). The direction of this polarization vector influences appreciably the size and shape of the associated magnetic anomaly. The ratio of the strength of remanent magnetization to induced magnetization is known as Koenigsberger ratio. If the Koenigsberger ratio is greater than one, it suggests that the remanent magnetization played a dominant role.

The observed data was used to compute, by least squares, the mathematically describable surface giving the closest fit to the magnetic field that can be obtained within a specific degree of detail. We exploited the fact that the regional field is a first-order surface of the form:

$$T(x, y) = ax + by + c \tag{1}$$

Where a, b and c are the coefficients and are computed so as to minimize the variation of the residual. This approach of computing the regional is suitable because higher order polynomials may be amenable to a large area over which the regional has many convolutions. The regional field was subtracted from the total intensity data to obtain the residual field data (Figure 5).

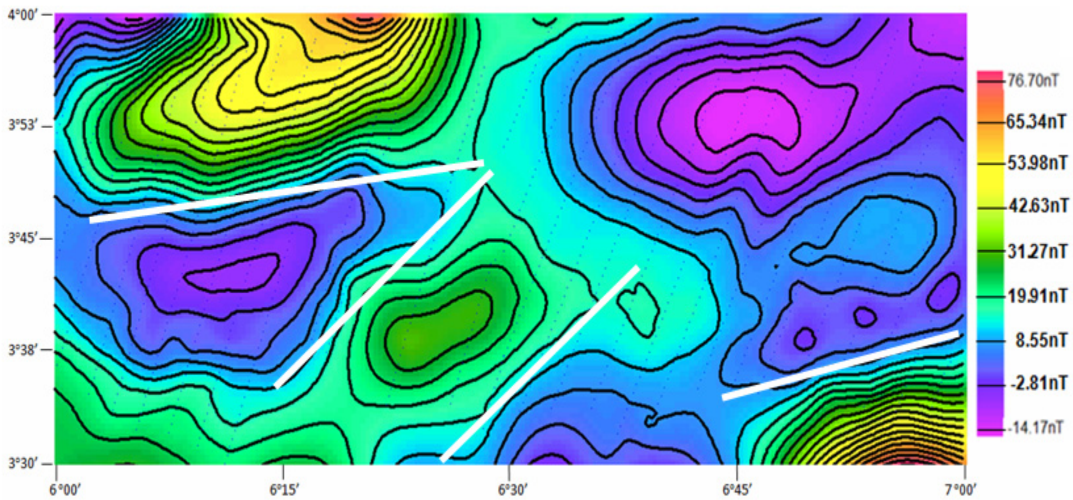


Figure 5. The residual magnetic basement surface showing some circular and elliptical contours not revealed in the total magnetic intensity data. The white lines indicate shear zones

In the total intensity data (lat. 4°00′ N - lat. 3°41′ N and long. 6°00′ E - 6°18′ E) an elliptical magnetic high and low trending E-W are separated by strong magnetic gradient. The low is closely flanked by a high trending NE-SW as shown in the total intensity and residual maps. The northeast sector is also characterized by elliptical anomaly trending E-W. The elliptical disposition is a pointer to dyke-like intrusions. The predominance of these lineaments striking NE-SW and E-W can be attributed to regional stresses in the basement. There is a high gradient in the southeast sector of the study area juxtaposed with elliptical anomalies. The elliptically shaped anomaly in the residual data has three small circularly shaped anomalies not revealed in the total intensity map. These are plug-like intrusives within the basement.

4. 3D Magnetic Modelling and Depth Determination

For resource exploration purposes one of the most useful inferences that may be derived from analyses of potential field (magnetic and gravity) data is the depth to crystalline basement beneath sedimentary cover (Milligan, Reed, Meixner, & FitzGerald, 2004). Most magnetic anomalies come from only a few rock types, such as volcanics, intrusives and basement rocks. Magnetic data therefore can be used to estimate depth to basement- a classic use for such data (Gibson, 1998a). Generally, there are two approaches to potential field modeling: inverse and forward modeling. In magnetic modeling the inverse approach is whereby a 2D or 3D susceptibility or geometric model is computed to satisfy (invert) a given observed magnetic field. In this case, the input is the observed data while the output is the geologic model. That is, the observed data is used to draw conclusion about the physical properties of the system. Physics principle allows the means for computing the data values given a geological model. This constitutes forward modeling (problem).This implies that if one has the knowledge of the properties of a system one can predict the response of that system. Therefore, the input of a forward model is the geologic model while the output is the computed values. Forward modeling commences by erecting a model based on geologic knowledge and geophysical intuition, then calculating the predicted magnetic field and comparing with observations. The next important step is to iterate the model to fit. The most significant aspect of forward modeling is that it could show if the postulated geologic model is incompatible with potential field data. This reduces ambiguity in interpretation. Thus, in this study, we adopted 3D forward modeling because the geologic setting of the Niger Delta is well known.

The 3D model constitutes a network or grid values which models a geologic surface represented as a surface of susceptibility contrast. The residual magnetic field data (Figure 5) was used for modeling instead of the filtered/enhanced magnetic field data. It is not appropriate to model using filtered data, because we do not know if the component of the magnetic field removed by the filter is also removed in our model (Bird, 1997). If an interpreter has two to three depth points, two at the edges and one on the basin floor, these depths are contoured with knowledge of the expected structural style (Millegan & Bird, 1998). To fulfill the above condition profiles were taken to model the depth to the basement using rectangular wire frame in Figure 6. In our approach, we used a complete quantitative approach. Complete in the sense that the three types of information about the geologic target (the depth, geometry/dimensions and the contrast in the relevant physical properties) were estimated. The 3D forward modeling is based on models that accommodated both induction in the Earth's field and remanent magnetization. Magnetics like other geophysical methods are non-unique. One way we adopted to reduce the ambiguity in interpretation is by using geometric simple bodies. In potential field modeling, popular geometric bodies usually exploited are ellipsoids, plates, rectangular prisms, polygonal prisms and thin sheets. In this study, we used rectangular prism model because of its simple shape and because it makes the process of modeling simple and stable. Thus, simple models were created using rectangular prism that conform regularly well with the data on the profiles and that are consistent with anomalies on the image of the observed field. Secondly, ambiguity is reduced because we know the geologic (rift) setting of the Niger Delta. The most important element required for interpreting magnetic data is a geologic concept or structural model. We are never blind; even if the only data available in an area is magnetic data, we know the area is in rift setting or foreland basin or along a passive margin. The data is no longer non-unique (Bird, 1997). Another approach we used to account for non-uniqueness was to fix susceptibility and vary geometry until a reasonable fit was achieved. The modeled magnetic anomalies (Figures 8-10) resulted from lithologic and structural changes. Lithologic variation (igneous and metamorphic) usually produces the strongest magnetic signals. Amplitude of hundreds of nanoTesla is due to lithologic variations in the basement or igneous rocks within the sedimentary section while amplitude of tens of nanoTesla are related to basement structures. The amplitudes of the anomalies modeled have been moderated by two factors. The main factor is that the basement rocks in the study area are buried by thick sedimentary sequence, thus their amplitude is moderated. The second factor is that high amplitude anomalies would be observed where basement structures are not present. In the study area there are sufficient basement structures (for example, faults, contacts and dykes). Thus, if a small anomaly caused by a large structure is superimposed upon a large anomaly caused by lithologic contrast, the two features may be inseparable. Zones of lithologic contrast are often loci of structural disturbance (Gibson, 1998b). Magnetic and gravity data have been traditionally thought of as regional screening tools capable of providing basin edges or basement mapping. In recent years, the application of these data has greatly expanded to include modeling of prospect-level targets. If detailed prospect-level quantification of the basement structure is required, a 3D model would be more appropriate (Jacques, Parsons, Price, & Swhwartz, 2003). We exploited the algorithm of (Bhattacharyya, 1964) based on magnetic anomalies due to rectangular prism-shaped bodies to determine depth to basement. This algorithm helped to meet our objectives because it considered both induction in the Earth's field and remanent magnetization. The parameters defining the prisms are shown in Figure 7. Six profiles (Line 800E, Line 900E, Line 1400E, Line 2200E, Line 2400E and Line 2900E) in Figure 6 were modeled to obtain geometry, physical properties and depth to the basement sources. The attitude (orientation) of the body (sources) is affected by the manner in which the profiles cut the bodies. The shape of the magnetic anomalies in all the models were affected by the shape, depth of the sources, orientations of the profiles, inducing and remanent field which varies in intensity and direction of magnetization (Williams, Fairhead, & Flanagan, 2002). Five discrete basement depth values were obtained from the modelled data and these values provided additional depth control offshore. These basement depth values which are equivalent to the thickness of sedimentary section in the study area contribute to basin modeling and put an upper limit on the thickness of source rocks, the base of which may not be well imaged from seismic information (Jacques et al., 2003).

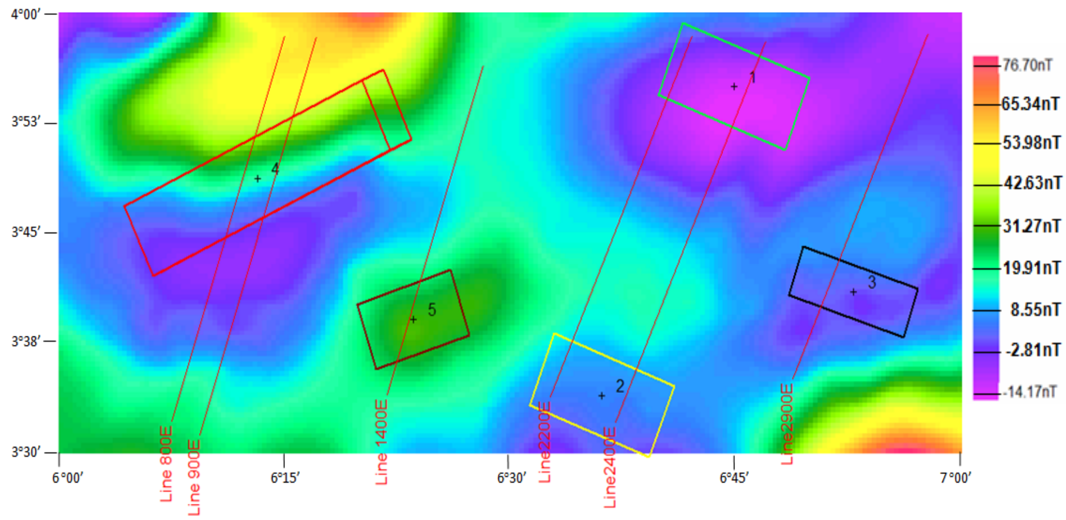


Figure 6. The location of profile lines 800E, 900E, 1400E, 2200E, 2400E and 2900E in the residual magnetic field data. The rectangular wire frames represent the magnetic sources

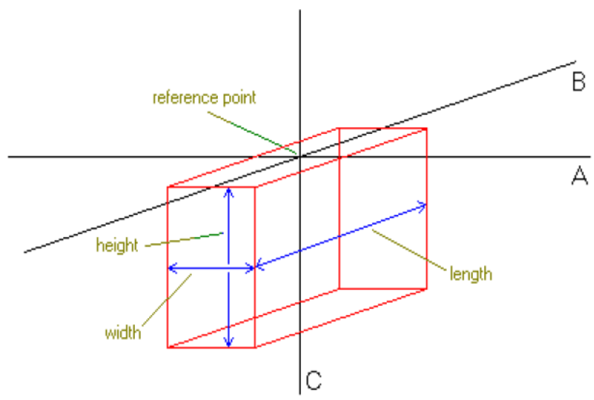
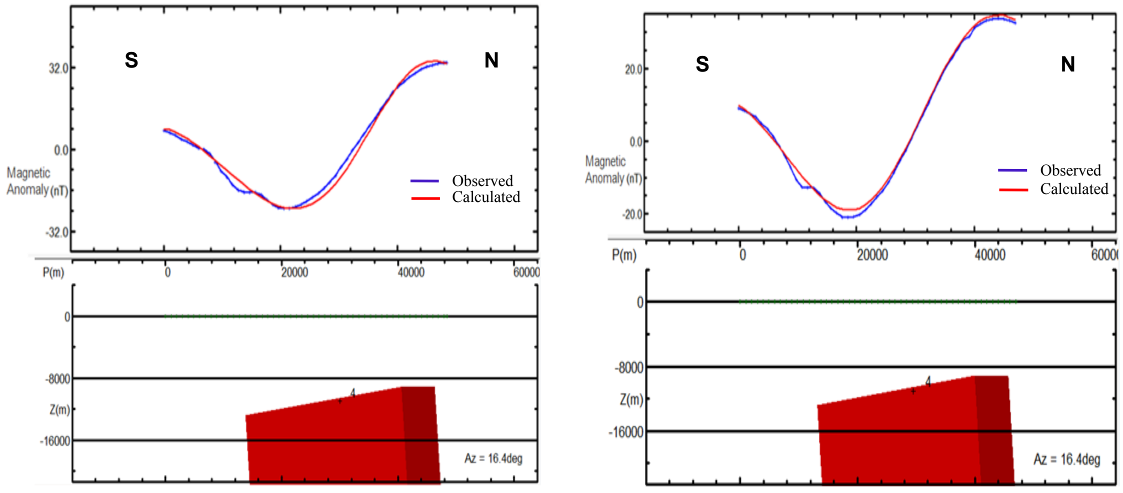
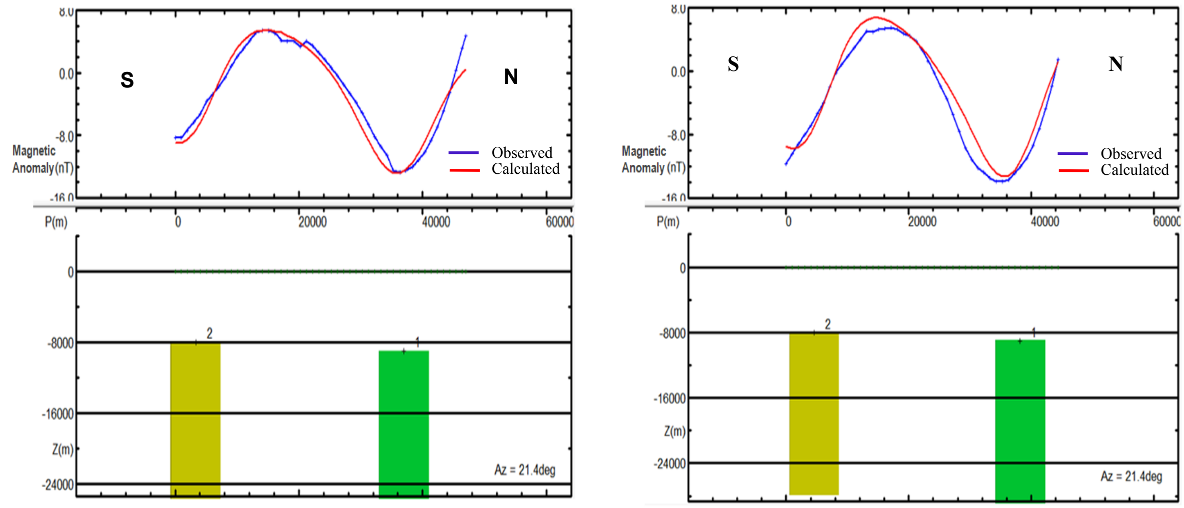


Figure 7. Rectangular prisms showing the parameters of the model



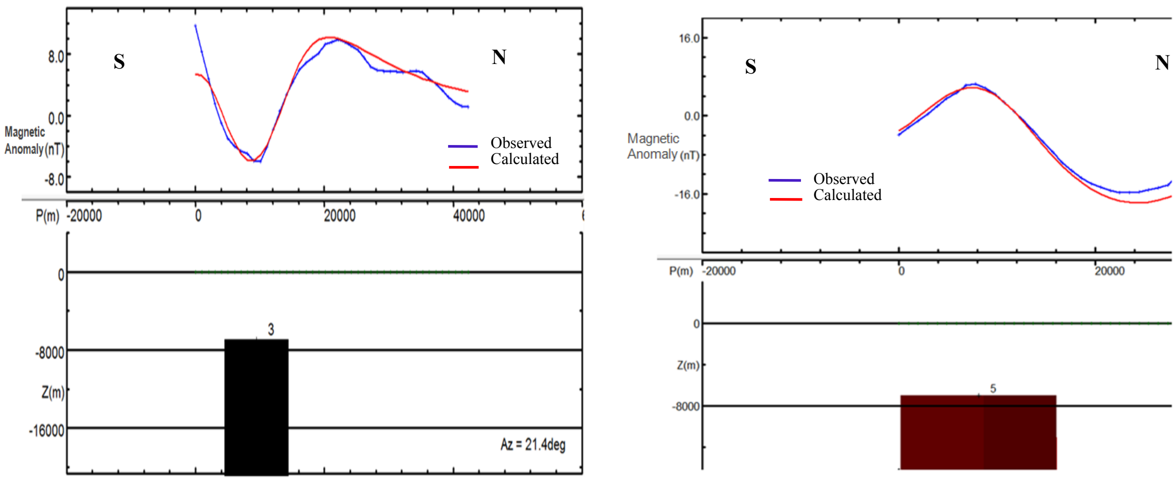
(a) (b)

Figure 8. Modelling of (a) profile line 800E, (b) profile line 900E showing dipping sources buried at depth 8,500m with a length of 28000m



(a) (b)

Figure 9. Modelling of (a) profile line 2200E (b) profile line 2400E. Magnetic signatures are due to remanence in the Earth's field and the rectangular sources are dykes in the deep basement



(a) (b)

Figure 10. (a) Modelling of profile line 2900E which revealed a dyke-like source, (b) Modelling of profile 1400E revealing a tabular body of length 1600m

The range in values of magnetic susceptibility and remanent intensity reflects sources of basaltic and ultrabasic composition which have utilized the tensional cracks in the fault system in the study area. The magnetic profiles, Line 2200E and Line 2400E over bodies 1 and 2 show strong remanence (strong magnetic minima in the north flanked by moderate magnetic high in the south). This is manifested in the intensity of remanence values (0.0600-0.1600Amp/m) and low susceptibility values of 0.007-0.008SI. These values point to a body of basaltic composition and the depth to the geologic body (dyke) is 9000m. Bodies 3 and 4 modelled with profile Line 2900E and Line 800E/Line 900E respectively show signatures that are entirely due to induction in the Earth's field (strong magnetic lows) which is consistent with results from equatorial belt. The geophysical explanation of this magnetic low is that the susceptibility of the anomalous body is lower than that of the host rock. That is, a basaltic body intruded into the ultrabasic source of magnetic susceptibility, 0.017SI at a depth of 11,000m. Modelling of profile Line 1400E incorporated both induced and remanent magnetization. The remanent magnetization of body 5 is -0.3700Amp/m while the magnetic susceptibility is 0.008SI. Relatively strong high to the south and very moderate low to the north in the magnetic signature suggest remanence.

The depth values obtained from the 3D modelling off shore were used to prepare magnetic basement depth map (Figure 11). However, modelling of residual magnetic field data (lat. 4°00′ - 4°30′ N and long. 6°30′ - 7°00′ E) at the adjacent onshore (Figure 12) shows that the depth to basement (thickness of sedimentary section) increased to 12000m as revealed in Figure 13. A reasonable detailed basement structure map is an integral part of any regional geological or hydrocarbon evaluation process. Such a map identifies critical structural trends, the locations of the regions prominent structural prospects and location and geometry of the hydrocarbon depocenters (Alexander, Pratsch, & Prieto, 1998). A magnetic basement low (thick sedimentary section) traverses the southwest and northwest sectors of the study area with a maximum sedimentary thickness of 11,736m offshore. This is a deep basement trough. At lat. 3°30′ -3°41′ N and long. 6°16′ - 6°28′ E there is a basement high indicating structural high with a maximum thickness of 5,583m. This basement high is flanked either side by structural lows. In the northeast sector there is a basement high flanked by basement low. Thus, there is spatial relationship between paleotopographic highs on the Precambrian basement and structural and thickness anomalies in the overlying Tertiary sediments. Thus, the depth to magnetic basement map (Figure 11) has located deep depocenters, high blocks, sedimentary fairways and basement flanks in the study area.

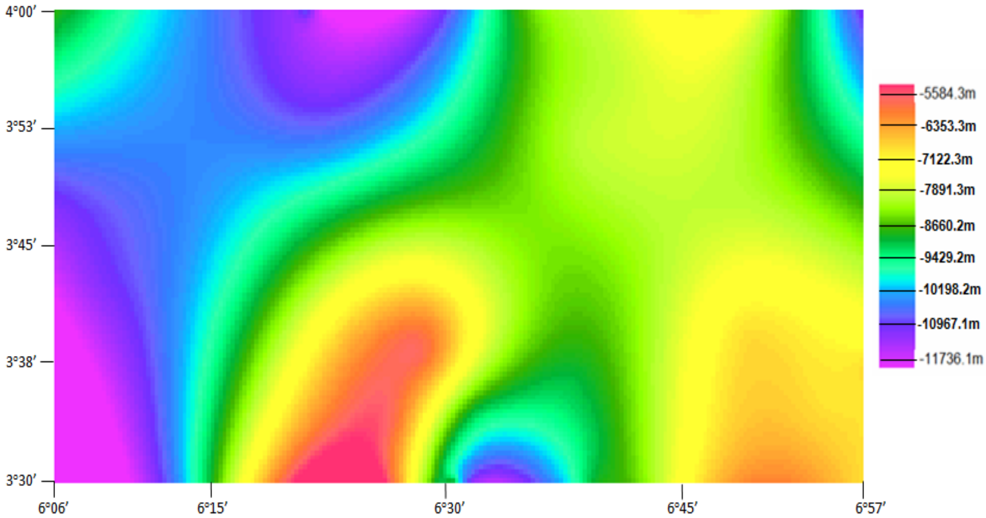


Figure 11. Depth to magnetic basement (thickness of sedimentary section), highlighting basement highs, basement flanks and depocenters

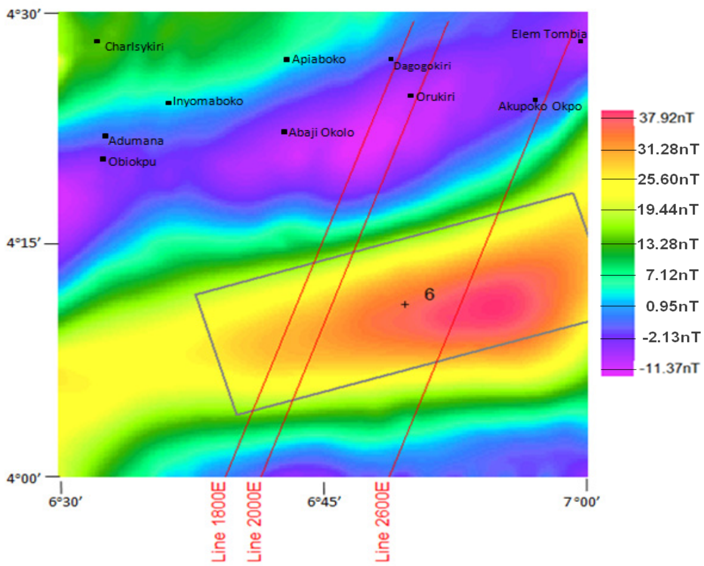
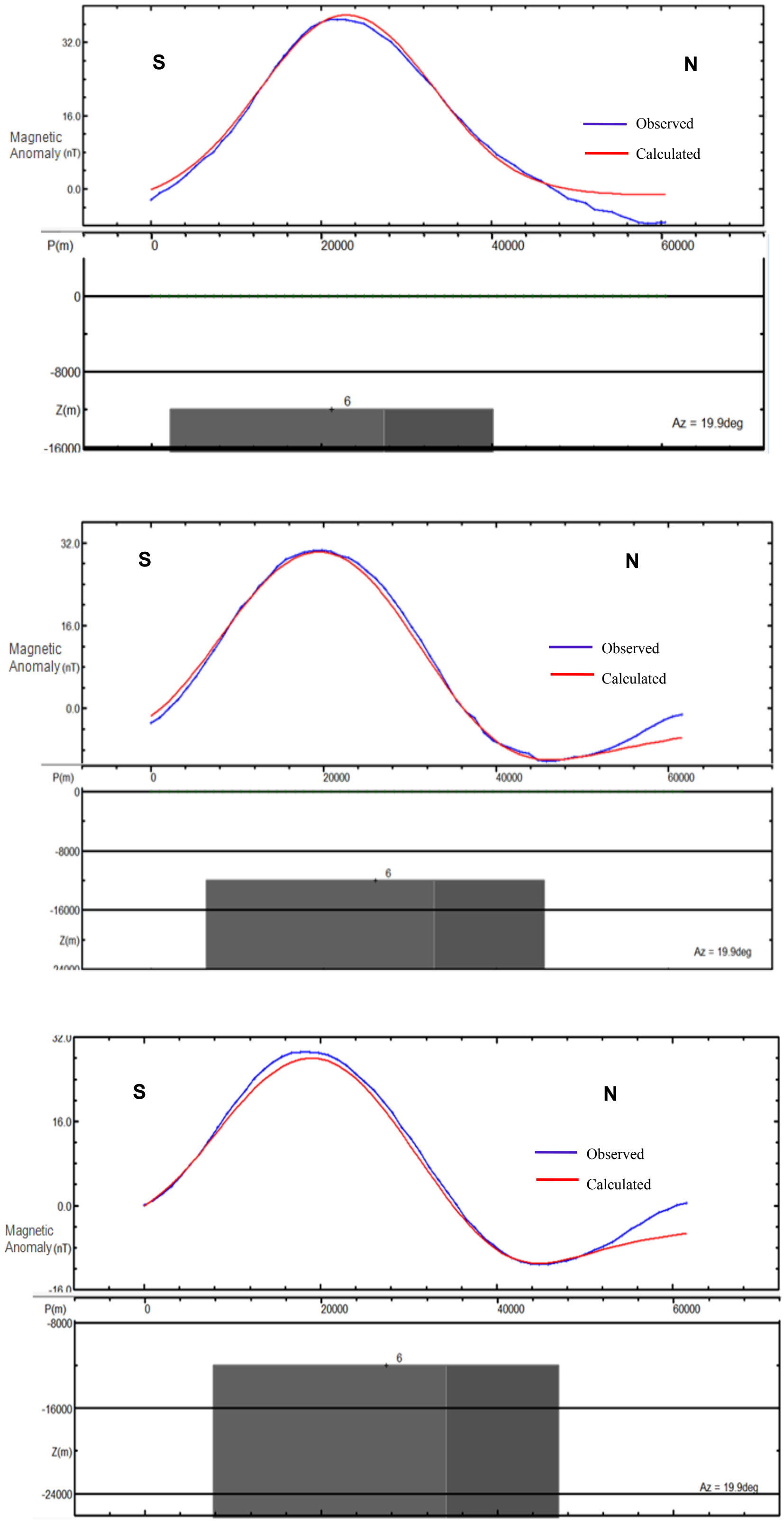


Figure 12. Location of profile lines 1800E, 2000E and 2800E on the magnetic data in the adjacent onshore



(c)

Figure 13. Modelling of profile line (a) 1800E, (b) 2000E and (c) 2800E revealed igneous plutons onshore Niger Delta

5. Magnetic Anomaly Enhancement

In order to examine basement influence on the sedimentary section in the study area we also performed basement structural analyses using transformed magnetic anomaly data and showed deformation patterns and structural architecture of the basement. Enhancements of magnetic anomaly data accentuate the internal structure and edges of magnetic sources. The most important and accurate information provided by magnetic data is structural fabric of the basement. Major basement structures can be interpreted from consistent discontinuities and /or pattern breaks in magnetic fabric (Li & Morozov, 2007). The basement structures manifest as shear zones, fault (brittle faults and domain fault boundaries) which are usually weak zones. These basement structural features are lineaments and in most cases subtle. Subtle potential field lineaments could be gradient zones, alignment of separate local anomalies of various types and shapes, aligned breaks or discontinuities on the anomaly pattern. Subtlety of desirable lineament requires detail processing using a wide range of anomaly enhancement technique and display parameters (Lyatsky, Pana, & Grobe, 2005). Filtering and image processing of aeromagnetic data are essential tools in mineral exploration. Directional horizontal derivatives enhance edges while vertical derivative narrows the width of anomalies and so locate the source bodies more accurately (Cooper & Cowan, 2004).

The most commonly applied techniques include the horizontal gradient and analytic signal. Other methods for detecting edges of structures and linear features such as faults include tilt and diagonal derivatives. (Cordell & Grauch, 1982, 1985) gave expression for magnetic field horizontal gradient as

$$HG(x,y) = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2} \tag{2}$$

Maxima in the horizontal gradient magnitude of the reduced-to-pole magnetic field are exploited to locate vertical contacts and estimate their strike directions; where M is the magnetic field. The analytic signal also reveals basement structure and uses its maxima to locate the outlines of magnetic sources and their edges. (Roest, Verhoef & Pilkington, 1992) defined the analytic signal from field derivatives as:

$$AS = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2 + \left(\frac{\partial M}{\partial z}\right)^2} \tag{3}$$

While the horizontal gradient is less prone to noise because it calculates only the two horizontal derivates, it is not well suited to analyzing potential field data at low latitudes. This is because it requires reduction to the pole. Reduction to the pole is very unstable in magnetic equator (equatorial belt). The width of a maximum or ridge in analytic signal data is an indicator of depth of the contact as long as the signal arising from a single contact can be resolved (GETECH, 2007). While the analytic signal could be discontinuous, the enhancement is very handy at low magnetic latitude because it eliminates the problems inherent with reduction to pole (RTP) at low latitude.

One technique we find very useful is the directional horizontal gradient (Figures 14 & 15a) which is very effective in revealing basement features. This technique is simple and like the analytic signal (Figure 14), it can reveal N-S structures which are difficult to identify in equatorial belt. The directional horizontal derivative does not require reduction to the pole. (Blakley, 1996) showed that the horizontal derivatives of a smoothly varying scalar quantity, $\phi(x,y)$ measured on a horizontal surface can easily be determined using simple finite-difference methods. The horizontal derivatives of $\phi(x,y)$ at point i, j are given approximately by

$$\frac{d\phi(x,y)}{dx} \approx \frac{\phi_i + 1, j - \phi_i - 1, j}{2\Delta x} \tag{4}$$

$$\frac{d\phi(x,y)}{dy} \approx \frac{\phi_i, j + 1 - \phi_{i,} j - 1}{2\Delta y} \tag{5}$$

This can be performed in the Fourier domain. Thus,

$$F\left[\frac{d^n\phi}{dx^n}\right] = (ik_x)^n F[\phi], \tag{6}$$

$$F\left[\frac{d^n\phi}{dy^n}\right] = (ik_y)^n F[\phi] \quad (7)$$

Where, $(ik_x)^n$ and $(ik_y)^n$ are filters that transform a function measured on a horizontal surface into nth-order derivatives with respect to x and y respectively. We exploited the Fourier domain technique. This approach enhances anomalies with specific orientation and is very useful where subtle yet important trend need to be revealed but are obscured and complicated by trends in other directions (Brodie, 2002). This option enabled us to calculate gradient in the direction of greatest rate of change and the trend. Since the angle of the output grid tends to zero (equatorial belt) then dx is the gradient to the east and dy is the gradient to the north. In Figure 14, N-S striking structures are clearly defined. E-W striking features in Figure 15 are not surprising at the magnetic equator. Generally, the interpretation of magnetic anomalies near the equatorial belt is difficult because the ambient (local) field is weak and horizontal. N-S striking structures are difficult to detect at the equatorial belt. Magnetic anomalies are generated when the flux density cuts the boundary of structures and if the structure strikes parallel with the field then in equatorial belt the flux stays within the structure and no anomaly is generated (GETECH, 2007). This effect can also be generated when magnetic field reduced to the equator (RTE) instead of reduced-to-the pole is carried out. In this case, the N-S structures in RTE data are difficult to identify.

The enhancement maps show that the digitized aeromagnetic data is amenable to mathematical transformation, valuable tools for tectonic interpretation and resource exploration in the Niger Delta basin. In Figures 14 and 16 the magnetic field defines a more N-S trending fabric. Some of the offsets and discontinuities in the gradient maps agree with changes in the total magnetic intensity and residual maps. This concurrence implies a major structural contact or faults and represents offsets in the basement which have controlled sedimentation patterns in the Niger Delta. The directional horizontal derivative maps and the analytic signal map show clear boundaries of major magnetized zones within the basement. The internal character and boundaries of the basement blocks and sub-domains are also revealed. Thus, the directional horizontal derivative data and the analytic signal map clearly demonstrate geophysical features and highlight trend directions of magnetic sources even though the aeromagnetic data is old and is of low resolution. Most of the important geologic features (faults and contacts) are reflected as lineaments in the magnetic data. A geologic lineament is a linear zone of weakness in the Earth's crust that may owe its origin to tectonic or glacial causes and often represents geologic features such as faults, dykes, lithologic contact and structural form lines (Lee, Morris, Harris, & Leblanc, 2012). Large-scale regional structures are revealed by low passed filtered data. Comparing the low-passed magnetic data (Figure 17) with the total intensity data reveals the anomalies that survived the filtering. Principal orientations of magnetic field anomalies and magnetic terrane boundaries are revealed in the low-passed data. The orientation of large scale features is E-W (the direction of the major domains) while the anomalies of short wavelength which reveals short scale features (Figure 18) are discordant with this trend.

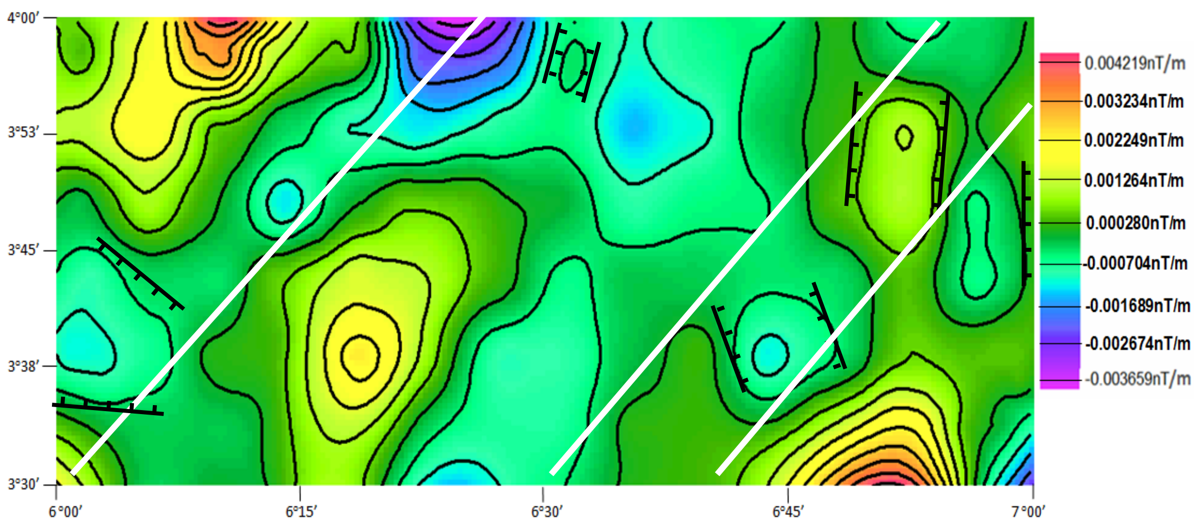
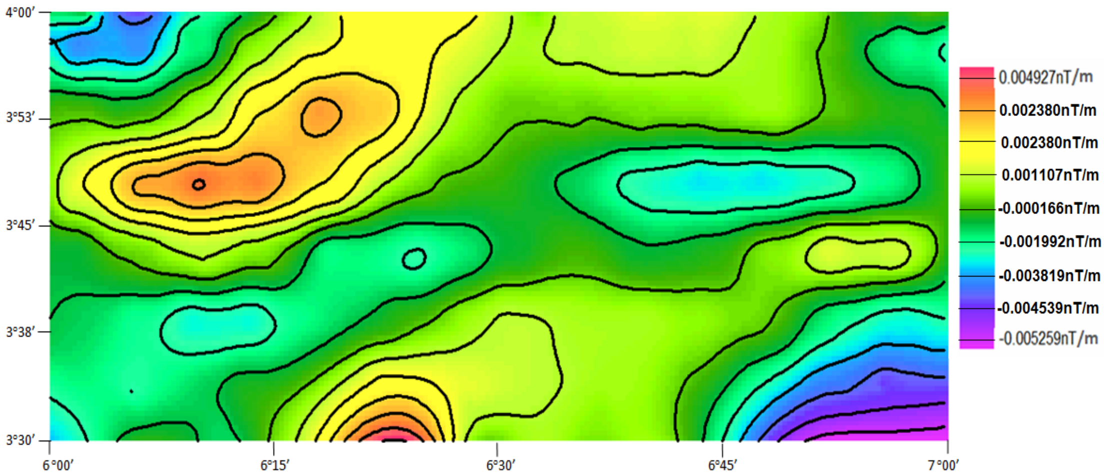
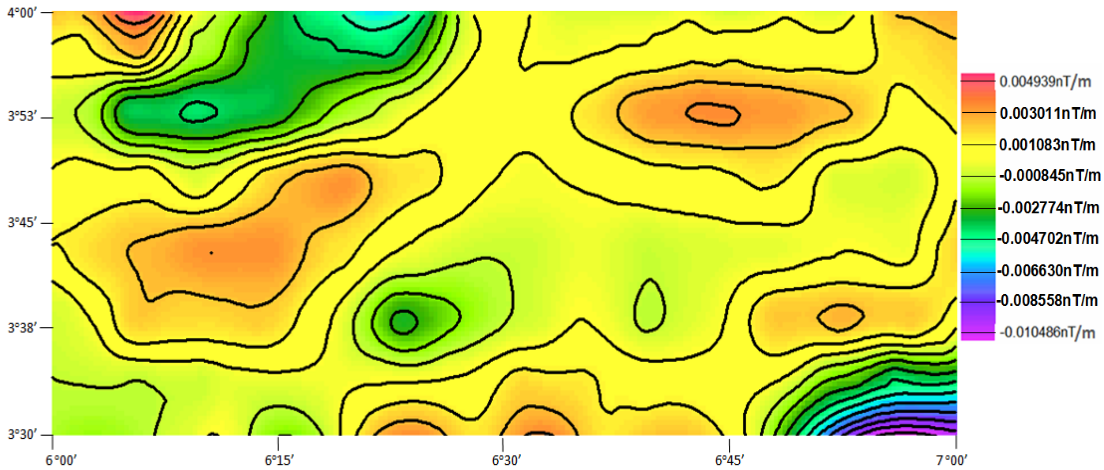


Figure 14. Directional horizontal derivative (dx) data highlighting subtle N-S structures and basement faulted blocks. White lines are inferred accommodation zones



(a)



(b)

Figure 15. Directional derivative maps revealing E-W structures (a) Data obtained by taking gradient (dy) in the north direction (b) First vertical derivative

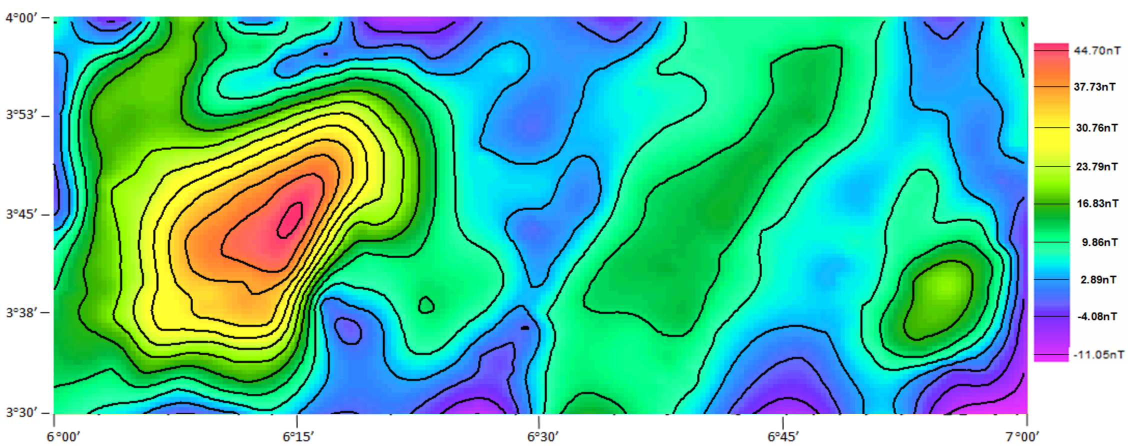


Figure 16. Analytic signal data highlighting anomaly texture, discontinuities in anomaly pattern and N-S structures

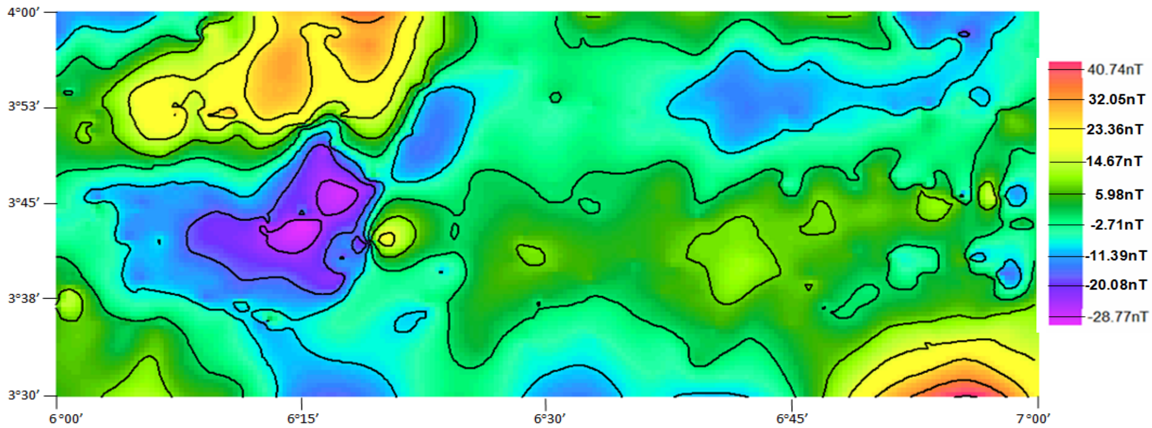


Figure 17. Low pass filtered data showing the major trends of the magnetic domains and magnetic terrane boundaries of the deep basement with some discordant small scale structures

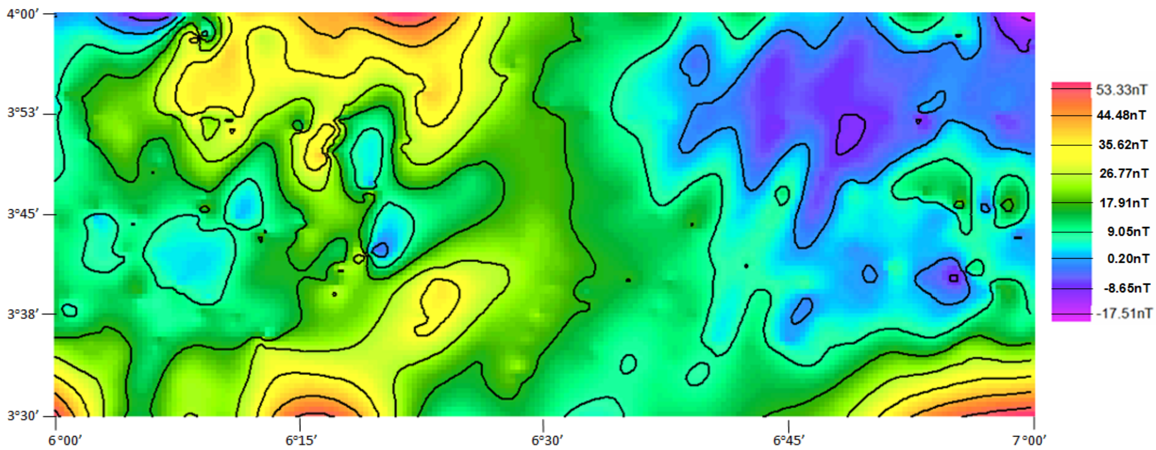


Figure 18. Filtered outputs of magnetic anomalies predominantly of short wavelengths which are discordant to the trend of the major magnetic provinces

6. Discussion

6.1 Basement Architecture and Tectonics

The depth to magnetic basement map (Figure 11) has revealed a spatial relationship between the paleotopographic highs and lows in the Precambrian basement and structure and thickness anomalies in the overlying Tertiary sediments. The basement paleotopography suggests movement in the shear/wrench fault systems that were active before, during and after sedimentation. The residual and total intensity data revealed NE-SW trending boundaries crossing almost the entire study area. The NE-SW trending boundaries are shear zones and are related to primary NE-SW crustal block faulting that are related to the unique position of the Niger Delta during the opening of the South Atlantic at the boundary between the southern area of crustal divergence and the equatorial zones of crustal translation (Evamy et al., 1978).This trending magnetic anomalies represent ductile healed basement structure of Early Proterozoic and earlier age. They predominate and obscure the desired subtle lineaments (brittle faults) trending N-S which were not revealed in the total intensity and residual magnetic maps. Appropriate processing using the directional horizontal derivative (Figure 14) and analytic signal map (Figure 16) clearly revealed the subtle anomalies. Specifically, the negative analytic signal reflects zones of low magnetization which is a pointer to faults and fractures that are associated with possible depletion of magnetite. The northeast-southwest basement trends indicate possible extensions within the African continent of the Charcot and Chain oceanic fracture zones. The northwest-southeast (Romanche fault zone) equivalent is as a result of block faulting that occurred along the edge of the African continent during the early stages of divergence; visible in Calabar flank which is not covered by the magnetic data. Babalola and Gipson (1991) recognized the NE-SW and ENE-WSW trends as lineations and interpreted them as fracture zones trends beneath the Niger Delta. (Hospers, 1965) interpreted the NE-SW and NW-SE trends as the megatectonic framework of the Niger Delta. A combination of the NE-SW, E-W and N-S structures from the residual and enhanced maps resulting from the shear/wrench-fault tectonics involving the basement created faulting, fracturing, downwarp and epeirogenic warping along zones of basement weakness. Both horizontal and vertical movements are involved in wrench-fault system but the horizontal movement predominated. Wrench-fault system often appears as scissor-type fault. The Faults in this study were recognized from a combination of offsets and truncations of anomalies and steep gradients in the magnetic data. The strong shearing in the study area along a wrench fault system has vertical and horizontal displacements. The vertical displacement could be vividly seen as north-south striking structures in Figures 14 and 16 and horizontal displacement in the E-W striking structures (Figure 15). The N-S and E-W bounded fault blocks are secondary faults which have influenced stratigraphy and major tectonic elements or as shears which controlled local features. (EI Gout, Khattach, Houari, Kaufmann, & Aqil, 2010) and (De Castro, 2011) mapped family of faults with similar trends that control depositional history of the sedimentary basin in north-eastern Morocco and Potiguar rift basin in north-east Brazil respectively. The N-S trending structures were probably induced by a combination of differential subsidence across a fault zone and by local uplift due to wrench movements. These displacements created minibasin and arching of the basement (Figure 11) and block faults (Figure 14). The basement block boundaries are lineaments which affected deposition in the delta. Thus, sediment geometry in the study area is linked to subtle tectonic readjustment of basement blocks. These lineaments create conduits which aid the flow of fluids and may also act as barriers. The N-S and E-W structures in the enhancement maps are relatively weak structures and were created subsequent to the formation of dominant and stronger NE-NW and NW-SE trending anomalies which reflects the shape of the Niger Delta basin. Thus, the N-S and E-W anomalies represent the reactivated structures. These two trends in addition to the NE-SW trend form the three potential stress regimes responsible for the structural architecture of the study area. In individual mega-tectonic provinces these three trends are the dominant trends (Affleck, 1964).

There are three evidences for reactivation. One of the evidences of reactivation is the arching up of the basement. During reactivation blocks within the basement may have moved along faults. The second evidence is that the N-S and E-W structures do not correlate with the basin shape. The third evidence is that when the thick sedimentary cover was forming pre-existing structures in the basement had the potential to become reactivated. This have been demonstrated for areas that are evidently tectonically stretched such as shelves or basins on or adjacent to continental margins and in a slowly subsiding epicontinental basin, where pre-existing tectonic structures were reported to have been reactivated at times and subsidence was enhanced (Wetzel, Alenbach, & Allia, 2003). The N-S and E-W structures are bounded by faults. These faults are brittle in nature and may have developed by shear reactivation of a previously formed weak surface in a body of rock. In the upper crust of the Earth, roughly 10km in depth, rocks primarily undergo brittle deformation, creating a myriad of geologic structures (Pluijm & Marshak, 2004).

6.2 Correlation between Basement Architecture, Tectonics and Hydrocarbon Target

In this study we opine that the basement structures are identified to play major role in sediment and hydrocarbon distribution in the Niger Delta in two ways: basement relief (basement highs and lows) and basement related faults. These two factors are episodic and appear to have controlled the trapping and migration of hydrocarbon in the Niger Delta. Gay (1995) identified two basic types of basement control on the overlying sedimentary section in Kansas: basement topographic control and reactivated basement faults or shear zones. Actual movement along the shear zones and lineament may be minimal but the minor change in topographic relief of the overlying sediments is an important control on deposition (Brown & Brown, 1987). The embryonic faulted margins of the Atlantic are now the continental margins of West Africa and are prolific oil-producing regions. The faulted rift systems of Africa developed major sedimentary basins along its length and generated major oil provinces in Nigeria, Central Africa and Sudan (Fairhead, 2012). The residual map, the enhanced maps and the depth to basement map show structural characteristics and they are used in this study as evaluation tool in this hydrocarbon exploration setting. The shear/wrenching and the block faulting in the residual and enhanced maps represent offsets in the basement that controlled sedimentation patterns. The development of the delta has been dependent on the balance between the rate of sedimentation and the resulting sedimentary patterns appears to have been influenced by the structural configuration and tectonics of the basement (Evamy et al., 1978).

The depth to basement map is characterized by structural highs flanked by structural lows. The structural low represents syncline/depocenter/subbasin. The structural high anomalies are interpreted in this study to be the focal points for the migration oil and gas while the regional (lows) structural anomalies are the generating depocenters. Thus, structural high (positive) anomalies near structural low (negative) anomalies are the preferred targets in hydrocarbon exploration. Thus, the shear/wrench system is reflected as a series of geometrically arranged downwarp, epeirogenic uplift that may be subjected to continuous adjustment and compressional stress. The uplifted blocks created the arches while downdropped ones produced the depocenters. Therefore, the flanks of the basement highs and basement lows are also attractive sites for oil and gas accumulation. Oil and gas generated in such regional lows will migrate updip, where possible onto adjacent structural highs. Structural highs located between two adjacent basement lows offer special attractions for oil and gas migration from both sides (Prieto & Pratsch, 2000). We strongly opine that the basement structures from the residual map, the enhanced maps and the depth to basement map are as a result of multiple deep-seated tensional and shear/wrench faulting within the basement and that jostling of basement blocks have strongly influenced deposition in the Niger Delta basin. The aftermath of the basement motion in conjunction with the impact of differences in topographic relief in the sedimentary section during the Tertiary gave rise to the generation of the structural lows and structural highs. Subsequent migration of hydrocarbon was aided by fault induced by basement faulting. The basement blocks jostling beneath the Niger Delta may have created fracture pattern that may have enhanced or reduced porosity and permeamibility. Basement faults are known to have commonly influenced the distribution of hydrocarbon traps and mineralization zones in sedimentary cover (Lyatsky, 1999). Plotnikova, 2006 linked oil pools in lower productive beds of sedimentary cover to faulted zones in crystalline basement in known platform hydrocarbon fields.

Using Figure 19 which identified the locations of oil and gas blocks - OML and OPL (oil mining lease and oil prospecting lease) in the Niger delta, oil/gas fields, exploratory wells in conjunction with the regional basement data analysis, we established a relationship between basement architecture/structure and hydrocarbon target. Thus, OML 116 and OPL 293 are within the basement structural lows. OML 116 is leased to the Nigerian National petroleum company (NNPC). OPL 238 and OPL 294 are associated with basement highs. These two blocks have been leased to Sun Link and CPC Starcr companies respectively. OML 131 leased to CONCO EP and OPL 090 and OPL295 are within basement flanks. In respect of the oil and gas fields in the area of study: the gas and condensate field (Ebitemi-1) is associated with basement flank while three oil fields (Bala, Agbara and Anyala) are within basement lows. Two oil fields (SEHKI-1 and ONGOLO-1) are associated with basement highs while NDA-1 is on the crest of basement. Thus, the oil and gas fields are probably formed by hydrocarbon leaking from deeper accumulations migrating updip directly from generating source beds via a fault induced by basement faulting. Thus, hydrocarbon migration pathways are basement controlled. Correlating Figures 11 & 19, a logical connection could be established between exploratory wells and basement architecture. Most of the exploratory wells are located on structural lows (basement lows) and structural highs (basement highs). Four exploratory wells are located on top of basement highs. These structural basement highs are associated with the location of oil and gas within Tertiary sand reservoirs. Five are located in basement lows; these structural lows are sites for increased sediment deposition (depocenters) associated with oil and gas accumulation.

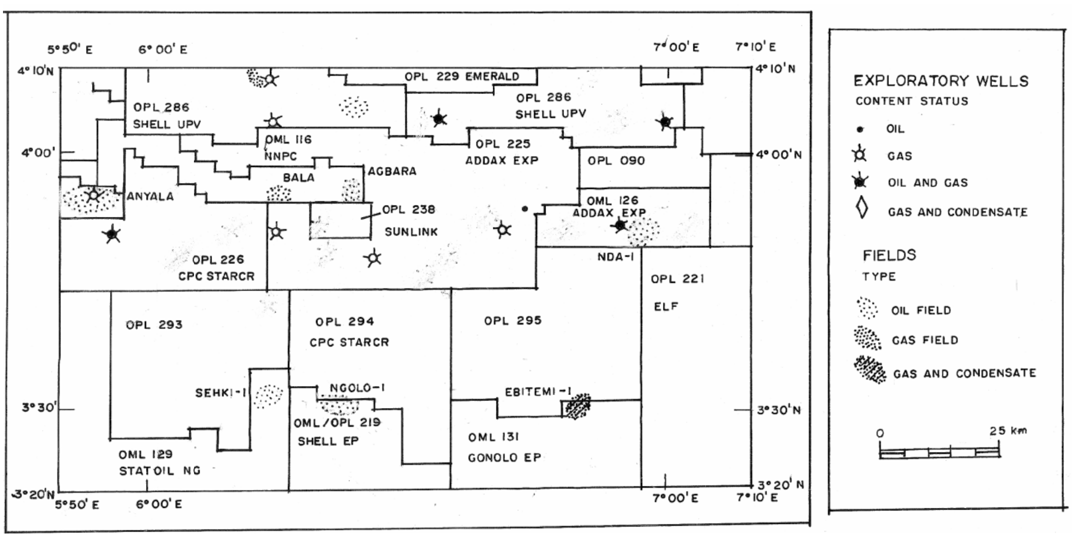


Figure 19. Exploratory wells and oil and gas field in the study area in the Niger delta (source: Global Exploration and production services, 2006)

7. Conclusion

The directional horizontal derivative data, the analytic signal data and filtered maps reveals the magnetic field lineaments and anomaly fabric that could be related to the basement faults beneath the Niger Delta basin. E-W striking structures are brittle faults/fractures which are usually subtle but are well highlighted even in the total intensity data probably because they are associated with dykes or mineralized. The N-S structures in the study area are due to extensional faulting in the Precambrian crystalline basement giving rise to alternating system of downwarp and epeirogenic uplift that pushed up the Tertiary sediments. Hence, the sediment geometry in the Niger Delta can be correlated to subtle tectonic readjustment of basement blocks beneath the sedimentary section. The downwarp in this study represents syncline/depocenter/subbasin while the structural high anomalies are interpreted to be the focal points for the migration oil and gas. The exploratory wells, oil blocks and oil/gas fields in the study area are associated with structural highs (basement highs), basement lows and steep/faulted basement flanks.

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