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Interpretation of high-resolution aeromagnetic data within Dahomey basin, Nigeria; case for hydrocarbon prospectivity

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Abstract

High resolution digital aeromagnetic data acquired by the Nigerian Geologic Survey Agency, over a part of the Dahomey Basin, Nigeria, were analyzed; to investigate the hydrocarbon prospectivity of the basin using magnetic hydrocarbon indicators. The Derivatives, Source Parameter Imaging (SPI) and Magnetic Forward modeling techniques were employed with the aim of determining geometry and depth/thickness of the sedimentary Basin. Intra-sedimentary magnetic anomalies with possible association with hydrocarbon occurrence were enhanced by the application of band pass filters. The derivative maps revealed parallel to sub-parallel trending NE-SW, NW-SE and E-W lineaments probably caused by fracture zones in the basement, some of which propagate as faults into the overlying sedimentary formations. The thickness of the sediments in the study area varies from 1.5 km in the north-eastern region, 6.5 km in the south-eastern region to 7.8 km in the east-central region. The results revealed that the eastern part has a higher hydrocarbon prospectivity which correlate with the well logs based on the magnetic indicators. The Butterworth band-pass filtered map displayed some magnetic aureoles, often associated with hydrocarbon seepages. These aureoles characterize the deepest parts of the basin in the east-central and south-eastern parts, which is an indication of the existing exploratory wells that are mostly dry. It was concluded that the east-central and south-eastern parts of the basin investigated show a combination of favorably thick sedimentary formation, faults, fractures and magnetic aureoles probably represented areas of better potential for hydrocarbon exploration and were thus recommended for detailed seismic surveys.

Keyword: Dahomey basin, Hydrocarbon prospectivity, High-resolution aeromagnetic imaging, Magnetic hydrocarbon indicators – Magnetic aureoles.

1. Introduction

The Nigerian section of the Dahomey Basin has been a subject of renewed exploration interests due to rejuvenated interest of the Nigerian government in increasing her crude reserve through exploration of frontier basin. Ojo *et al.* (2009) stated that the hydrocarbon prospectivity of the Nigerian segment of the Dahomey basin has been part of the country's geosciences debate in the last 40 years. However, with the vigorous wildcatting, discoveries and appraisals in neighboring deep Ghana and Cote d'Ivoire, considered part of the same

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cretaceous transform margin to which the basin belongs, the frontier is yet to receive the focused attention.

According to Coker and Ejedawe (1987), low petroleum potential was ascribed to the Dahomey (Benin) Basin, from earlier work in the basin, but recent exploratory efforts in the basin have resulted into discovery of commercial oil in Ise Field, offshore Lagos (Brownfield and Charpentier, 2006; Khaki, *et al*., 2013; Nton, *et al*., 2006; Whiteman, 1982). In this study, high resolution data augmented by magnetic hydrocarbon indicators were used to study the basin-wide intrasedimentary anomalies (magnetic aureoles). The current study was therefore an attempt to identify prospective areas for hydrocarbon exploration by collating, analyzing and interpreting new digital magnetic data and comparing the results with those of some exploratory wells in the area. Oladele *et al*. (2008) and Ojo *et al*. (2009, 2012) reported that the results of earlier studies carried out on the contiguous Niger Delta and Anambra Basin confirmed the results of other studies (Foote, 1997; Stone *et al*., 2004; Urquhart, 2003) that correlation exists between the presence of intra-sedimentary magnetic anomalies and hydrocarbon producing areas (Aderoju et al., 2016; Nabighian, *et al*. 2005).

Magnetic properties morphology of geological structures in the sedimentary cover and influence of hydrocarbon fluids on the magnetic properties of rocks occurring over oil and gas deposits (Eventov 1997; Foote, 1992; Opara *et al*., 2012, Gadirov et al., 2018). And Gadirov *et al*. (2018) aptly stated that there are three main directions for the magnetic prospecting application: (1) mapping the crystalline basement, (2) identifying local structures possibly containing hydrocarbon and (3) “direct” searches of hydrocarbon deposits.

1.1 Geological Background

The Dahomey Basin (Figure 1) is a sedimentary basin that was initiated during the Mesozoic in response to the separation of the African–South American Plates and the subsequent opening of the Atlantic. The geology of the basin has been extensively discussed by various authors (Oladele *et al.*, 2015; Onuoha and Ofoegbu, 1988; Omatsola and Adegoke, 1981). Principal basement structures in the Benin Basin are those associated with Early Cretaceous rifting and are dominated by normal faults bounding a series of linked half-grabens (Oladele, *et al*., 2015). Assorted school of thoughts have worked on the stratigraphic framework of Dahomey basin (Adediran and Adegoke, 1977; Adekeye and Akande, 2006; Nton *et al*., 2006). And they have it that, Cretaceous sequence in the Eastern Benin Basin began with the

Abeokuta Group, which is made up of three formations namely; the Ise, Afowo and Araromi Formations.

The Ise Formation unconformably overlies the Basement complex of southwestern Nigeria and consists of conglomerates and grits. Overlying the Ise Formation is the Afowo Formation, which consists of coarse to medium grained sandstones. The Araromi Formation overlies the Afowo Formation and it is composed of fine to medium grained sandstone, shales, siltstone with interbedded limestone, marl and lignite (Billman, H. 1976; Omatsola and Adegoke, 1981).

The Ewekoro Formation, which is an extensive limestone body overlies the Araromi Formation. Overlying the Ewekoro Formation is the Akinbo Formation, which is made up of shale and clayey sequence. The claystones are concretionary and are predominantly kaolinite. Oshosun Formation overlies the Akinbo Formation and consists of greenish – grey clay and shale with interbeds of sandstones (Okosun, 1995). The Ilaro Formation overlies conformably the Oshosun Formation and consists of massive, yellowish, poorly consolidated, cross-bedded sandstones. Capping the sequence is the Coastal Plain Sands (Jones and Hockey, 1964) which consists of poorly sorted sands with lenses of clays, the cross section of Benin basin is shown in Figure 2.

The current study area is limited to within latitudes $6^{0}30^{'}00^{''}$ N – $7^{0}30^{'}00^{''}$ N and longitudes $3^{0}0^{'}00^{''}$ E – $4^{0}0^{'}00^{''}$ E. It encompasses the southwestern Nigerian portion of Dahomey Basin, in Figure 1, covering an area of 12,056.04 km^{2}.

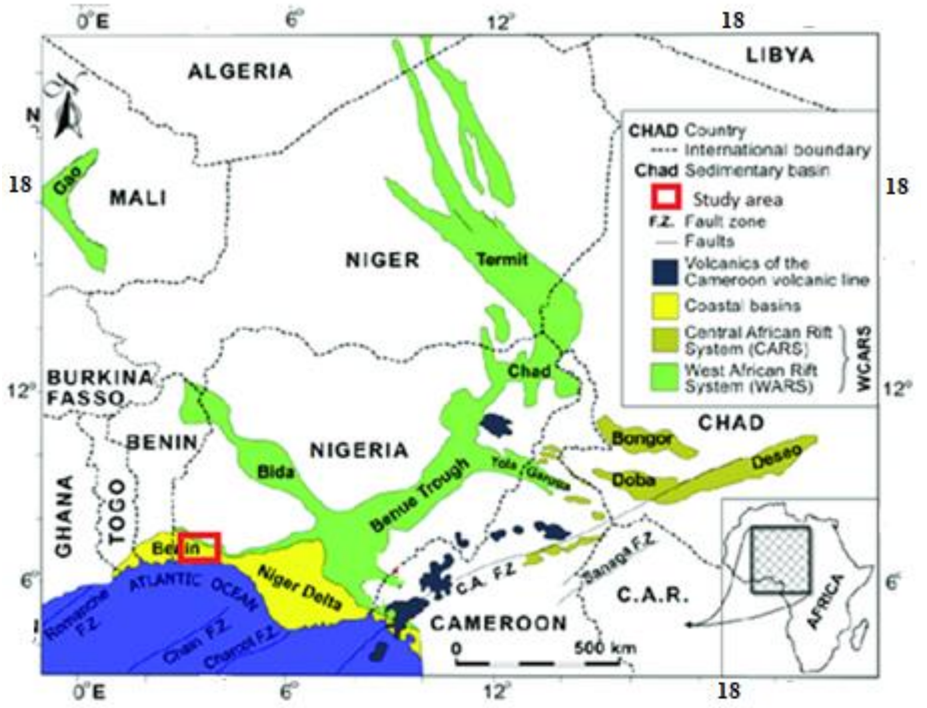

Figure 1: Dahomey Basin within the West and Central African Rift System Showing the Relative Locations of the Dahomey, Bida, Doseco, Bongor and Termit Basins (Modified after Genik, 1992)

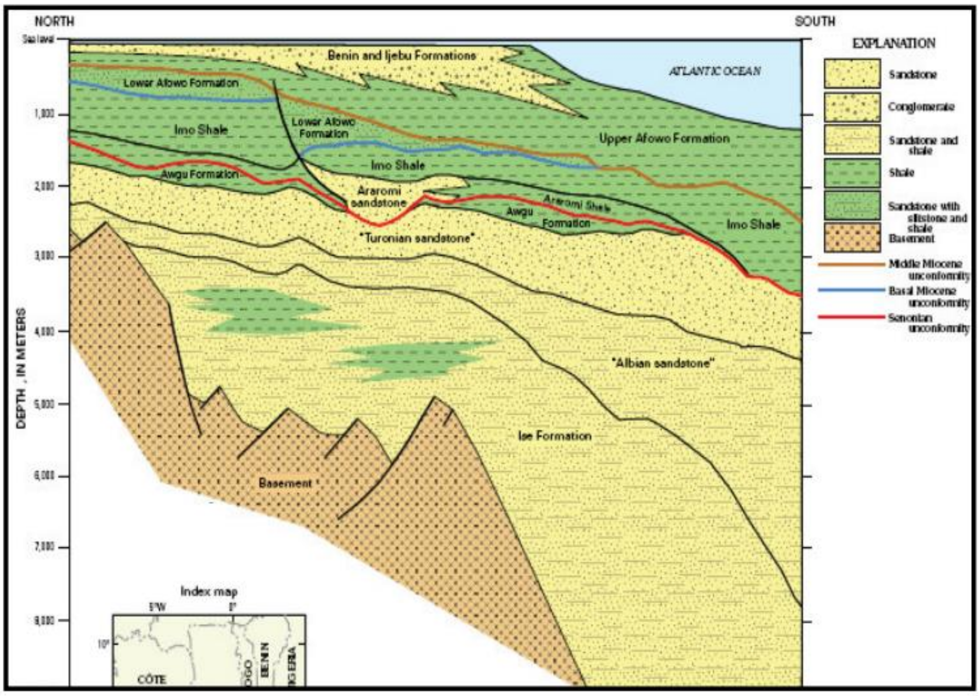

Figure 2: The cross-section of Dahomey basin (After Brownfield and Charpentier, 2007).

1.2 Principle of Hydrocarbon Related Magnetic Anomaly

Aderoju *et al*. (2016) recorded that Hydrocarbon move continuously from reservoirs to the surface through faults and micro fractures. Temperature gradients, compaction, and changes in atmospheric pressure help to drive this upward migration. The hydrocarbon sometimes reacts with the surrounding strata to create alteration features that can be mapped by geophysical methods. Oladele *et al*. (2008), Ojo *et al*. (2009) and Aderoju *et al*. (2016) recorded that the use of magnetic methods for direct or semi-direct location of oil and gas is based on the detection of diagenetic magnetite caused by hydrocarbon seepage (Eventov, 1997; Urquhart, 2003). Figure 3, such hydrocarbon induced anomalies include changes in density, magnetic susceptibility, radioactivity and conductivity. To be detected, the respective anomalous response must be greater than the background. Most reservoir are found to leak. The ratio of hydrocarbon migration and micro-seepage varies from less than one meter per day to tens of meters per day (Klusman and Saeed, 1996).

In furtherance of the record of the hydrocarbon seepage model (Figure 3), the process leading to the shallow precipitation magnetic minerals appears to occur within a subsurface redox zone that forms at the interface between the reducing environment created by the hydrocarbon seep, generated largely by the microbial action, and a sub-soil oxidizing environment generated largely by a non-static present day or paleowater table. It is within this environment that magnetite is concentrated through a dynamic cycle of conversion and re-conversion (precipitation and dissolution) often forming annular/aureole micromagnetic anomalies when imaged in plan (Stone *et al*., 2004).

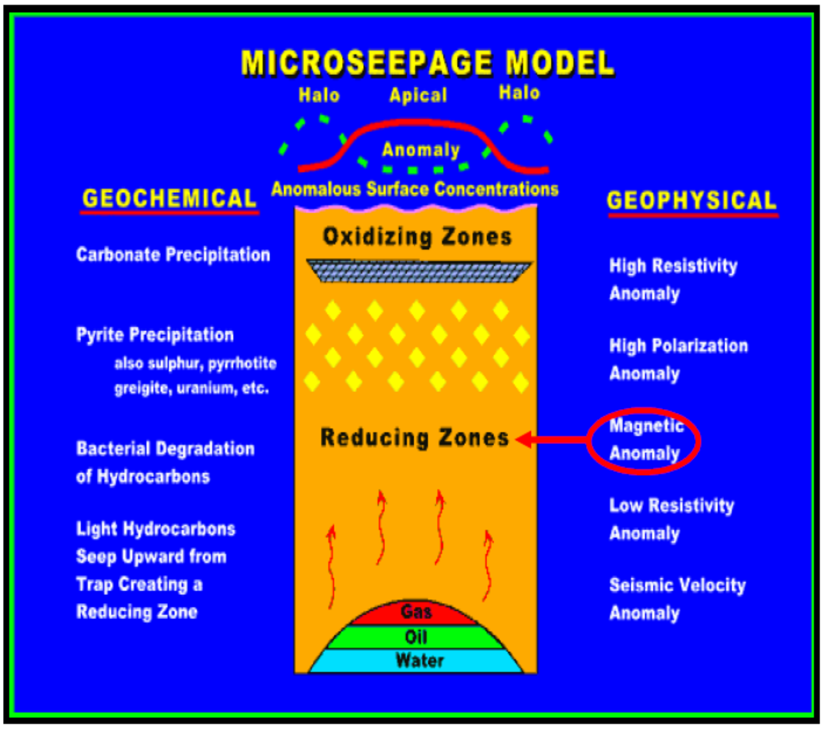

Figure 3: Generalized hydrocarbon induced effects in sedimentary rock - magnetic anomaly is highlighted in red circle (After Urquhart, 2003).

2. Materials and Methods

2.1 The Aeromagnetic Data

The aeromagnetic dataset used in this study were aeromagnetic maps of Ibadan, Abeokuta, Ilaro and Ijebu-Ode; Sheet numbers 260, 261, 279 and 280 respectively on a scale of 1: 100,000 each, (Fig. 4). They were obtained from the Nigerian Geological Survey Agency (NGSA). The Mean Terrain Clearance (MTC) used was 80m. (NGSA, 2009). The data was processed into a uniform grid of constant terrain clearance of 0.1 km with 0.1km line spacing. The data was recorded in digitized form (X, Y, Z text file) after removing geomagnetic gradient from the raw data using International Geomagnetic Reference Field (IGRF, 2005) model for the calculation of declination and inclination. The X and Y represent the longitude and latitude of the study area respectively, while the Z represents the magnetic intensity measured in nanoTesla. (Figure 4).

2.2 Well Information

Information from ten wells acquired from individual major oil and gas players (were used for the current study. The locations of these wells are shown in Figure 5. These wells were for the most part dry while a few had some gas or oil shows (Table 1). The deepest of the wells, (Ayetoro-1) attained a depth of 3689 m while shallowest (Itori-01) reached a depth of 548 m. Five of the wells reached the basement at varying depths and consequently provided controls for depth to basement analyses in this study. The wells are Ayetor-01 (3694 m), Ishaga-01 (1918 m), Ise-01 (3287 m) and Ise-02 (2914 m). (Obaje, 2009; Opara, *et al*., 2011; Oladele, *et al*., 2008).

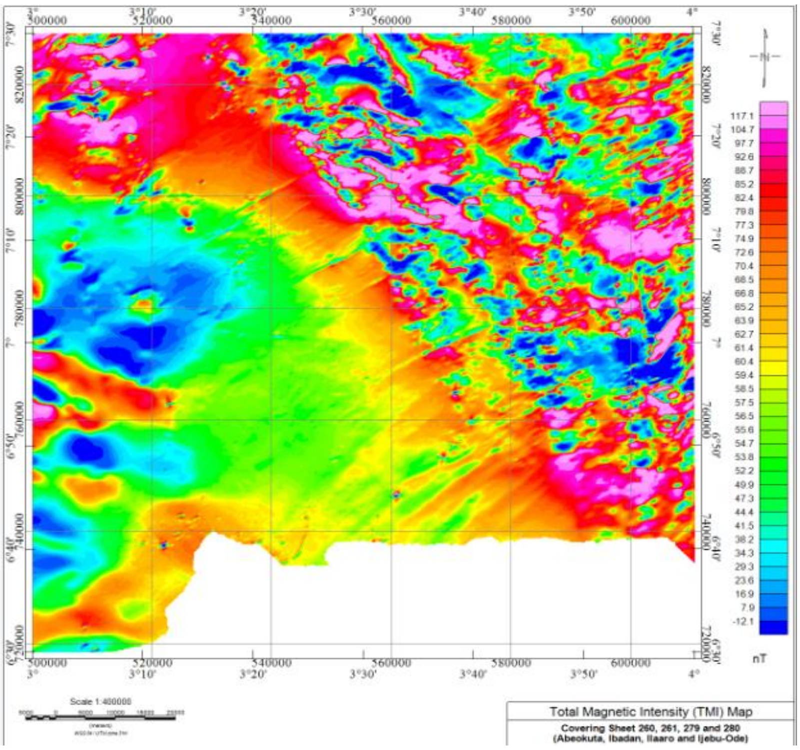

Figure 4: Total Magnetic Intensity Map of the Study Area. (After NGSA, 2009).

Table 1: Status of Ten Wells Drilled in Different Sections of the Study Area by Individuals

	Well Name	Well Prognosis
1.	Itori-01	Dry
2.	Onigun-1	Dry
3.	Erinmi-1	Dry
4.	Araromi-1	Gas show
5.	Ayetoro-1	Gas show
6.	Afowo-1	Oil show
7.	Ise-01	Oil show
8.	Ise-02	Oil show
9.	Bede-01	Dry
10.	Ishaga-1	Dry

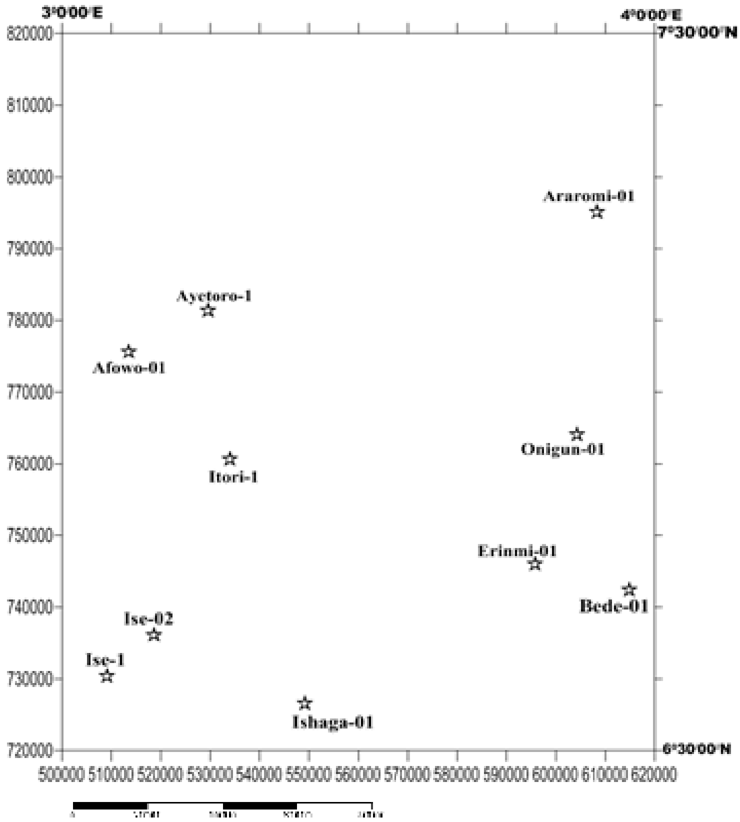

Figure 5: Base Map showing Well locations based on Coordinates supplied by individuals (the vertical and horizontal Axes represent Northings and Eastings (in meters) respectively.

2.3 Methodology

The digital aeromagnetic datasets were processed using the Oasis montaj^{TM} software from which the total magnetic intensity (TMI) and the residual magnetic maps were produced (Aderoju *et al.,* 2016). The total magnetic intensity (TMI) map was transformed into Reduced-to-the-Equator (RTE) map in order to remove the asymmetry associated with low magnetic latitude anomalies and to directly position observed magnetic anomalies over their respective causative bodies. Other transformation techniques such as horizontal and vertical derivatives (Aderoju *et al*., 2016; Anakwuba, *et al*, 2012; Phillips, 2000) and vertical continuations were carried out on the data to map various contacts and fracture zones in the deep basement. The enhancement of intra-sedimentary magnetic anomalies having possible association with hydrocarbon occurrence (MHIs) was also explored by the application of fourth order band pass filters to TMI-RTE data as outlined by Stone *et al*. (2004) and Aderoju *et al*. (2016).

Other advanced data processing techniques such as Spectral Analysis (Spector and Grant, 2000), tilt depth methods (Salem *et al*., 2007) were employed to determine the depth, geometry and location of the sources. 2D-forward modelling of some selected profiles across the study area was carried out using the GM-SYS^{TM} module of Oasis software to determine the variations in the thickness of the sedimentary sections and the probable effect of the basement on the disposition of the intra-sedimentary structures in the area.

3. Result and Discussion.

The interpretation of the results of the aeromagnetic data from the aeromagnetic map, sheets; 260, 261, 279 and 280 covering the study area commenced with the qualitative analysis of the total magnetic intensity map of the area as shown in Figures 6 and 7 reveal the different colour aggregates from the qualitative interpretation of the study area. The magnetic intensity in colour aggregates of the area ranges from 117.1 nT to -12.1 nT. The maximum intensity value of 117.1 nT is observed in the NW, NE and SE part of the study area while the minimum value of -12.1 nT is recorded in most parts of the study area, though it occurs dominantly in the western and northeastern parts. The study area is marked by the high (pink colours) and low (blue colours) magnetic signature. Thus, the magnetic relief of 95 nT in the area is attributed to differences in magnetic mineral content between various lithologies and to variations in the depth to magnetic rocks. Viewed anomalies with amplitude of the order of 100 nT is to be related to variations in basement lithologies (Ojo, *et al*, 2009).

3.1 Structural Lineament Analysis and Mapping of Deep-seated Fracture Zones

The surface lineaments map of the study area (Figure 8) showed NE-SW, N-S and E-W (inset) to be the dominant trends. Oladele, *et al* (2015) recorded that the lineament map obtained from the horizontal gradient of the tilt derivative of the residual aeromagnetic map (Figure 9A) features lineaments that originated from shallow sources. Rosette diagram of the shallow lineaments. (Figure 9B) indicates four major lineament trends - NE-SW, NW-SE and E-W - that characterize the shallow subsurface. The interpreted deep lineaments strike in NE-SW, NW-SE and E-W directions (Figure 9C). Oluyide (1988) recognised the principal lineaments directions in the Nigerian Basement complex as N-S, NNE-SSW, NE-SW, NNWSSE and NW-SE and to a lesser extent, the E-W- which are rather localized. (Oladele *et al*, 2015). These predominant structure trends conform to Pan-African structural pattern (Kaki *et al*., 2013). The trends generated are shown on the residual and the Reduce-to-Pole maps.

The residual magnetic anomaly shaded relief maps of the area depicted the structural lineament trends on the magnetic basements beneath the study area. The Linear, circular, elliptical and broadened contours as shown in Figure 6 & 7 are obvious on both the total magnetic intensity and residual aeromagnetic maps. The qualitative analysis further displayed that the area is composed of four main magnetic regions namely; north-western, north-eastern, central and southern region. These regions are distinguished on the basis of the variations of intensity of magnetic response.

The north-western and north-eastern regions were characterized by high magnetic response (which attained magnetic amplitude of 117.1 nT). The southern and north-eastern regions are characterized by relatively lower anomalies compared to the north-western region. Visual inspection of the aeromagnetic map reveals that the most dominant trend in the study area is NE-SW direction, related to the Pan African trend, (figure 8). The second dominant trend observed is the E-W to ENE-WSW directions in the eastern area of the map. Jones and Hockey (1964), Olasehinde *et al*. (2004) and Oluyide (1988) observed that these trends often coincide with litho-tectonic domains. Zone of broad magnetic anomaly NE and SE bounded from two sides (north and south) by relatively steep magnetic gradients (Nabighian, *et al*, 2005; Ojo et al., 2008).

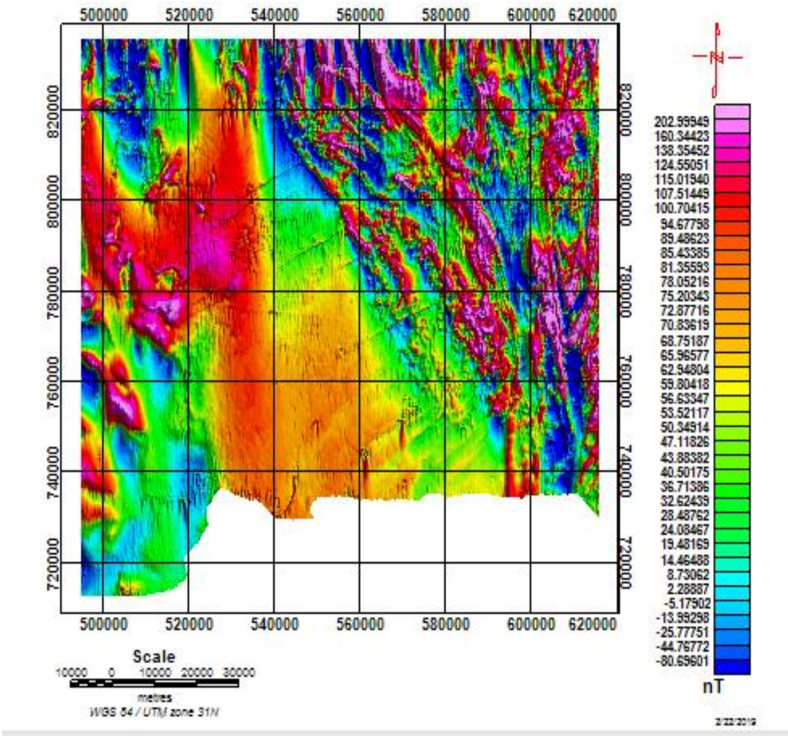

Figure 6: Reduced-to-magnetic Equator (RTE) map of the study area

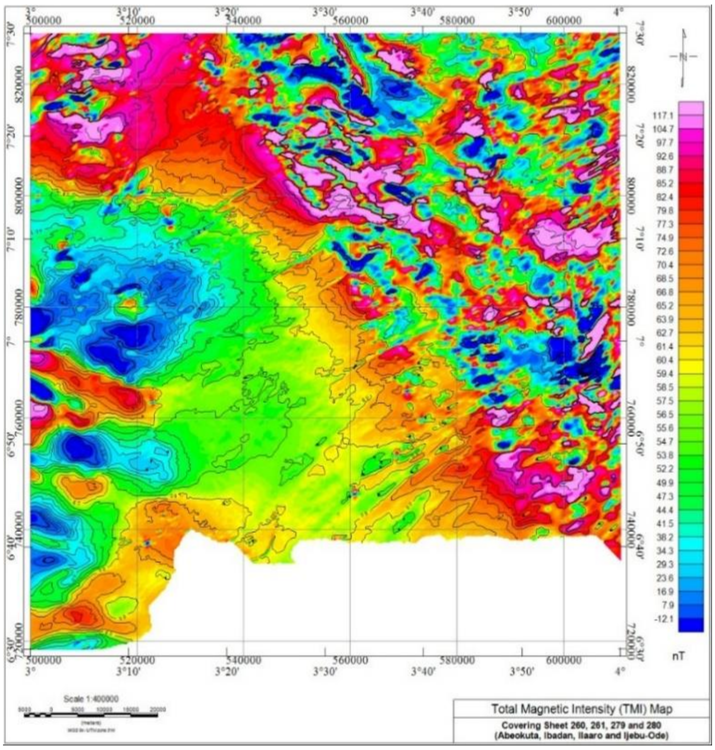

Figure 7: Contour map of total magnetic field anomalies in the study area.

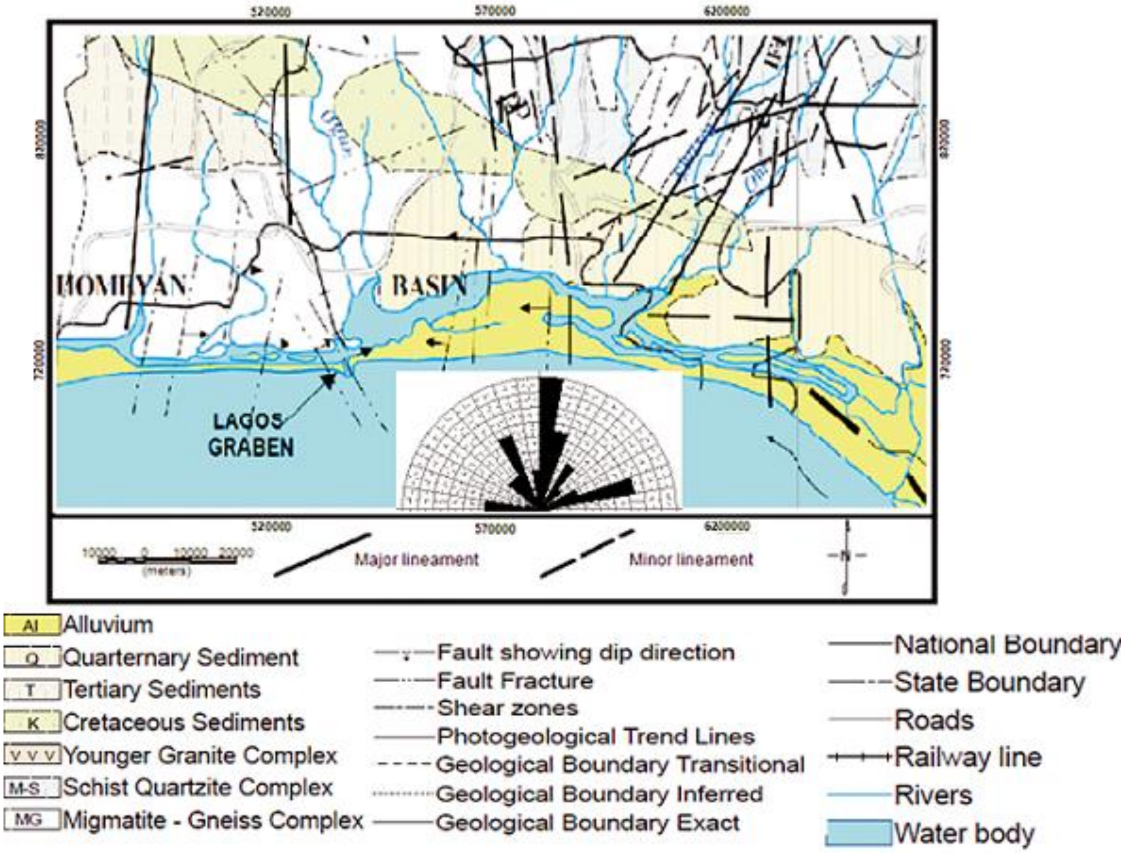

Figure 8: Surface Lineament Map (NGSA).

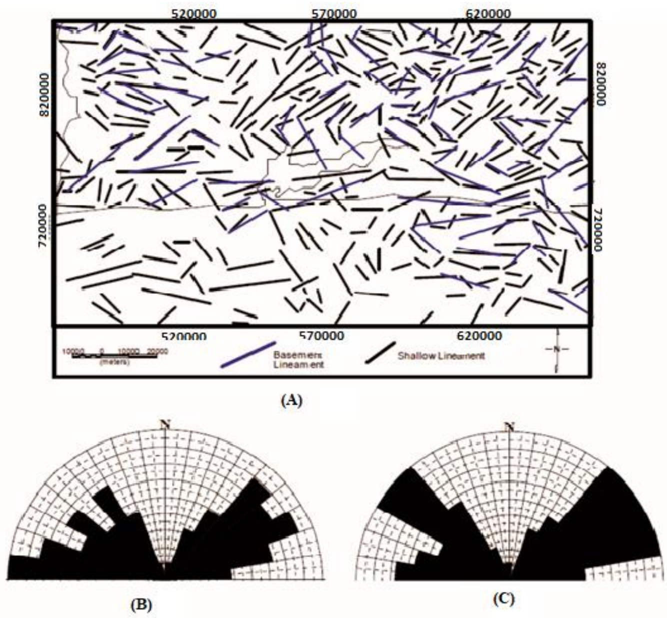

Figure 9: (A) Superposition of Shallow and Deep Lineaments of the study area. B and C are rosette diagrams showing the dominant trends of shallow and deep lineaments respectively. (Modified after Oladele *et al*, 2015).

3.2 The qualitative interpretation of the study area:

(1) There are two major rocks in the study area:

a. Magnetic low coinciding with sedimentary basin to the west

b. Magnetic high coinciding with the basement rocks to the east.

(2) Both high and low Magnetic intensity within the sedimentary basin, and the basement complex respectively, trend NW-SE.

(3) The boundary between sedimentary and basement rocks is trending NW-SE

(4) Principal Structural lineaments within the basement rocks trend mainly N-S, NNE-SSW, NE-SW, NNW-SSE while the rocks are aligned NW-SE.

3.3 Quantitative Interpretation of High-Resolution Aeromagnetic Data

The quantitative interpretation techniques employed in this study include:

1. Depth Estimates
2. Magnetic hydrocarbon Indicators
3. Magnetic Forward Modelling

3.4 Depth Estimates from Power Spectrum and Tilt Angle Methods

Figure 10 presents the radially averaged energy spectrum of the aeromagnetic map of the study area. According to Aderoju *et al*. (2016), this plot illustrates the typical reduction in energy with increasing wave number. The energy spectrum clearly shows the ensemble of sources that contribute to the energy from low to high wave numbers. The highest wave number anomalies represent magnetic sources close to the surface as well as noise. The lower wave numbers generally reflect deeper sources. Magnetic sources at similar depths fall on the straight-line segments in a graph of log of energy versus wave number. The slope of a line segments is a function of the average depth of the sources that it characterizes (Spector and Grant, 1970).

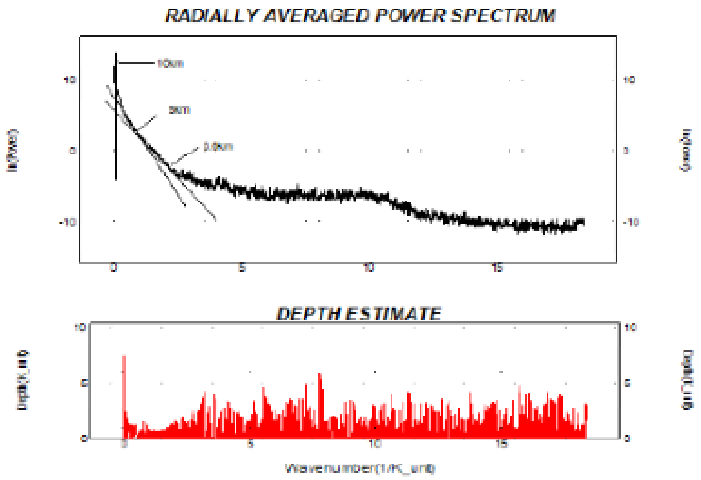

Figure 10: Radially Averaged Power Spectrum of the Study Area.

According to Aderoju *et al*. (2016), in order to obtain a better indication of the variation in depth to source, the study area was divided into smaller square blocks of dimensions 40 km x 40 km and the average depth was computed for each block. The depths were further constrained by depths from three wells within the study area which reached the basement, Afowo-1, Ise-1, Ise-2, at approximately 3.1 km, 2.4 km and 2.6 km respectively. Depth computation for these blocks revealed that the average depth to shallowest sources is 1.5 km and the deepest is 7.4 km below flight level.

Two important magnetic layers were therefore revealed in this study with magnetic basement depths varying from 4.219 km to 7.01 km and average basement depth of 6.039 km. This layer may be attributed to magnetic rocks of the basement, lateral variation in basement susceptibilities and intra – basement features like faults and fracture. Depth to the shallow magnetic layer ranges from 0.0101 km to 0.884 km with an average depth of 0.543 km. This agrees with Opara (2011) which estimated depth of 6.039 km to the basement in the eastern part of Dahomey (Benin) Basin.

3.5 Depth Estimates from Source Parameter Imaging

Figure 11, present the thickness of the basin that overlies the basement complex. Figure 12, shows the major sources in the study area; shallow sources found at the east (purple, red, yellowish and green colour) and deep sources at the west (blue colour). The western part of the study area is shown as deep-seated sources and the eastern area is shallow source area. The western area has depth to magnetic sources greater than 500 meters, the intermediate magnetic sources have depth ranging between 200 meters to 500 meters. while shallow sources on the eastern side have depth less than 200 meters. The shallow sources originate from within shallow basement complex rocks. The eastern part has thick sediment to about 200 m. this is clearly pronounced in the eastern, south-eastern and partly south. But the thickness of sedimentary rock of the basin ranged from 710.5 m – 1,965.7 m and this is pronounced in the north-western part. This emanates from deep sources which are mainly located in the western part (south-west and north-west) of the study area. In the study area, the first layer which is Recent Alluvium of 1128 m, it was observed that this first layer could be cross bedded sand of Benin Formation.

Magnetic Basement depth map derived from Source Parameter Imaging (SPI) shows alternation of Basement high and low from east to west. The deepest area in the east – central region is interpreted to have had the thickest sediments, that is, the area with the greatest potential for accommodation space or accumulation sites for petroleum. In figure 13, the 3-D map shows the depth to magnetic basement using spectral depth, with the locations of some of the Wells.

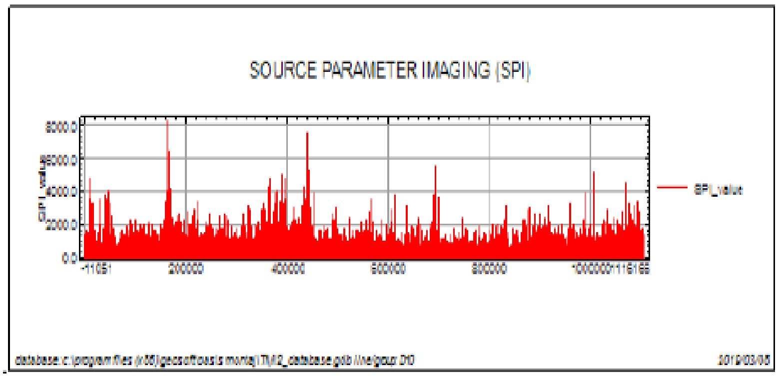

Figure 11: Source Parameter Imaging of the Study Area.

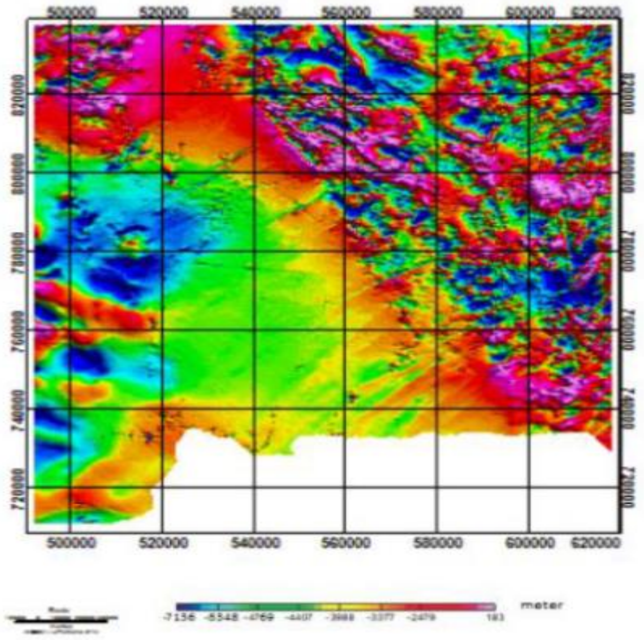

Figure 12: Depth to Magnetic Basement derived through SPI Method.

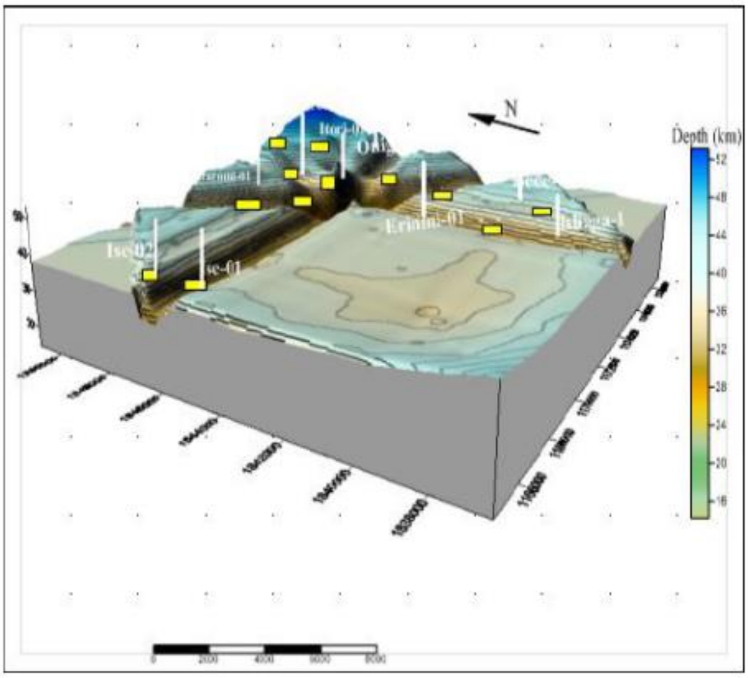

Figure 13: 3-D Map showing Depth to Magnetic Basement Computed Using Spectral Depth Method and Locations of Some of the Wells.

3.6 Total Horizontal Derivative

The total horizontal derivative maps are shown in Figures 14a and 14b for derivative in X- and Y- direction respectively. High and low magnetic anomaly dominates the western part of the study area while intermediate magnetic anomaly is of high dominance in the eastern part of the study area and cut across the south, west and northwest of the area. Linear features such as lineament, fault may be of high dominance in the eastern part of the study area which is intermediate magnetic anomaly with magnetic intensity value of 50.2 nT/m and 58.7 nT/m as shown in Figure 14a and 14b.

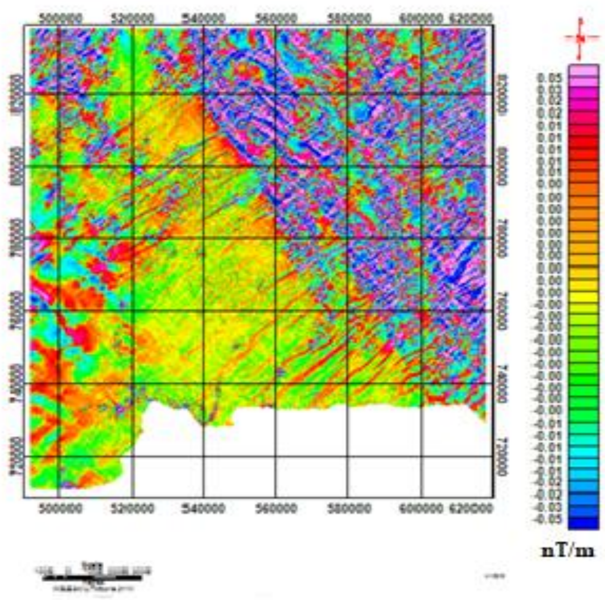

Figure 14a: Map of derivative in X – direction of the Study Area.

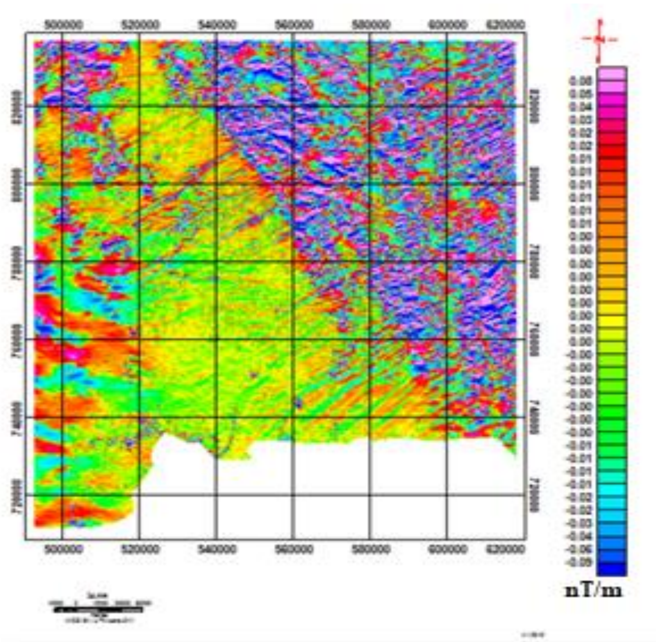

Figure 14b: Map of derivative in Y – direction of the Study Area.

3.7 Basin Geometry

The geometry of the Study area was clearly shown on the Analytical Signal of the upward continued to 10 km data which shows rock magnetization distribution in the study area (Figure 15). Low magnetization at the center of the study area is interpreted as presence of thick non-magnetic sedimentary rock within the Ibadan and Ilaro metropolis Figure 15. These areas correspond to the 'Basin proper' of Coker and Ejedawe (1987), characterised by drop in Basement floor. The eastern and western parts are dominated by high magnetization values indicating presence of crystalline rock at the shallow depth, hence thin sedimentary accumulation. Abeokuta and Ijebu-Ode areas are characterized by narrow belt of intermediate magnetization viewed as significant region of sediment accumulation. The Analytical Signal map therefore revealed that the basement beneath the basin is not topographically flat, but characterized by a large Basement depression flanked by Basement highs (Omatsola and Adegoke, 1981). This observation as recorded by Oladele *et al*. (2015) thus imposed a horst and graben architecture on the basin geometry, the graben is viewed as zones of significant sediment accumulation where hydrocarbon exploration could be focused.

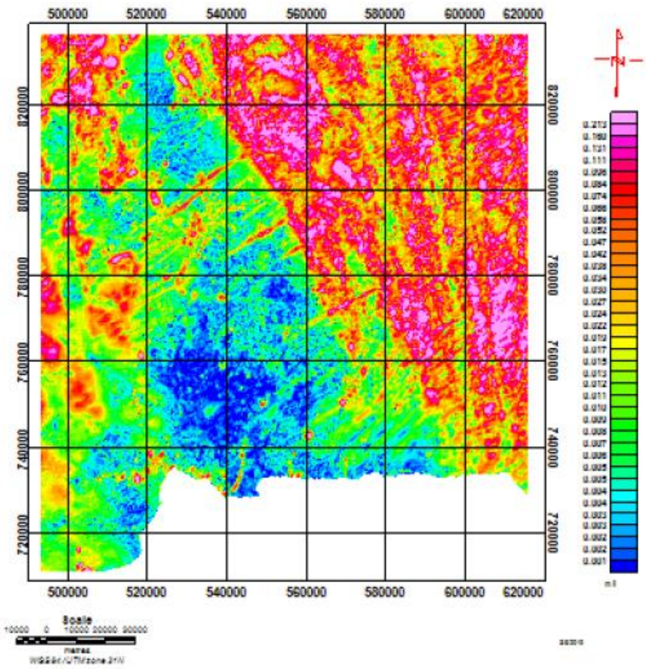

Figure 15: Analytical Signal map of the study area.

3.8 Derivative Maps

The horizontal derivative map is shown in figure 16. The lineaments inferred are superimposed on the map (white colour). The lineaments trend mainly NW – SE with a few

NE – SE. The lineaments trend in northwest – southeast in the Western parts and northeast – southwest structural trend mostly in the eastern part. The magnetic intensity across the area of the study area ranges form - 60.253 nT to 56.445 nT. But from the map (figure 16) the features displayed are linear features with short anomalies. Two geological environments (shallow basement complex and sedimentary terrain) were clearly indicated in Figure 17; however, shallow basement rocks sources dominated the north-east and south-east region and partly the southern region. But the sedimentary terrain was deep seated with a thickness close to 2000m (2.0 km). This indicates that in the north-east and south-east regions there are linear structures with the probable features which are pronounced in the region compared to the western part of the study area. This implies also that in eastern region hydrocarbon exploration could be as a result of thick sedimentary cover and fracturing. The presence of lineaments in the study area could be as a result of seep related aureoles from shallow basement rock underlying the basin. These lineaments may likely contribute to hydrocarbon accumulations.

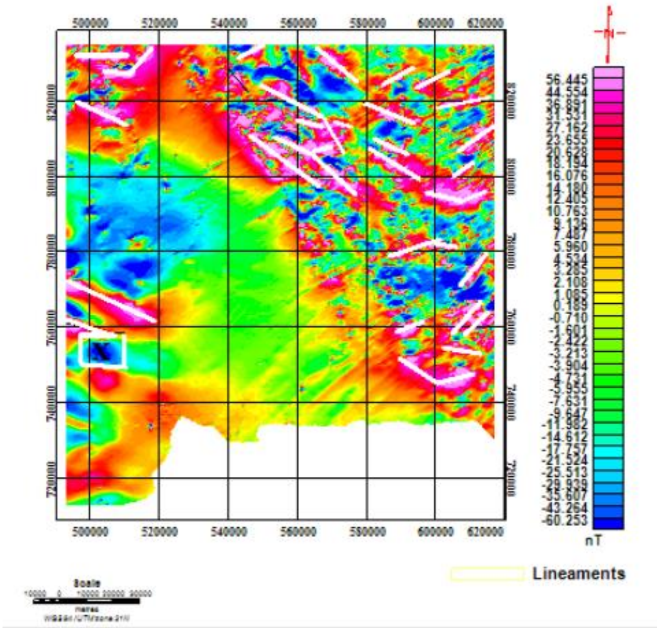

Figure 16: Horizontal Derivative Map of the Study Area Superimposed with Lineaments.

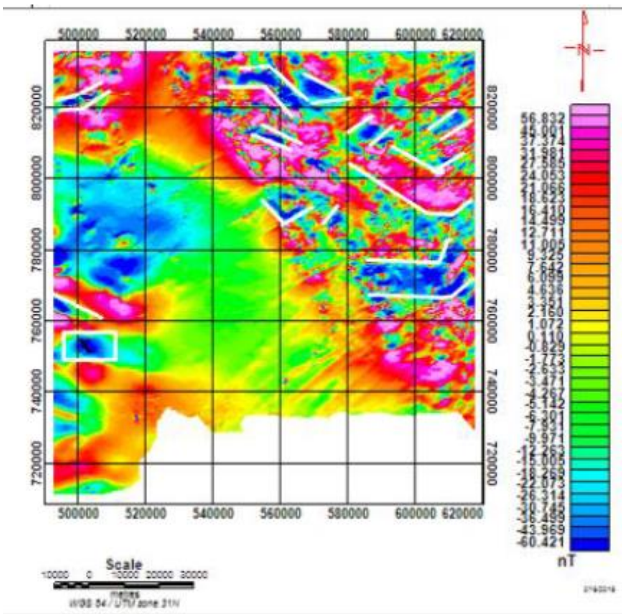

Figure 17: Second Vertical Derivative Map Superimposed with Inferred Lineaments.

The map reveals parallel to sub-parallel NS-SW, E-W and NW-SE trending fracture zones (marked by white lines) deep seated in the basement underlying the study area. The second vertical derivative (2VD) map, it also reveals a great amount of detail such as definition of body edges not obvious on the original TMI data. This result is comparable with that obtained from the horizontal derivative. All the NE-SW trending fracture zones are easily recognized. (Oladele *et al*., 2015) The identified fault trends are attributed to extensional basin tectonics that created the Dahomey (Benin) Basin. Many of the features shown by these derivatives maps are vaguely apparent in the total intensity data. The structure labelled X appears to be a deep intrusive rock (Opara, 2012). The anomaly on the HD map reveals two maximums representing the edge of the intrusive rock, while these maxima coincided with the zero contour on the 2VD map.

3.9 Magnetic Hydrocarbon Indicators: Magnetic Aureoles

The distribution of inferred aureoles is shown in white boxes (Figure 18) and it can be observed that the magnetic aureoles do not appear to coincide with the wells, hence, the wells were essentially dry (Table 1) with a few of the wells exhibiting some gas or oil shows. It is strongly believed that the wells could have been more successful if drilled over the region of the magnetic aureoles based on their characteristic association with hydrocarbon seepage. Geomagnetically induced anomalies are characterized by east – west trending magnetic low flanked to the north and south by magnetic highs. The E-W anomaly is typical of the anomaly induced around the equator where the field is horizontal (Stone *et al*, 2004).

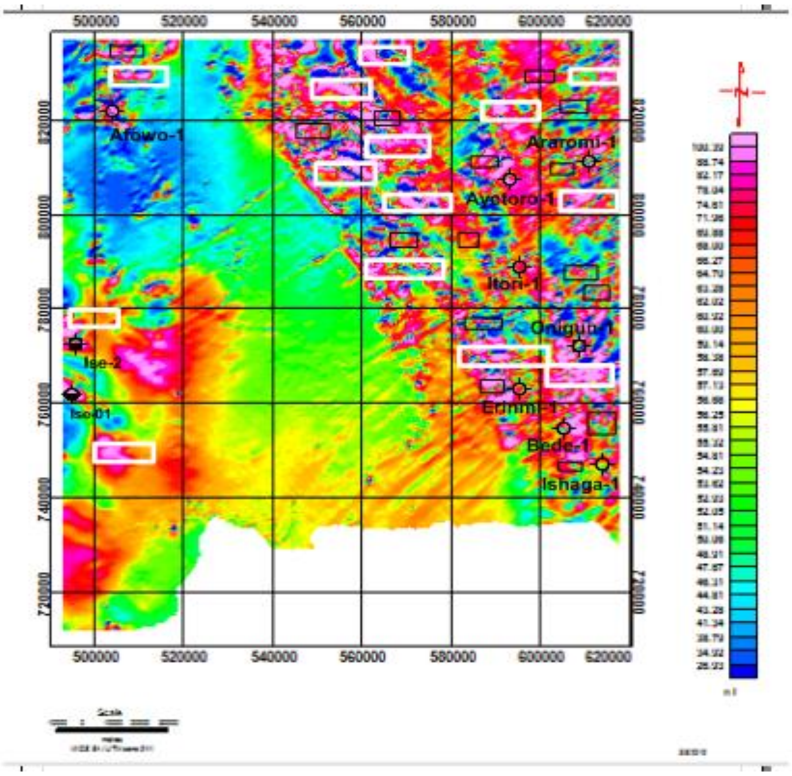

Figure 18: Residual map showing the seep related aureoles (black boxes); geomagnetically induced anomalies (white boxes) and Well locations.

3.10 Magnetic Forward Modelling

Figure 19, presents the profiles taken in directions orthogonal to the prominent trends / structures (Oladele et al., 2015). These profiles used as the observed profiles for 2-D modelling retained the long deep-seated sources. GM-SYS^{TM} module of Oasis montaj^{TM} was employed. The profiles were taken perpendicular to the most prominent anomalies' strike direction to obtain the best estimate of body parameters from the profiles so selected. Anudu *et al*. (2014). Cross-sections constructed though the study area via joint forward modelling of the magnetic profiles are shown in Figure 19.

According to Oladele *et al*. (2015), the major sedimentary units of the study area were lumped together as one and were assigned zero magnetic susceptibilities. In these profiles A-A', B-B' and C-C', as shown in Figures 20a, b and c the potential field amplitude was accounted for by variations in depth (0.2-5km) magnetic susceptibility (0.033 to 0.050 SI) and density (2642 to 2701kg/m3) of crystalline basement. The W – E transects profiles A-A' and B-B'. Omatsola and Adegoke (1981) had recognised a number of horst and graben sectioned by

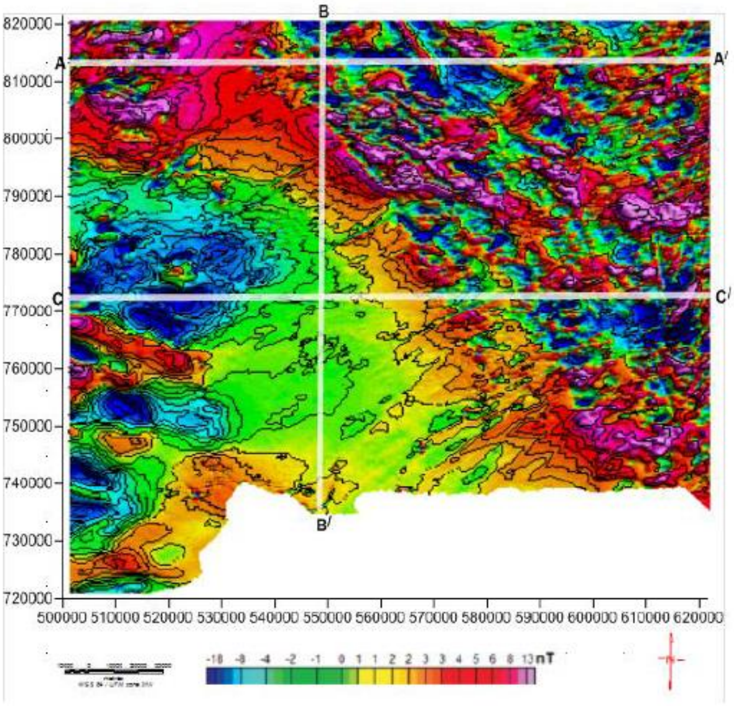

Figure 19: Residual map showing the locations of the modelled profiles A – A/ to C – C/.

N – S and NE – SW trending faults from a number of wells drilled to Basement along the coastline, while the N – S transect (profile C – C') in Figure 20C revealed that the basement generally slopes from north to south. The N – S section of Billman (1992) imaged a regional southerly tilt of the basement which was attributed to series of narrow step faulted Basement blocks aligned parallel to the coastline (Coker and Ejedawe, 1987).

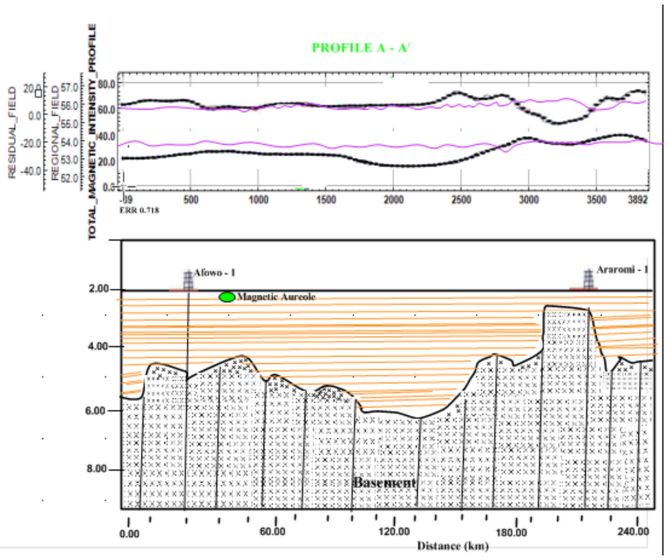

Figure 20a: Geological model along magnetic profile A – A/ (nT).

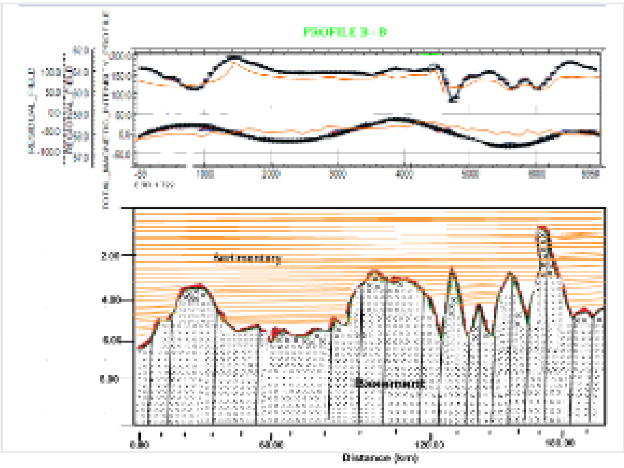

Figure 20b: Geological model along magnetic profile B – B/ (nT).

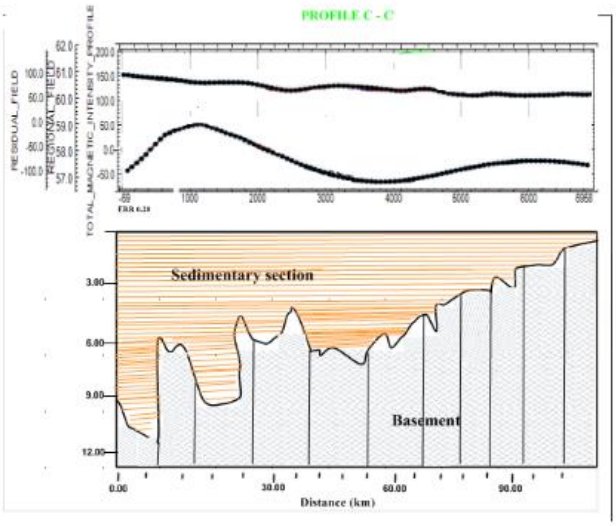

Figure 20c: Geological model along magnetic profile C – C/ (nT) (Oddiah, 2019).

Two depth source models which were established using depth values revealed the deeper sources ranged from 0.88km to 5.15km, anomaly values varying from -32nT to -225nT, characterized by longer wavelength anomaly, while the shallower sources ranged from 0.23km to 0.76km, anomaly values ranging from -10nT to 20nT, characterized by short wavelength anomaly. The shallower sources probably depicted depths to pre-Cambrian basement or near surface basic igneous intrusive rocks (such as basalt flows and dolerites) and/or low-lying river valleys. The deeper sources were characterized by high negative anomaly values having longer wavelength and depicted hydrocarbon accumulations.

The 3-D depth map is presented in Figure 13. Maximum basin depth is observed in the east-central area where the magnetic basement attains a depth of 7.0 km below the surface. Depth value attains 1.7 km in the north-western area, indicating the shallowest basement area. A basement ridge trending E – W straddles the northern part of the study area. From this ridge, the basement subsides gradually to the central part of the area of investigation. The central region of the basement surface is generally deep and is characterized by an E-W trending signature.

Oladele, *et al*. (2015) have stated that the basement morphology rises abruptly to 3.0 km in the southern part of the basement low and then subsides to a depth of 3.8 km further southwards before ascending steeply further southwards; the maximum depth around this area is not determinable due to lack of continuity in the data. The depth values obtained for the study area also agreed with those computed from aeromagnetic data over some parts of the Benue Trough by Ojo (1990) and Onyedim *et al*., (2006) hence, depicts the sedimentary cover (sediment thickness) across the sedimentary part of the study area being generally low and therefore not likely to favour hydrocarbon (oil and/gas) generation or formation. The shallower sources may be a result of activities in the basement complex of southwestern Nigeria. These tectonic activities account for the complex fracturing in the area with some fractures extending towards the northern part. The magnetic lineament map shows the major fault trend in the NE-SW direction with a minor fault trend NW-SE (Figure 21). These trends are in conformity with the structures of the basement complex of northeastern region and could have served as a migratory pathway for hydrocarbon or hydrothermal fluid.

Thus, Anakwuba *et al*. (2012) stated that, the sedimentary cover at the southwestern part is generally low and may not support hydrocarbon formation. This area is therefore designated as an area to be avoided during detail hydrocarbon exploration. Apart from the southwestern part, all the other parts of the study area have a sedimentary thickness that is moderately high. In line with this, for any area to be viable for hydrocarbon formation, the thickness of the sediment must be at least 2.0 km as well as other conditions necessary for hydrocarbon formation (Whiteman, 1982). Also, Kaaki, *et al*. (2012) said that in the Dahomey (Beini) Basin the Awgu and Akinbo shales are the source rocks, while the reservoirs are the Ise, (Albian and Turonian) Sandstones. Based on the computed sedimentary thicknesses (1.5-7.8 km), and the fractures which serve as migratory pathways for hydrocarbon or hydrothermal fluid, then the possibility of hydrocarbon generation in the east central and southeastern parts of the study area is feasible. These areas have been marked for detail hydrocarbon exploration. (Figure 22).

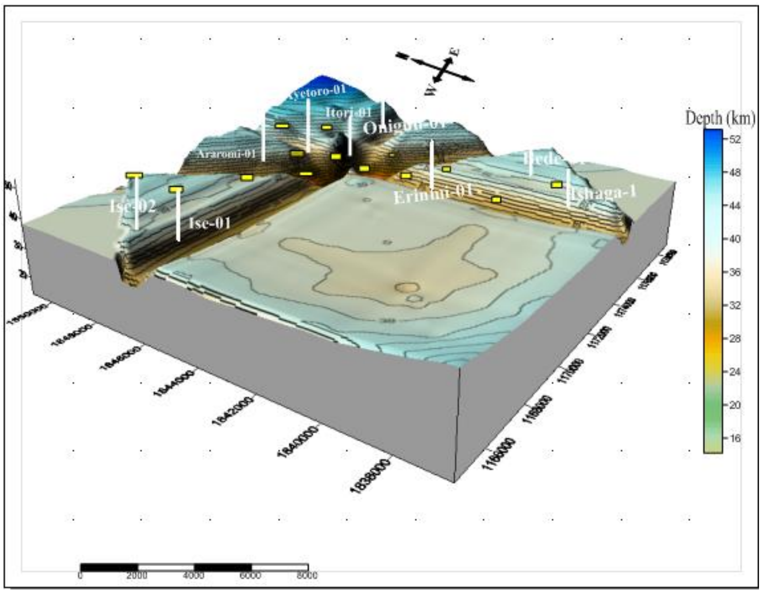

Figure 21: 3-D Depth to Basement Map Computed from 2D Model Profiles on which Well and Magnetic Aureole Locations are superposed as White Sticks and Yellow Boxes Respectively.

3.11 Magnetic Signature of the Study Area

The Reduced to Magnetic Equator (RTE) of TMI response of the study area is characterized by anomalies of varying intensity (-12.1 to 117.1 nT), wavelength and trends implying different sources, depth, compositions as well as tectonic character. The residual TMI Map reveals short wavelength anomalies that are concealed in the original map by the long wavelength anomalies. The anomalies exhibit high magnetic gradient implying vertical to steeply dipping walls of the Basement blocks.

The Total Magnetic Intensity (TMI) and residual magnetic maps generated from the high-resolution magnetic data clearly identified three main structural trends, NE-SW, NW-SE and E-W trends. These structural trends were further supported by results from first horizontal (HD) and second vertical derivative (2VD) of the RTE map which revealed parallel to sub-parallel NE-SW, E-W and NW-SE trending fracture zones, deep-seated in the basement underlying the study area. The NE-SW trend which appeared to be the oldest and the most abundant trend affecting the area is consistent with the major structural trend of the basement complex of Nigeria observed from aeromagnetic maps by different workers (for example: Ojo, 1990; Ako, *et al*., 2004).

Depth to basement analyses using two-dimensional (2D) power spectrum and tilt-depth techniques constrained by depths from five wells which reached the basement as well as 2D modeling of several equally spaced profiles across the study area showed that there was adequate accommodation space to host hydrocarbon reservoirs. Generally, basement depths range from 1.5km to 7.2km below the flight level. There was good agreement in trend and location between basement structures and trends of the overlying sedimentary fault systems, strongly suggesting that the sedimentary section has been influenced by the underlying basement architecture. The maximum depth obtained is slightly higher than the value obtained by Kaki *et al.* (2013) from seismic data but much less than the value obtained by Opara *et al.* (2011). Studies by several workers (for example: Billman *et al.,* 1992; Brownfield *et al.,* 2006; Kaaki *et al*., 2013; Oladele *et al.,* 2015) on the hydrocarbon potential of some potential source rocks in the Dahomey (Benin) Basin, such as Afowo and Araromi Formations, through the evaluation of their total organic matter (TOM), total organic carbon (TOC), hydrogen index (HI), vitrinite reflectance, and the thermal and burial history, indicated that the formations had good oil generating potential. The Ilaro and Ise Sandstones within the Dahomey (Benin) Basin are also suitable reservoirs.

Petrophysical parameters such as porosity, permeability, water saturation, hydrocarbon saturation, bulk water volume, computed and interpreted by Kaaki *et al*. (2013) suggested that the Ise Sandstone is a potential reservoir for hydrocarbon accumulation. In spite of all these, however, available records from the exploratory wells by individual record acquisition showed that most of the wells were dry or at best had some gas shows. Nonetheless, the presence of magnetic aureoles in the analyzed maps in the east-central and south-eastern region of the study area, presumably due to diagenetic activities which might be associated with some hydrocarbon seepage, suggest that there might be favourable hydrocarbon reservoirs in these areas. The magnetic aureoles could not be associated with the wells drilled in the area, thereby suggesting that the wells were probably not optimally located.

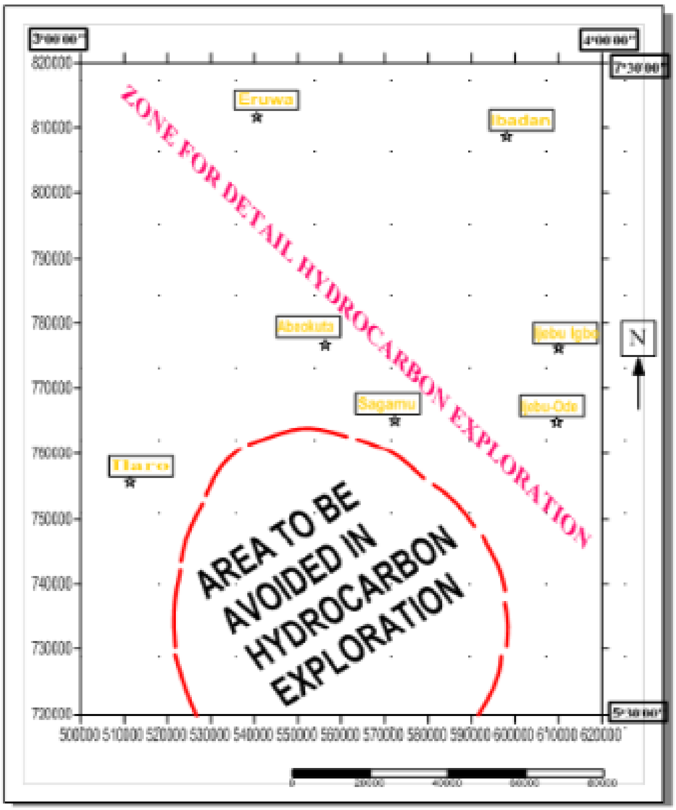

Figure 22: Isolated zone of possible hydrocarbon potential in the study area (Oddiah, 2019).

4. Conclussion.

The hydrocarbon prospectivity of part of the Dahomey Basin has been evaluated using magnetic hydrocarbon indicators. This approach involves the use of Spectral analysis in delineating the depth to the basement and structural features that can act as hydrocarbon seeps. The conclusions of the study are as follows:

(1) The detailed study of the Seep - Induced Aureoles and Geomagnetically induced which are tools for Magnetic Hydrocarbon Indicators in the area showed that northeast and southeast area of the studied area revealed hydrocarbon accumulation zones, hence, emphasis to be laid on hydrocarbon exploration within the specified zones in the studied area.

(2) The east-central and south-eastern parts of the study area with a combination of thick sedimentary formation, accompanied by faults, fractures and magnetic aureoles have a better potential for hydrocarbon Prospectivity than the present well locations (Onigun-1, Erinmi-1 are two of the dry holes in the study area, believed not to be optimally sited). These areas are thus recommended for more detailed seismic surveys.

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