Chapter 3

3D Modelling and Basement Tectonics of the Niger Delta Basin from Aeromagnetic Data

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Additional information is available at the end of the chapter

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1. Introduction

Basement structure is crucial in determining the origin, deformation and evolution of basin as well as the influence of the basement in the overlying Phanerozoic rocks and deposition and migration of hydrocarbon within a basin [1]. In petroleum exploration the structural surface interpreted from magnetic depth estimates is often the best available approximation to the true crystalline (metamorphic/igneous) basement configuration and estimate of basement depth (sedimentary thickness) is a primary exploration risks parameter [2]. Specifically, the magnetic basement is very relevant in the application of magnetics to petroleum exploration. Magnetic basement is the upper surface of igneous or metamorphic rocks whose magnetization is so much larger than that of sedimentary rocks. Magnetic basement may or may not coincide with geologic or acoustic basement. In the application of magnetic method, the source depth is one of the most important parameters. Others are the geometry of the source and contrast in magnetization. Basement structure determined from magnetic depth estimates provides insight into the evolution of more recent sedimentary features (subbasin, localization of reservoir bearing structures) in areas where the inherited basement fabrics or architecture has affected either continuously or episodically basin evolution and development [2]. Depths to the magnetic basement are very useful in basin modeling such as determination of source rock volume and source rock burial depth. 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 [3], [4]. 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 [5].

Magnetic anomalies are a result of two things: a lateral contrast in rock composition (lithology) or a lateral contrast in rock structure [6], [7]. Where there is no contrast in magnetization no anomaly is produced. The magnetization could be due to normal induction in the Earth's field or due to remanent magnetization. For accurate modeling and interpretation of magnetic data it is important to recognize and incorporate the remanent component where they exist.

Magnetic anomaly transformation/enhancement provides the opportunity to unravel the basement structure and lithology. Such information is not readily available from the total intensity data sets especially if they are of low resolution. Our objective in this study is to demonstrate the relationship between basement framework, magnetic expression and hydrocarbon prospect in the Niger Delta basin using 3-D modelling and enhancement data sets. In the Tertiary Niger Delta basin exploration (seismic) for hydrocarbon is confined to the sedimentary section despite the fact that basement structure analysis has been used in locating hydrocarbon targets in other sedimentary basins of the world. We show that the geodynamics of the deep basement are important phenomena to the explorationist and could be an important factor that can directly lead to the risk assessment of specific prospect sites in hydrocarbon exploration. Specifically, we demonstrate that basement structure in the offshore Niger Delta have control on oil and gas discoveries even though the basement is known to be beyond drillable depths. It is not possible to prove basement control neither with subsurface mapping, as few wells penetrate basement, nor with seismic, as the basement reflector is not always mappable; residual aeromagnetics is the principal technique used in mapping basement and it is generally applied only to outline the basement fault block pattern [8]. [9] used aeromagnetic data to show that axis of hydrocarbon pool in Alberta basin is coincident with the strike of the basement sourced magnetic signals. [10] reported the relationship between tectonic evolution and hydrocarbon in the foreland of the Longmen Mountains and showed that superimposed orogenic movement and related migration of sedimentary basins controlled the generation, migration, accumulation and disappearance of hydrocarbons. [11] reported three-sets of traps from geophysical and geological data in offshore United Arab Emirate of which one is basement related.

2. Location, geologic and tectonic setting

The study area, fig.1 (Niger Delta) is situated in the Gulf of Guinea. From the Eocene to the present, the delta has prograded southwestward, forming depobelts that represent the most active portion of the delta at each stage or its development [12]. The ideas expressed on location, geologic and tectonic setting is from [13]. The depobelts in this basin form one of the largest regressive deltas in the world with an area of some 300,000km^2, sediment volume of 500,000km^3 [14] and a sediment thickness of over 10km in the basin depocenter. The onshore portion of the Niger Delta Province is delineated by the geology of Southern Nigeria and Southwestern Cameroon. The northern boundary is the Benin Flank – an east-northeast trending hinge line south of the West Africa basement massif. The northeastern boundary is defined by outcrops of the Cretaceous on the Abakaliki High and further east-south-east by the Calabar Flank – a hinge line bordering the adjacent Precambrian. The offshore boundary of the province is defined by the Cameroon volcanic line to the east, the eastern boundary of the Dahomey basin (the eastern-most West African transformed-fault passive margin) to the west [13]

The Niger Delta Province contains only one identified petroleum system [15]. This system is referred to as the Tertiary Niger Delta (Akata-Agbada) petroleum system. The maximum extent of the petroleum system coincides with the boundaries of the province. Most of the petroleum is in the fields that are onshore or on the continental shelf in waters less than 200 meters deep and occurs primarily in large, relatively simple structures. The Tertiary section of the Niger Delta is divided into three formations (fig.2), representing prograding depositional facies that are distinguished mostly on the basis of sand-shale ratio. The type sections of these formations are described by [16] and [17]. The Akata Formation at the base of the delta is of marine origin and is composed of thick shale sequences (potential source rock), turbidite sand (potential reservoirs in deep water) and minor amounts of clay and silt. Beginning from the Paleocene and through the Recent, the Akata formation formed during lowstands when terrestrial organic matter and clays were transported to deep water areas characterized by low energy conditions and oxygen deficiency. Turbidity currents likely deposited deep sea fan sands within the upper Akata Formation during development of the delta. Deposition of the overlying Agbada Formation, the major petroleum-bearing unit, began in the Eocene and continues into the Recent. The formation consists of paralic siliciclastics over 3700 meters thick and represents the actual deltaic portion of the sequence. The clastics accumulated in delta front, delta-topset and fluvio-deltaic environments. In the lower Agbada Formation, shale and sandstone beds were deposited in equal proportions but the upper portion is mostly sand with only minor shale interbeds. The Agbada Formation is overlain by the third formation, the Benin Formation, a Continental latest Eocene to Recent deposit of alluvial and upper coastal plain sands that are up to 2000m thick [16].

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 [13].

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 (fig.3), back-to-back features and steeply dipping closed spaced flank faults [18]. Deposition of the three formations occurred in each of the five off-lapping Siliciclastic Sedimentation Cycle that comprises the Niger Delta. The cycles (depobelts) are defined by synsedimentary faulting that occurred in response to variable rates of subsidence and

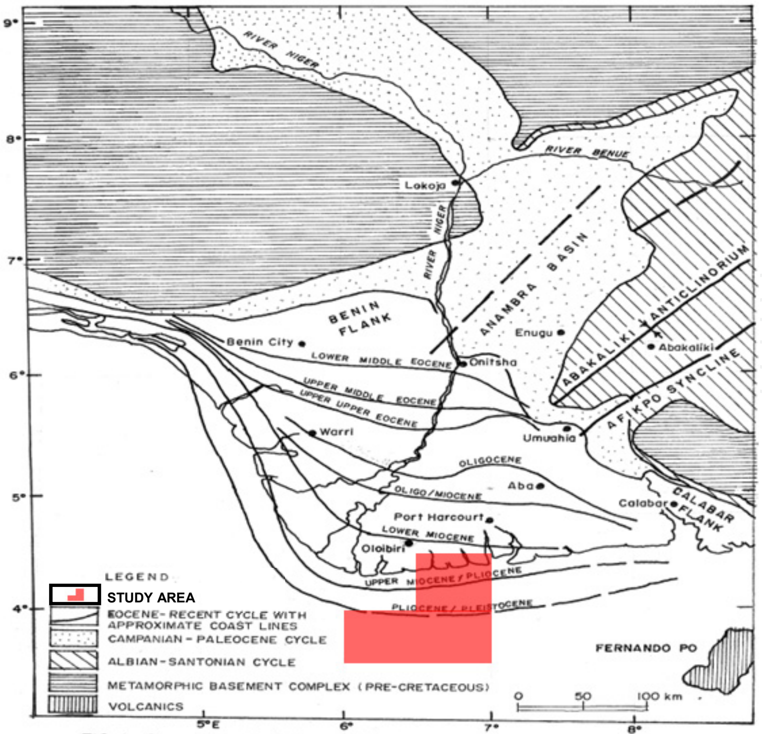


FIG. I General geological map of the Niger Delta and environs

Figure 1. Generalized geological map of Niger Delta Basin

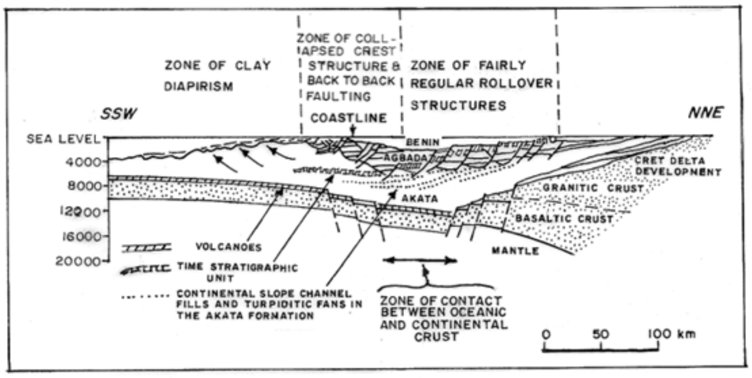


Figure 2. Schematic dip section of the Niger Delta

sediment supply. The interplay of subsidence and supply rates resulted in deposition of discrete depobelts. When further crustal subsidence of the basin could no longer be accommodated, the focus of sediment deposition shifted seaward forming a new depobelt. Each depobelt is separate unit that corresponds to a break in regional dip of the delta and is bounded landward by growth faults and seaward by large counter-regional faults or the growth fault of the next seaward belt [18]. Five major depobelts are generally recognized, each with its own sedimentation, deformation, and petroleum history. The northern delta province, which overlies relatively shallow basement, has the oldest growth faults that are generally rotational, evenly spaced with increased steepness seaward. The central delta province has depobelts with well defined structures such as successively deeper roll over crests that shifts seaward for any given growth fault. Lastly, the distal delta province is the most structurally complex due to internal gravity tectonics in the modern continental slope.

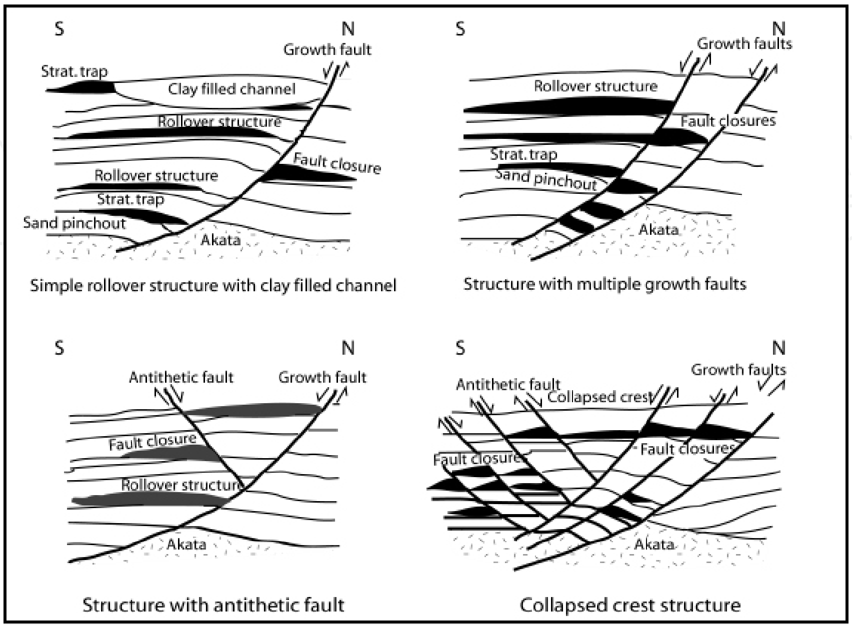


Figure 3. Principal Types of oilfield structures in the Niger Delta with schematic indications of common trapping configurations (After Tuttle etal., 1999)

3. Magnetic data

The total intensity magnetic data (fig. 4) was flown at an elevation of 2500ft (762m) above sea level with flight line spacing of 2km. This is therefore a low resolution data sourced from geological survey of Nigeria. The magnetic anomalies are sourced overwhelmly 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 [19]. 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.

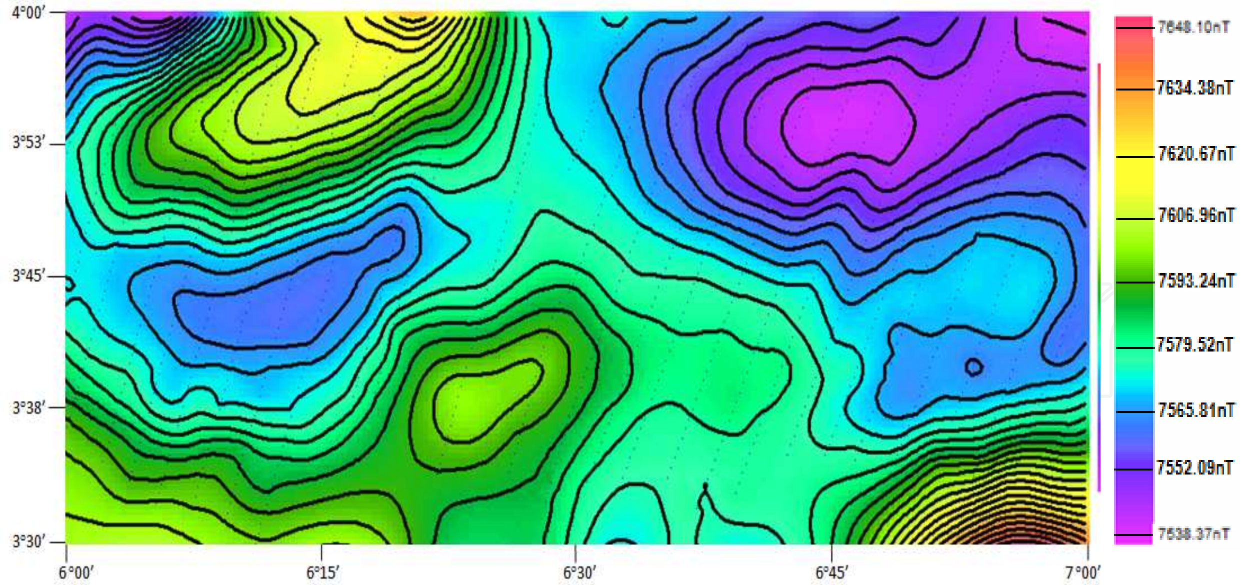


Figure 4. Total magnetic intensity data offshore Niger Delta. The gradient zones and elliptical contours reflects basement structures

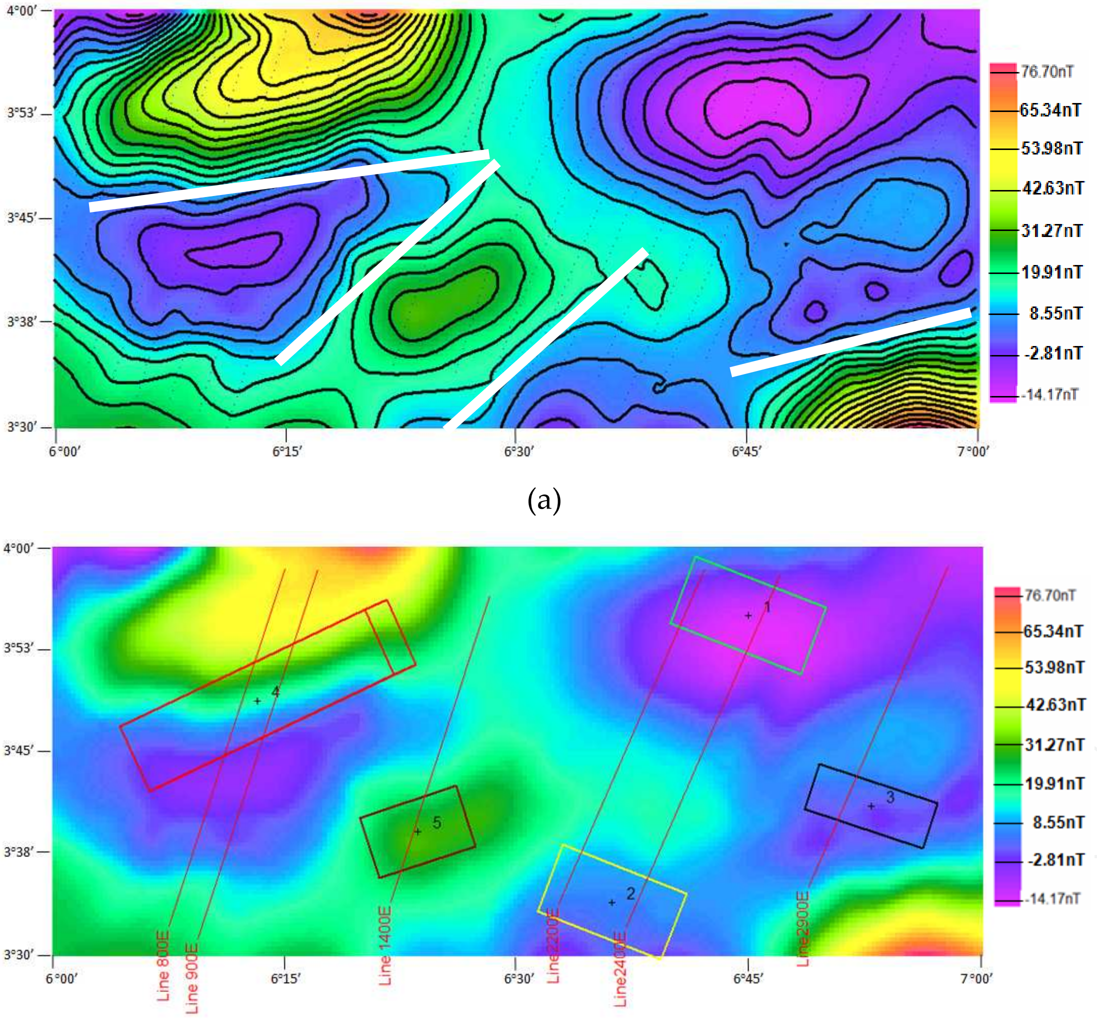
The magnetic anomalies in fig.4 are as a result of total magnetization of rock and represent the vector sum of the induced and remanent magnetizations. The induced magnetizations are produced as a result of the interaction of magnetic minerals with the Earth's magnetic field. This is contrary to the 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 permanent magnetization is often the rule than the exception, in the rocks of the Earth crust and permanent magnetization associates itself with induced magnetization to orient the polarization vector of the rock mass in some arbitrary direction [20]. 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 (fig. 5a).

In the total intensity data (lat. 4^{0} 00'N - lat. 3^{0} 41'N and long. 6^{0} 00'E - 6^{0} 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 with elliptical anomaly trending E-W. The elliptical disposition is a pointer to dyke-like intrusives. 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.



(a)

(b)

Figure 5. a. The Residual magnetic anomaly data showing some circular and elliptical contours not revealed in total magnetic intensity data. The white lines indicate shear zones. b. The location of profile lines 800E, 900E, 1400E, 2200E, 2400E and 2900E in the residual magnetic field data. The rectangular wire frames represents the magnetic sources.

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 [21]. 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 [22]. Generally, there are two approaches to potential field modeling: inverse and forward modeling. In magnetic modelling 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 or compatible with potential field data. This reduces ambiguity in interpretation. Thus, in this study, we adopted 3-D 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 (fig. 5b) 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 [23]. 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 [6]. To fulfill the above condition profiles were taken to model the depth to the basement using rectangular wire frame in fig. 5b. 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 body. 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 modelling 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 setting (rifting) 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 [23]. Another approach we used to account for non-uniqueness was to fix susceptibility and vary geometry until a reasonable fit was achieved. The modelled magnetic anomalies (figs. 6-9) 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 [23]. The amplitudes of the anomalies modelled 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 [24]. 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 modelling of prospect-level targets. If detailed prospect-level quantification of the basement structure is required, a 3-D model would be more appropriate [25]. We exploited the algorithm of [20] 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 fig. 10. Six profiles (Line 800E, Line 900E, Line 1400E, Line 2200E, Line 2400E and Line 2900E) in fig.5b were modeled to obtain geometries (figs. 6-9) and physical properties of 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, inducing and remanent field which varies in intensity and direction of magnetization [26]. Five discrete basement depth values were obtained from the modelled data and these values provided additional depth control offshore. A depth to basement at the adjacent onshore (fig. 11) gave a value of 12000m (fig. 12) by modeling body 6. 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 [25]

The range in values of magnetic susceptibility and remanent intensity reflects sources of basaltic and ultrabasic composition which may have utilized the tensional cracks in the fault system in the study area.

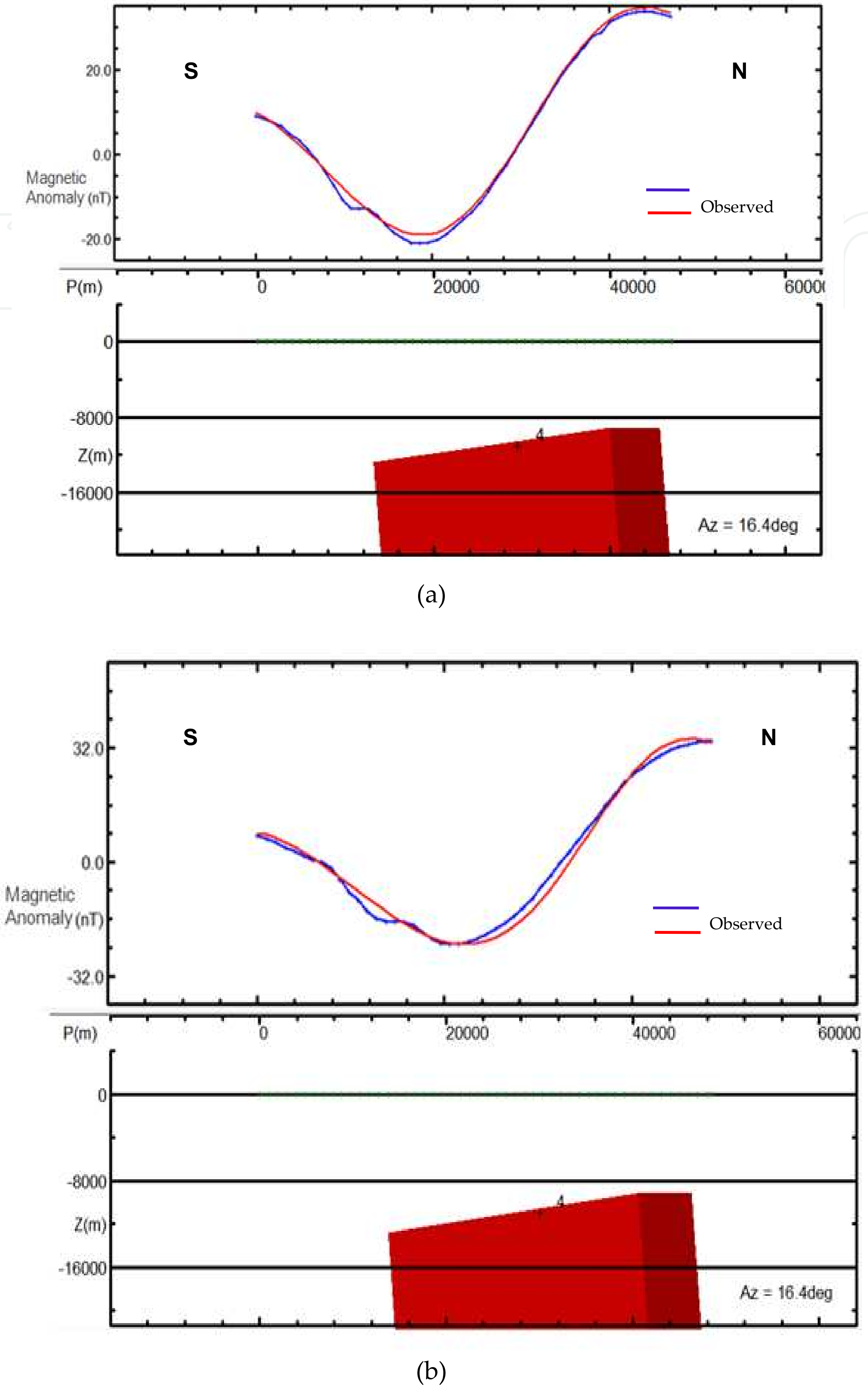
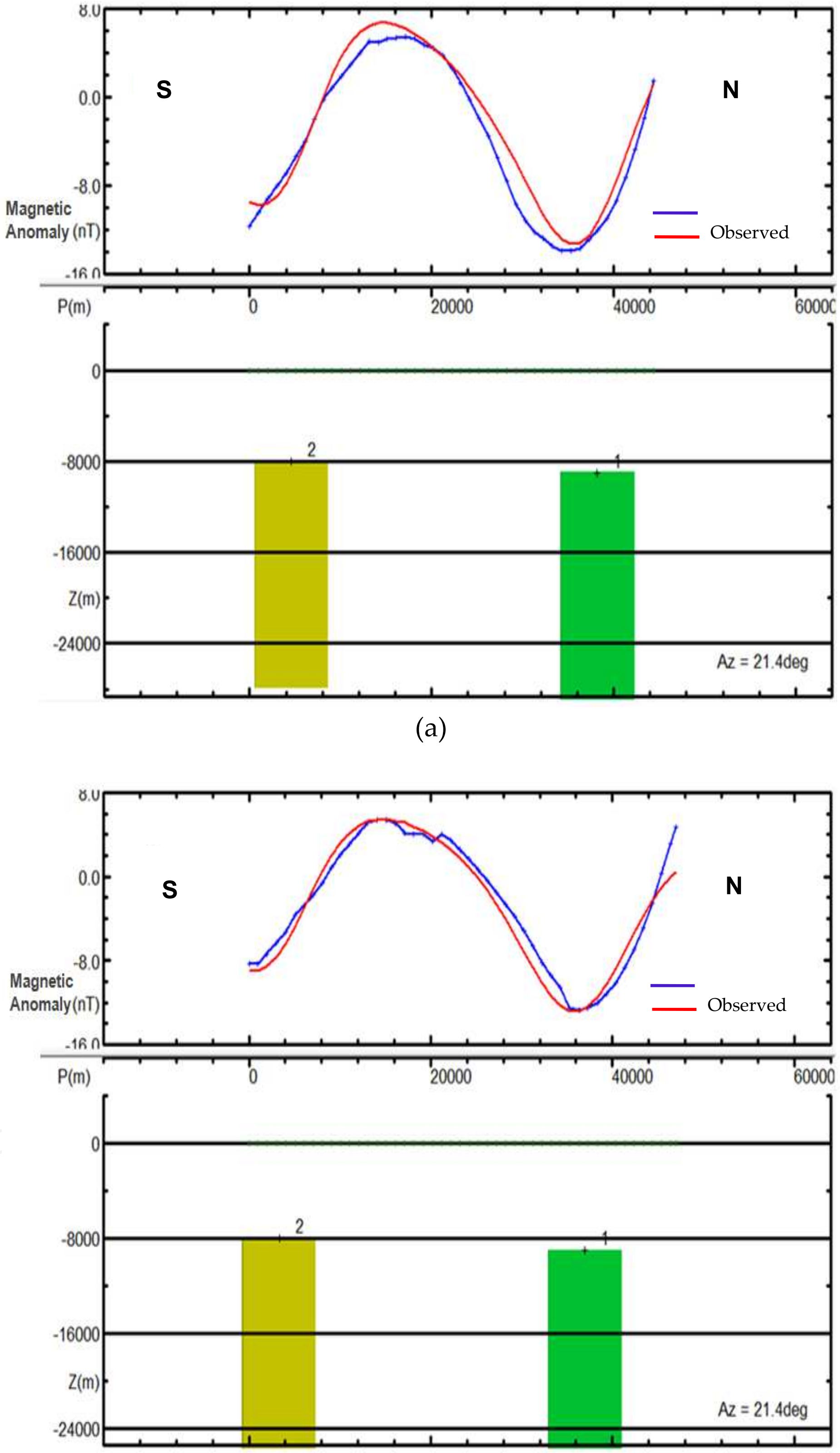


Figure 6. Modelling of (a) profile line 800E (b) profile line 900E showing dipping sources buried at depth 8,500m with a length of 28000m.



(a)

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Figure 7. Modelling of (a) profile line 2200E (b) profile line 2400E. Magnetic signatures are due to remenance in the Earth's field

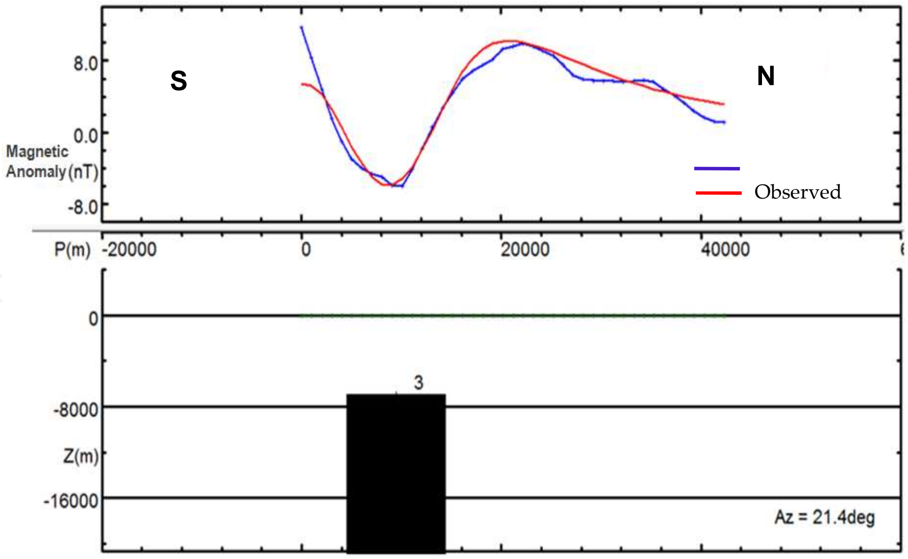


Figure 8. Modelling of Profile line 2900E which revealed a dyke-like source

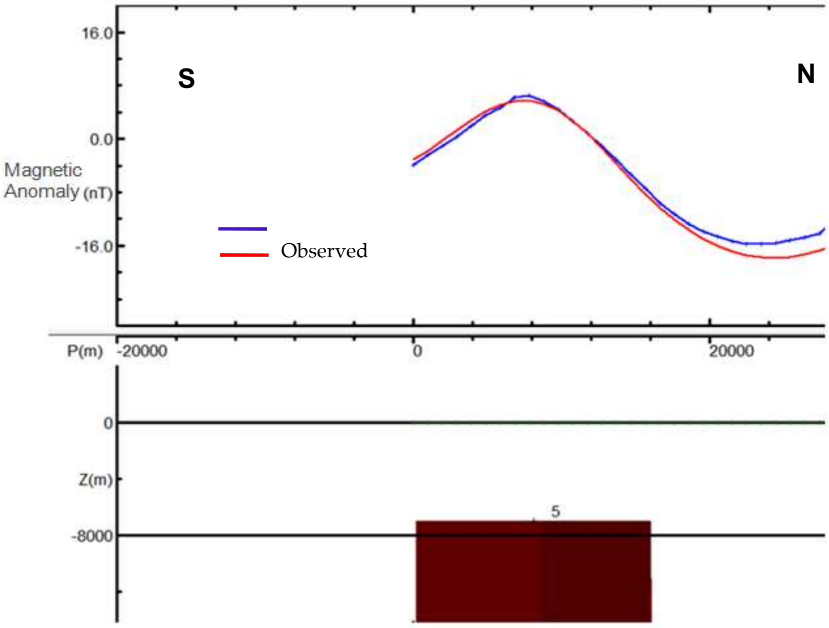


Figure 9. Modelling of profile line 1400E revealing a tabular body of length 16000m.

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 (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 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.

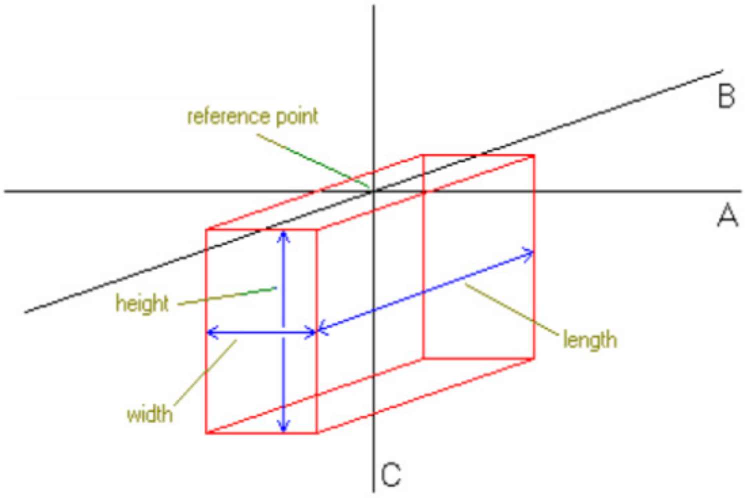


Figure 10. Rectangular prisms showing the parameters of the model

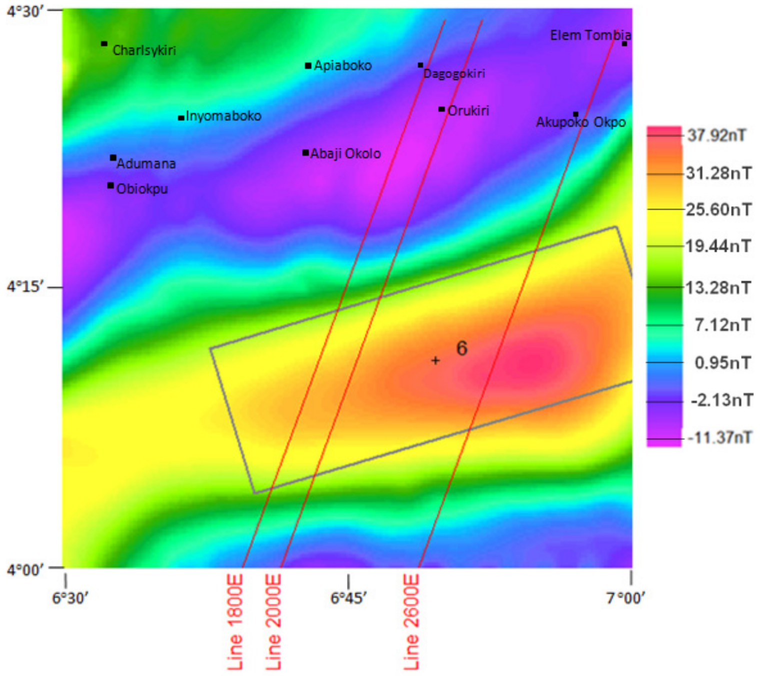
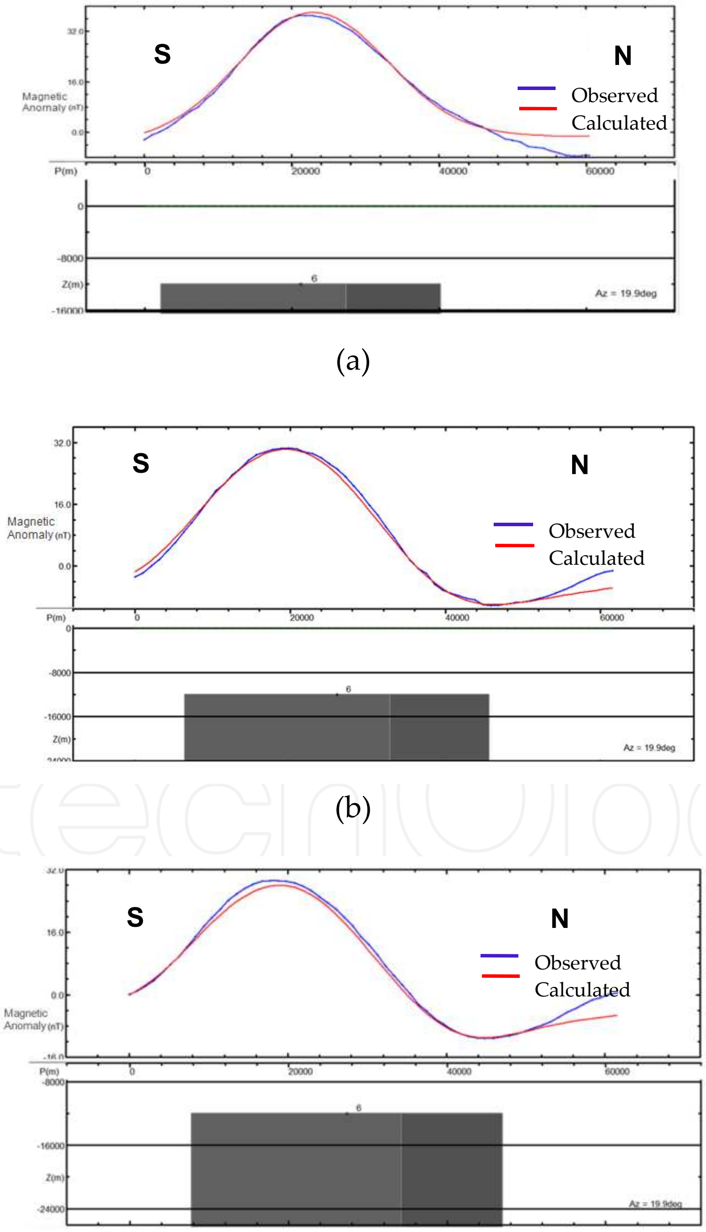


Figure 11. Location of profile lines 1800E, 2000E and 2600E on the magnetic data in the adjacent onshore

The depth values obtained from the 3-D modelling were used to prepare magnetic basement depth map (fig. 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 deponcenters [27]. 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. This is deep basement trough. At lat.3^0 $30^{'}$ -3^0 $41^{'}$N and long.6^0 $16^{'}$ - 6^0 $28^{'}$ 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. Therefore, the depth to magnetic basement map (fig. 13) has located deep depocenter, high blocks and major sedimentary fairways in the study area.



(a)

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Figure 12. Modelling of profile line (a) 1800E, (b) 2000E and (c) 2600E revealed a sill-like body onshore

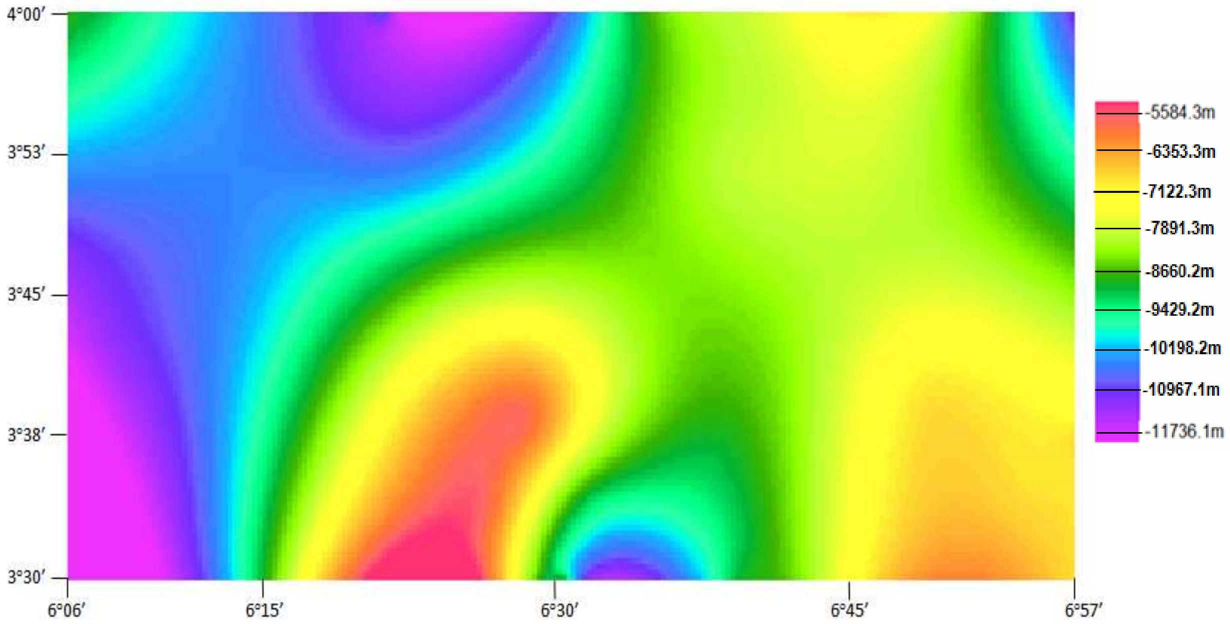


Figure 13. Depth to magnetic basement (thickness of sedimentary section), highlighting basement high, basement flanks and sedimentary fairways

5. Magnetic anomaly enhancement

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 [1]. 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 [29]. Filtering and image processing of aeromagnetic data are essential tools in mineral exploration. Directional horizontal derivatives enhance edges (figs. 14 & 15a) while vertical derivative (fig. 15b) narrows the width of anomalies and so locate the source bodies more accurately [30].

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. [31] and [32] 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. [33] 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 [34]. 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. It appears not to be popular but it is very effective in revealing basement features. This technique is simple and like the analytic signal (fig. 16), 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. [35] showed that the horizontal derivatives of a smoothly varying scalar quantity, $\varphi(x,y)$ measured on a horizontal surface can easily be determined using simple finite-difference methods. The horizontal derivatives of $\varphi(x,y)$ at point i,j are given approximately by

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

$$\frac{d\varphi(x,y)}{dy} \approx \frac{\varphi_i, j + 1 - \varphi_{i,} j - 1}{2\Delta y} \tag{5}$$

This can be performed in the Fourier domain. Thus,

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

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

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 [36]. 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 in equatorial belt then dx is the gradient to the east and dy is the gradient to the north. In fig. 14, N-S striking structures are clearly defined. E-W striking features in fig. 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 [34]. 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 fig. 14 & fig. 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 [37]. Large-scale regional structures are revealed by low pass filtering. Comparing the low-passed magnetic data (fig. 17) with the total intensity data reveals the anomalies that survived the filtering. Principal orientations of magnetic field anomalies are revealed in the low-passed data and made the lineaments to be more pronounced indicating that the lineaments are associated with large scale features. The orientation of large scale features is E-W (the direction of the major domains) while the anomalies of short wavelength [short scale features] (fig. 18) are discordant with these major trends.

6. Discussion

The depth to magnetic basement map (fig. 13) 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 [18].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 (fig. 14) and analytic signal map (fig. 16) clearly revealed the subtle anomalies. Specifically, the negative analytic signal in fig. 16 reflects zones of low magnetization which is a pointer to faults/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.

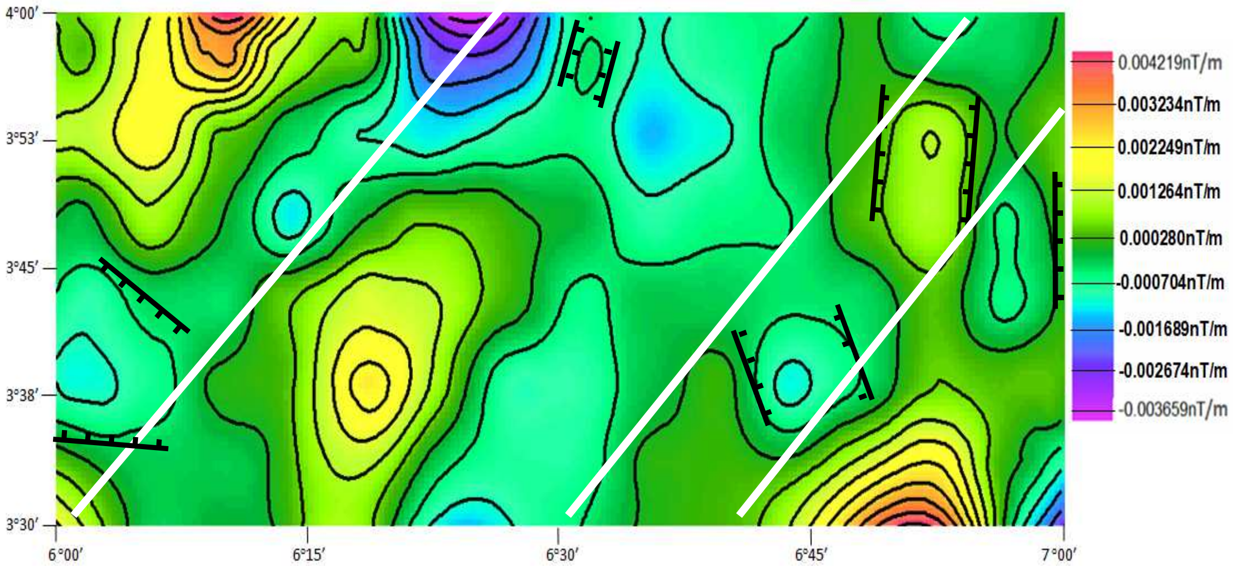
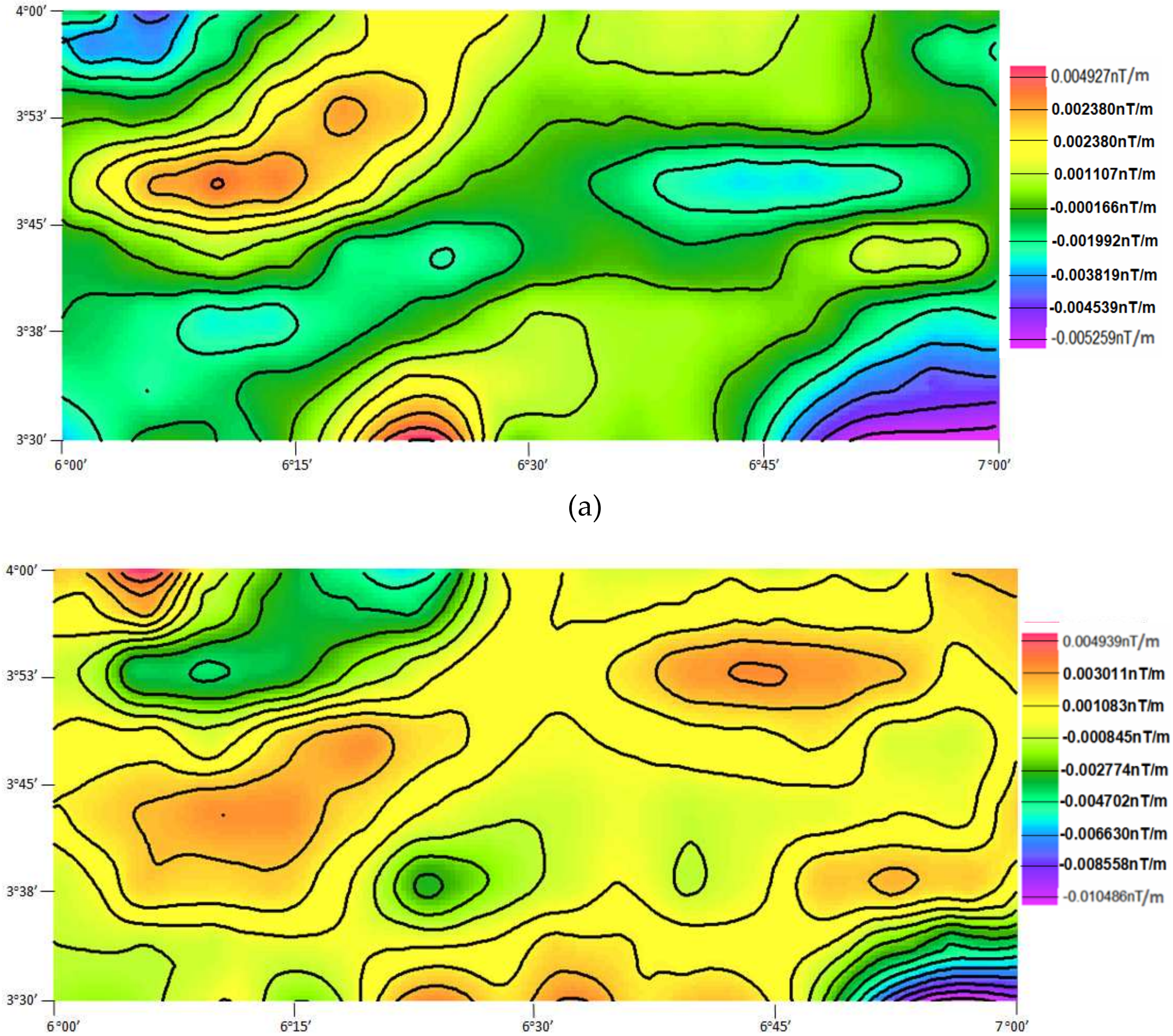


Figure 14. Directional horizontal derivative data highlighting subtle N-S structures and basement fault blocks. White lines are inferred accommodation zones



(a)

(b)

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

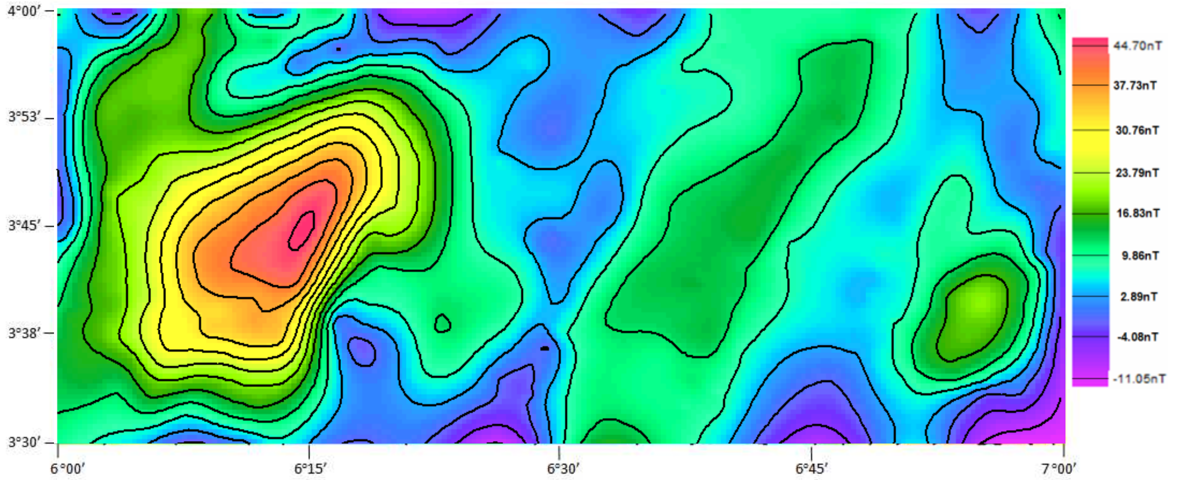


Figure 16. Analytic signal data highlighting basement block patterns and N-S structures

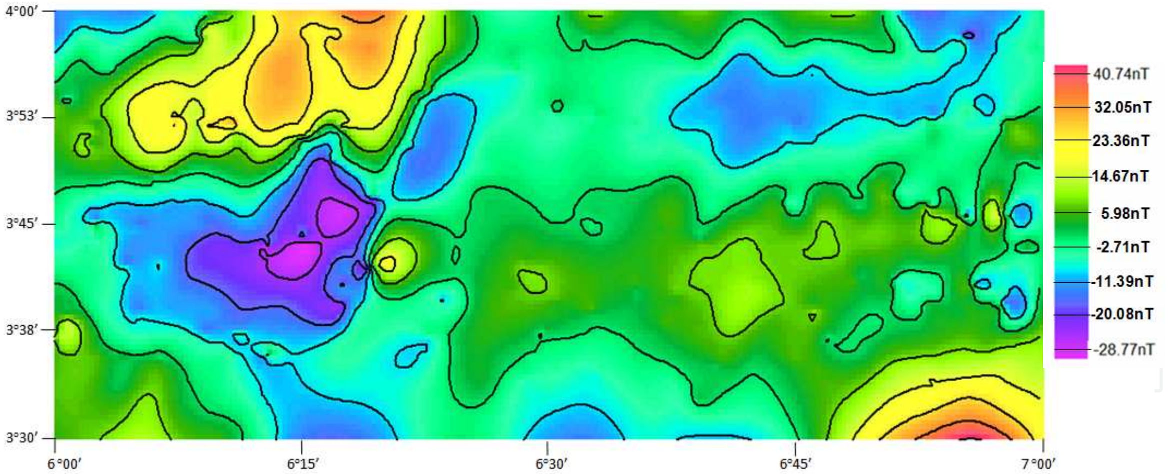


Figure 17. Low pass filtered data showing the major trends of the magnetic domains of the deep basement with discordant small scale structures

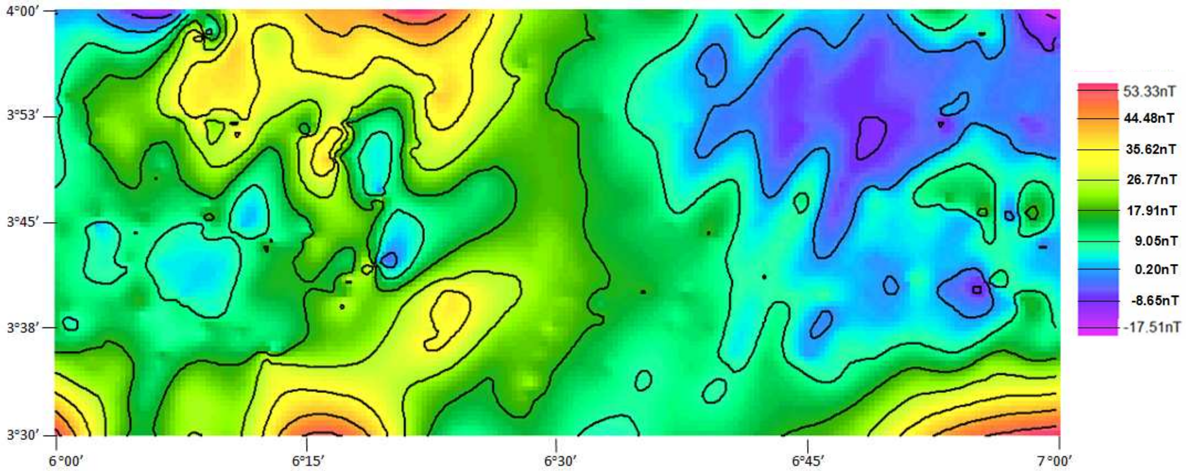


Figure 18. Filtered outputs of magnetic anomalies predominantly of short wavelengths which are discordant to the trend of the major magnetic provinces

The northwest-southeast trend (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 this magnetic data. [38] recognized the NE-SW and ENE-WSW trends as lineations and interpreted them as fracture zones trends beneath the Niger Delta. [14] recognized the NE-SW and NW-SE trends as the mega-tectonic 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 usually predominates. 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 figs. 14 & 16 and horizontal displacement in the E-W striking structures (fig. 15). The N-S and E-W bounded fault blocks are secondary faults which must have influenced stratigraphy and major tectonic elements or as shears which controlled local features. [39] and [40] 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 (fig. 13) and block faults (fig. 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 [41].

There are three evidences for reactivation. One of the evidences of reactivation is the arching up of the basement (fig. 13). 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 a thick sedimentary cover is forming pre-existing structures in the basement have 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 is enhanced [42]. 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 [43].

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. [8] 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 [44]. 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 [45]. 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 and 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 [18].

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 of 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 [44]. The uplifted blocks created the arches while downdropped ones produced the depocenters and we therefore opine that the flanks of the basement highs and basement lows are 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 [46]. 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 [47]. [48] linked oil pools in lower productive beds of sedimentary cover to faulted zones in crystalline basement in known platform hydrocarbon fields.

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 mineralized or associated with dykes. 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 may have 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.

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