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Geomagnetic modeling of potential hydrocarbon traps in the lower Niger Delta, Offshore West Africa

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ABSTRACT

A renewed interest to continually search for hydrocarbon prospects in the deep offshore West Africa climaxed after the discovery of a rewarding oil prospects around the deep offshore basin of Mauritania. However, recent statistics showed that, viable prospects along this region are increasingly becoming difficult to locate and that, future success will greatly depend on identifying 'structural and stratigraphic traps' within prospective areas. In this study, digitised aeromagnetic data covering part of Niger Delta was processed and gridded to generate the residual map as well as the depth to basement maps. On these maps, potential areas for hydrocarbon traps were delineated accordingly. Oasis Montaj geophysical software was used throughout the data processing and analysis. The average thickness of the sediments or depth to basement varies from 0 km on the outcrops to as much as 10.7 km within the study area, large enough for hydrocarbon accumulation. In addition to that, eleven intrusives were mapped from 2.5D forward and inverse modeling, with lateral extents of 1.5 km - 6.0 km. The presence of these intrusives made parts of the study area less favourable for hydrocarbon exploration. The structurally low areas were also outlined from the depth to basement maps. Interestingly, most of the oil producing fields were reportedly located within the structurally low areas of the basin. Hence, it is recommended that a detailed seismic prospecting be carried out around the structurally low areas in 'the new frontiers'.

Key words: Aeromagnetic, Residual Map, Basement rock, Source rocks, Intrusives and Hydrocarbon traps.

INTRODUCTION

Airborne magnetic survey was initially employed for hydrocarbon exploration especially in regions where oil-bearing sedimentary layers are primarily controlled by topographic features, such as faults, ridges etc and can also be used for direct detection of hydrocarbon [1]. Several oil fields have been located using this method, like the Hobbs in the New Mexico [4].

Magnetic susceptibility is basically the fundamental parameter of magnetic survey, used for hydrocarbon exploration, as it reflects changes in the subsurface geologic structures [19] and this property of rocks vary from place to place below the earth's surface. This variation in the magnetic susceptibility can cause small magnetic variation in the magnetic fields of rocks measured on the surface [10]. Weak anomalies or low magnetic readings on the residual map may reflect the presence of a local relief on the basement surface which are to be analysed quantitatively [15]. It can also indicate the presence of oil traps in some cases [1].

In hydrocarbon exploration, residual maps also play a key role in identifying the presence of intrusives, lava flows and igneous plugs, which are areas to be avoided in the course of an exploratory exercise [17]. However, intrusives are not completely detrimental to the hydrocarbons *per se* but could also provide the geothermal energy needed for the maturation of petroleum source rocks [12]. Problem arises only when they are in large quantity meaning that, more geothermal energy will be released, which may lead to over-maturation of source rocks. At this point, the temperature window for hydrocarbon generation could be exceeded, thus, affecting the quantity to be generated. The presence of Intrusives may also serve as hydrocarbon traps or reservoir rocks [16].

There are lots of challenges confronting viable exploratory oil and gas prospects in the Offshore West Africa as reported by PGS geophysical with Niger Delta inclusive [14]. Repsol Oil Company maintained a constant presence throughout the year 2011 exploring deep Offshore West Africa, but the results of its seismic database revealed a disturbing outcome as no viable prospects was in sight. However, they are hopeful that the deeper offshore basin between Benin and Senegal seemed to be promising but ‘risky’ [18]. In addition, reports of the exploratory exercise by PGS Geophysical indicate that series of wells located around the Offshore Niger Delta revealed a ‘disturbing’ outcome, with no viable prospects in sight. Though efforts are being shifted to the Miocene sands of the basin, for direct “hydrocarbon indicators”, after a huge discovery of oil deposits by Chevron Texaco in OPL 249 within the deeper Oligocene sand sheets [14] .

This study is part of the efforts being made to address some of these daunting challenges in a bid to locate new hydrocarbon prospects in the Niger Delta. The objectives are to map out potential areas suitable for hydrocarbon accumulation; to estimate the average thicknesses of the sediments throughout the study area; to delineate some of the intrusives and their corresponding lateral extents, and finally to effectively outline ‘structurally low’ areas for detailed seismic prospecting within the study area.

Location and the geology of the study area

The study area lies between longitudes 4^0 30’ E and 7^0 30’ E, and latitudes 4.0^0 N and 5.0^0 N, with an approximate area of 35000 km^2 (Fig. 1 and Fig. 2) respectively. About 14,375 km^2 is on the onshore while 20625 km^2 is in the deepwater offshore. The Niger Delta sediments (Fig. 3) are divided into three distinct units of Eocene to Recent ages that form major transgressive and regressive cycles. The upper part, which is the Benin Formation, comprises of the continental fluviate and backswamp deposits with an average thickness of 2500m.This unit is overlain by the Agbada Formation (the main petroleum reservoir), which is of paralic, brackish to marine, coastal –marine deposits, with an average sedimentary thickness of 34000m.The underlying Akata formation is of marine prodelta clays with an average thickness of 6500m. The Shale of the formation (Akata) forms a world – class source rock for hydrocarbon [14]. Fig. 4 shows a typical structurally low area in the Niger Delta [9].

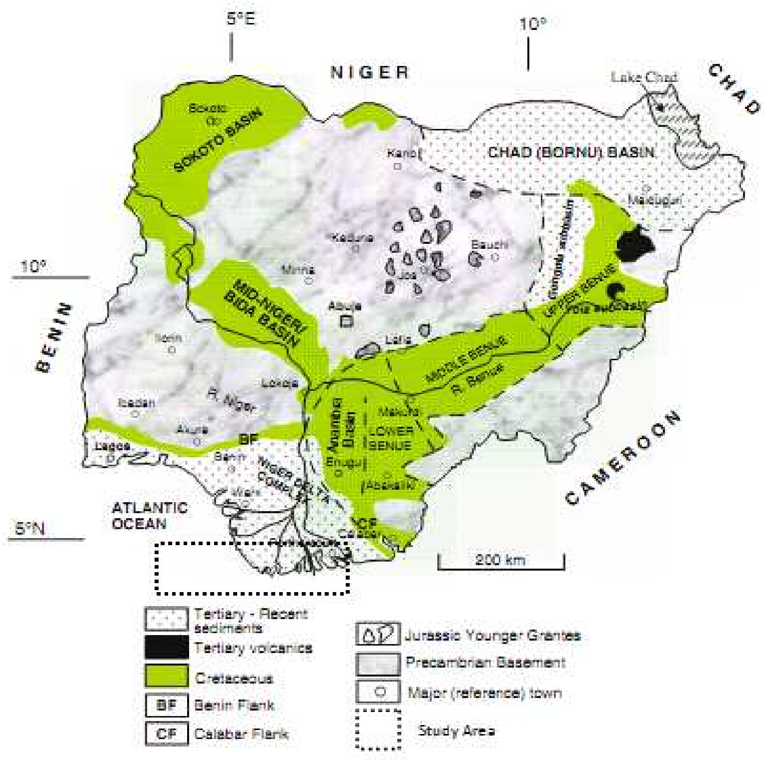

Fig. 1: Geological map of Nigeria Showing the location of the study area (modified from Obaje, 2009)

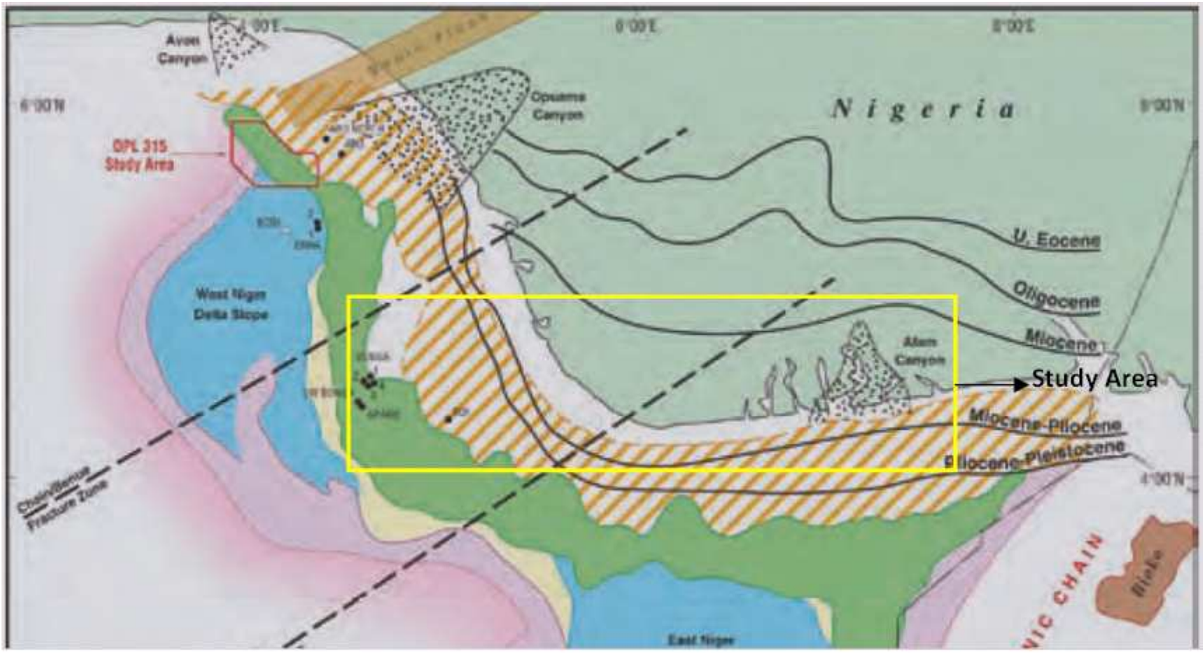

Fig. 2: Outline geologic map of Niger Delta showing the sand sheets within the study area (Modified from TechLink, 2006)

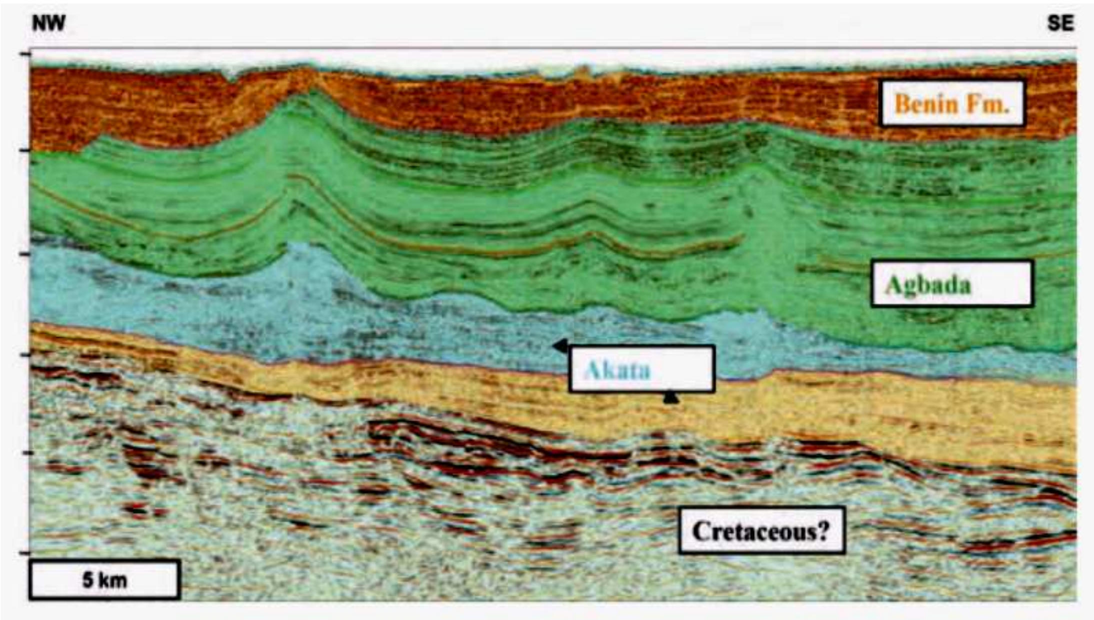

Fig.3: Seismic Stratigraphic Sections of the Niger Delta basin showing the three formations (Modified from TechLink, 2006)

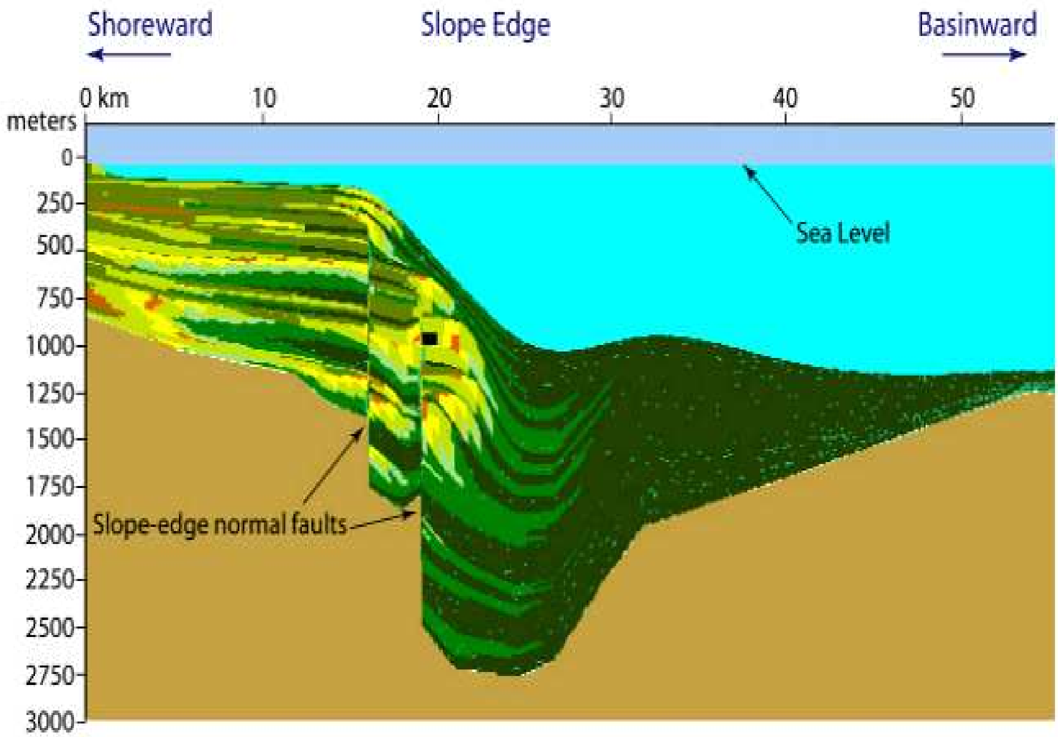

Fig. 4: Slope edge normal fault simulation for the Niger delta showing a typical structurally low area (Modified after Michele et al. 1999)

MATERIALS AND METHODS

Digitized aeromagnetic data covering the study area was obtained from Nigerian Geological Survey Agency (NGSA). The flight lines are 2 km apart in the NW-SE direction, with an elevation of 150m and a tie line of 20km. Oasis montaj geophysical software [5] was used for the data analysis, processing and interpretation. The raw data was gridded to produce the Total Magnetic Intensity map (TMI). Upward continuation filter was used also to smoothen the data in order to suppress the effects of shallow features and enhance deeper ones. The TMI grid was upward continued to 10 Km and the resulting grid was used to plot the Reduction to the Equator (RTE) map, taking into account the geomagnetic field elements of Inclination (I) = - 18.5^0, Declination (d) = - 6.5 and Total Magnetic Field (F) = 31,463.8nT .The Regional field, known as IGRF, was removed from the data by upward continuation of RTE grid to 40 km. The resulting grid was then subtracted from the original grid of the RTE to generate residual map. Spectral Analysis for depth estimate was carried out on the residual map. This map was divided into 14 blocks and the average depth of each block was estimated using Magmap module of the software. These depth estimates were utilised in generating depth to the basement maps for the first and the second layers respectively. Finally, GM-SYS module was used for the 2.5D forward and inverse modeling to map out some of the intrusives within the study area.

RESULTS AND DISCUSSION

Total Magnetic Intensity Map (TMI)**:** This map (Fig. 5) shows that the study area is characterised by high, low and intermediate amplitude anomalies. It is generally believed that zones of low magnetic intensity correspond to sedimentary rocks, while intermediate intensity corresponds to granitic rocks, and those of high magnetic intensity values are associated with igneous rocks (intrusive / extrusive) [13] .The study area falls within the three zones with the northern, north-western, south-western and southern parts dominated by intermediate intensities. The high magnetic intensity, with a value of 59.1nT, was recorded in the northern and southern parts of the study area. The dashed lines indicate the presence of magnetic lineaments or local fracture zones within the study area.

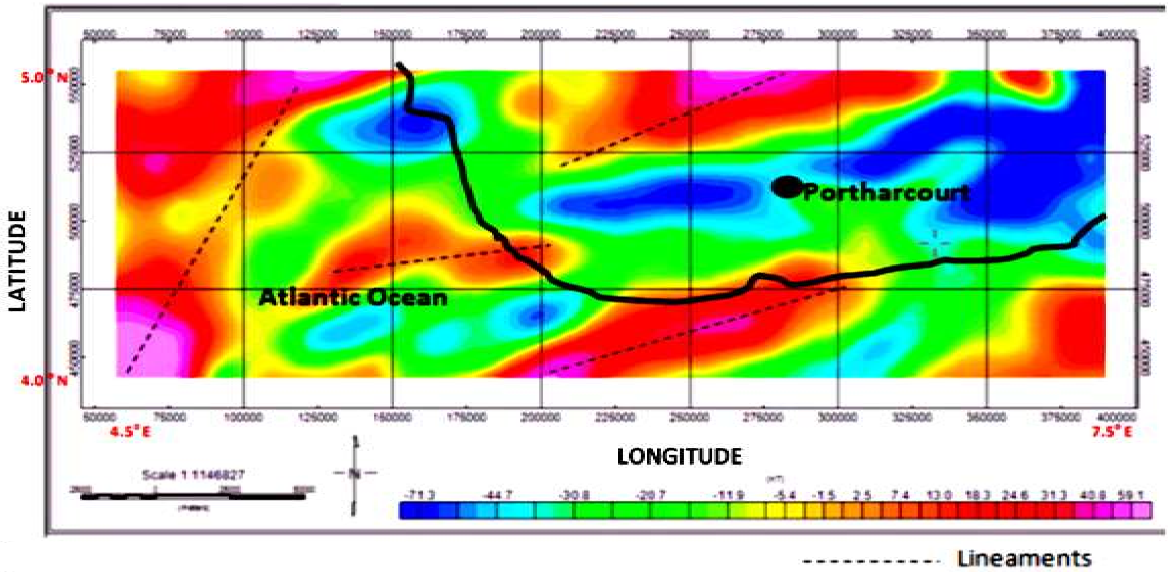

Fig. 5: Total Magnetic Intensity Map of the study area

Reduction to Equator (RTE): This technique transforms the magnetic anomaly to that which will be observed at the pole. Anomalies are known to be simplified and easy to interpret as the earth's main field becomes vertical at the pole. Moreover, it also centres the anomalies directly over their causative bodies. Visual inspection of Fig. 6 shows that, there was a northward shift in the anomalies. The geomagnetic field elements used in this transformation are the angle of inclination (I = -18.5 ^{0}) and the angle of declination (d = 6.5 ^{0}) and they are known to greatly influence the shapes of anomalies to be formed.

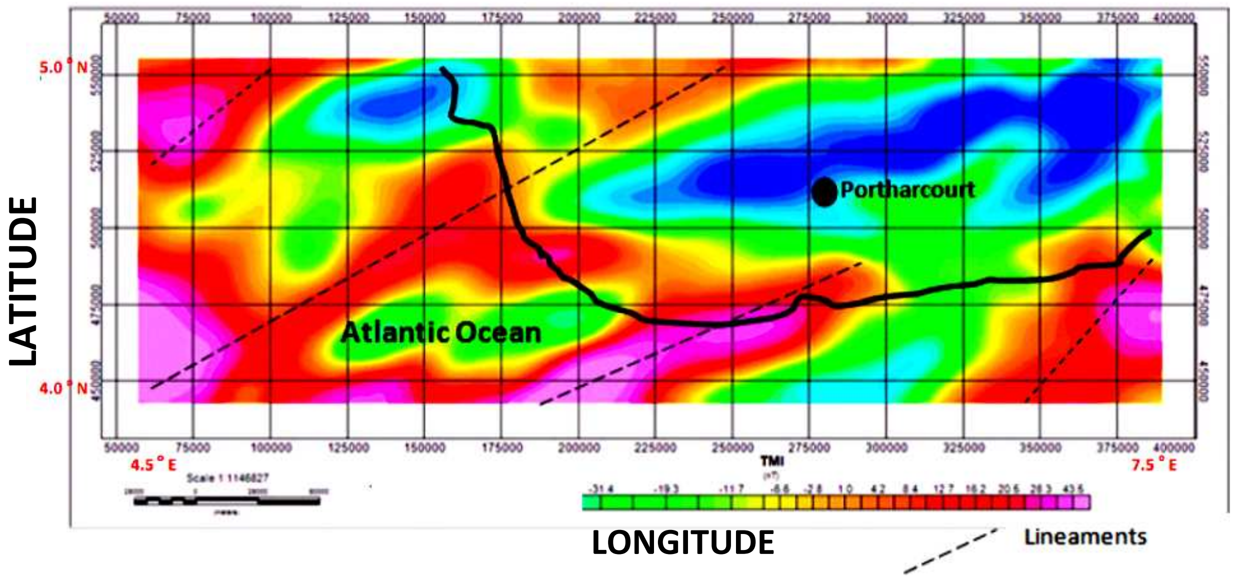

Fig. 6: Reduction to the Pole Map of the Study Area

Removal of Earth's regional Magnetic Field: This operation removes a well-defined model of the regional field of the Earth Known as the Geomagnetic Reference Field (GRF) [8]. The regional field which was removed from the data by upward continuation of the RTE gridded data to 170km to obtain series of parallel lines (Fig. 7). These field lines correspond to model magnetic fields of the Earth that are undisturbed, which need to be removed from the data in order to get the residual or local fields.

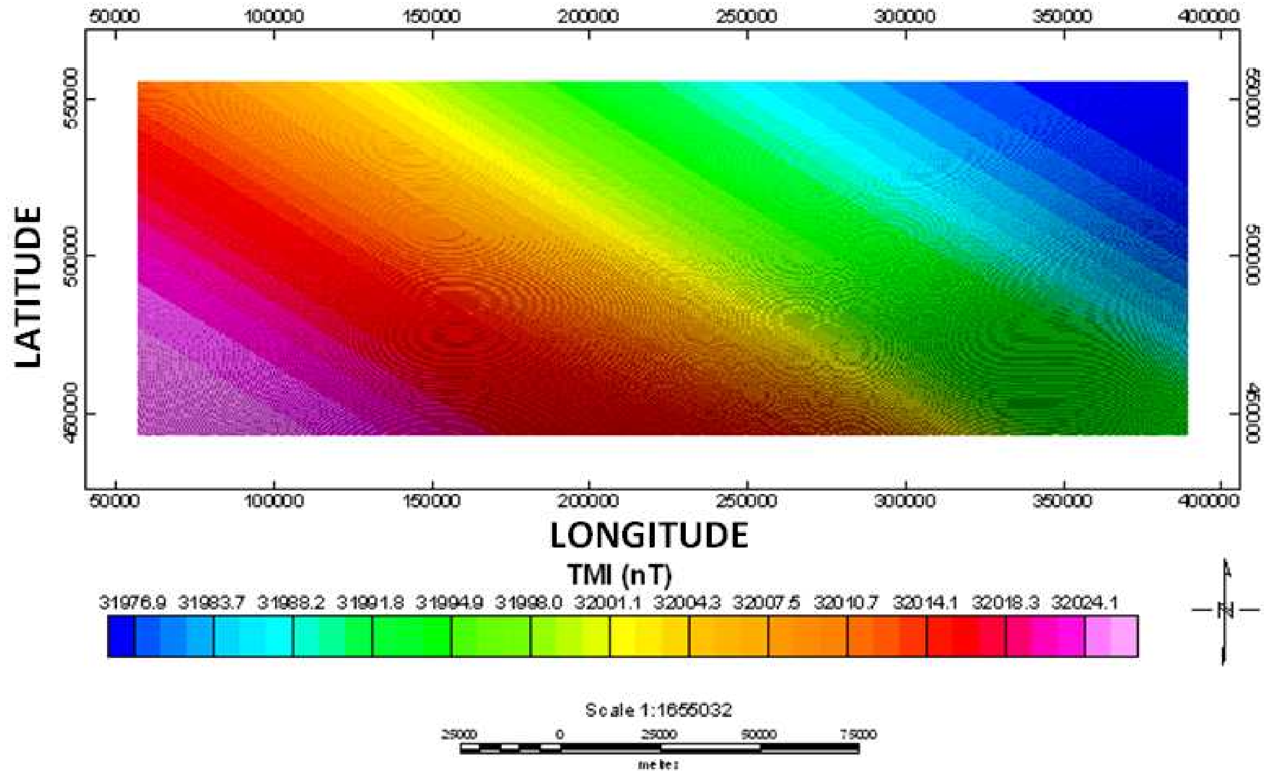

Fig. 7: The regional field of the study area

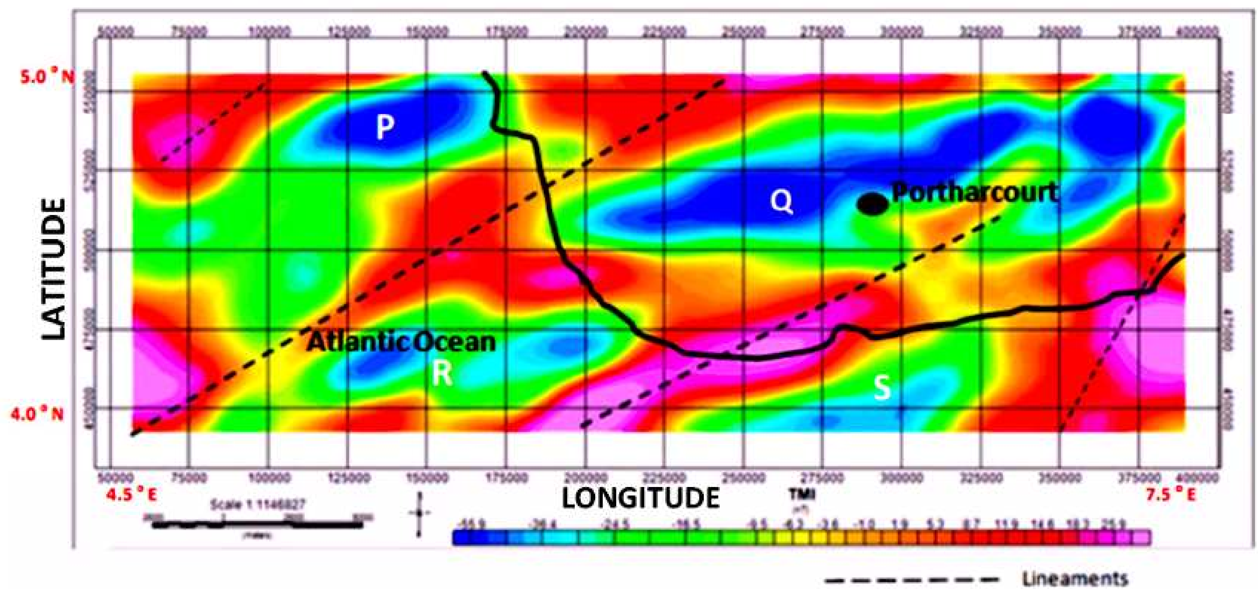

Figure 8: Residual Anomaly Map of The study Area

Residual Anomaly Map**:** The high amplitude anomaly, with a value of 25.9 nT (Fig.8) was observed in the Southern part, south-eastern, south-western, north eastern as well as north central parts of the map respectively. This high magnetic value is associated with igneous intrusion onto the basement surface or within the sedimentary section. The igneous and the granitic rocks are believed to be intruded onto the basement surface or within the sedimentary layer, resulting in the observed magnetic anomaly in the Earth's main field measured on the surface. More so, the lineaments denoted by dotted lines, trending NE-SW correlated with that of Niger Delta itself and are said to be formed during the opening of the Mid-Atlantic Ocean in the late Jurassic to early Cretaceous times [6] . These features are characterised by steep magnetic gradients as sharp susceptibility contrasts are generally believed to exist across a fault or fracture zone, due to the oxidation of magnetite to haematite [7].

The points P, Q, R, S areas characterized by a ‘Magnetic Low’ or weak anomalies, are attributed to the presence of potential hydrocarbon traps or a local relief [1].

Spectral Analysis: When a collection of magnetic sources exist around a specific depth, then a plot of the natural logarithm of energy against wavenumber of those sources is a straight line with a slope of - 4 h [3]. Results from Spectral Analysis showed a sedimentary thickness ranging from 2.9 km - 4.7 km. The depth estimate for block 1 is as shown in Fig. 9. Line L_1 and L_2 represent the first and the second magnetic layers respectively .These values are in agreement with previous investigation [2]. The depths to the basement rock, for the second layer, within the study area varied from 5.31 -10.7 km and previous work estimated the depths to the basement ranging from 6km to 12km for the whole basin [2].

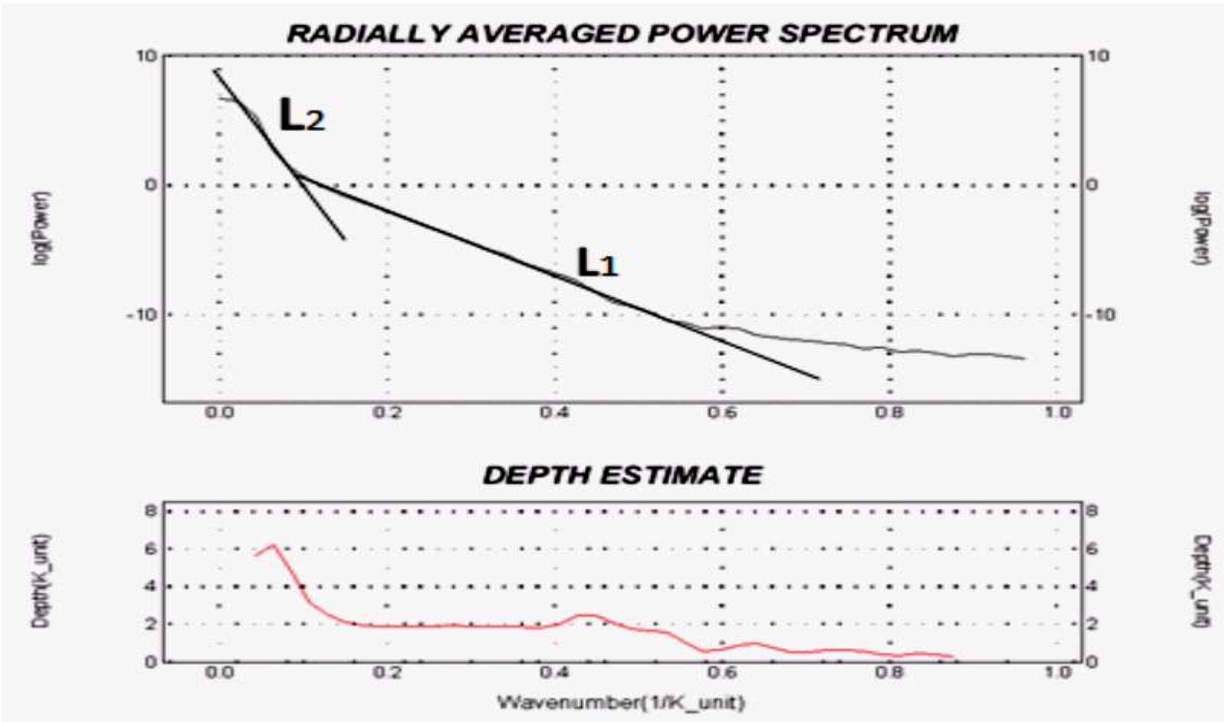

Fig. 9: Radially average power spectrum for block 1

Depth to Basement Maps**:** These maps (Fig. 10 and Fig. 11) represent the average basement topography of the study area and also provide information about the thickness of the sedimentary basin with respect to the basement structures. The average depth estimates of the first and second magnetic layers for the study area were utilised separately using spectral analysis results. These maps showed some features that are structurally high while others are low. On the depth to the basement map of the study area for layer 1 (Fig. 10) structurally high areas were noticeable in NE, NW and SW parts of the study area, with only one distinct structurally low area labelled A. This continued to the second layer in Fig. 11 corresponding to another structurally low area C. On the depth to the basement map for the second layer in Fig. 11, there are two distinct areas that are structurally low labelled B and C. The structurally low areas on both maps are potential hydrocarbon traps within the study area and several oil producing fields were reportedly located around these areas within the basin e.g. Bonga Field [2].

Magnetic Modelling: The presence of some igneous intrusions on the basement surface and/ or within sedimentary basin is visible on the residual map (Fig. 8). To delineate these intrusives, a 2.5D forward and inverse modeling was carried out. Three profiles were taken in the NW- SE direction across the anomalous zones on the residual map in Fig. 12 below using GM-SYS module of Oasis Montaj. This modeling technique involves generating a magnetic field, using an output data extracted from a profile, then comparing it with an observed field to obtain a match between them and obtaining a minimum error bar (the line in red colour). The parameters used for this process are shown in table 1 below. Caution was taken to minimise the error by taking into consideration the geology of the study area, the depths to the basement, and the susceptibility of the sedimentary section to obtain the line of best fit. The susceptibilities of the sedimentary and the basement rocks respectively were also varied in the in this exercise, as contained in Table 2.

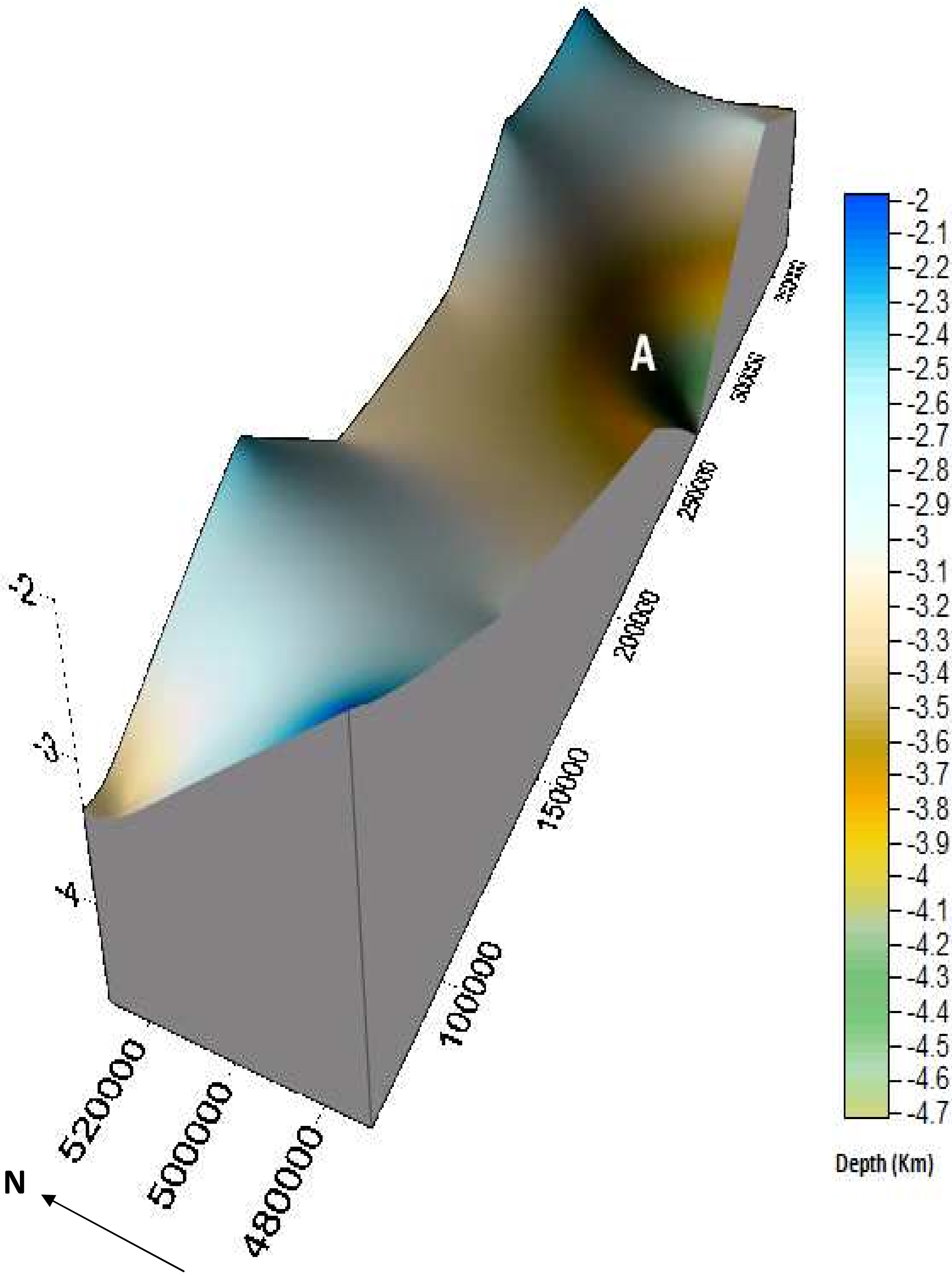

Fig. 10: Depth to the basement map for the first magnetic layer

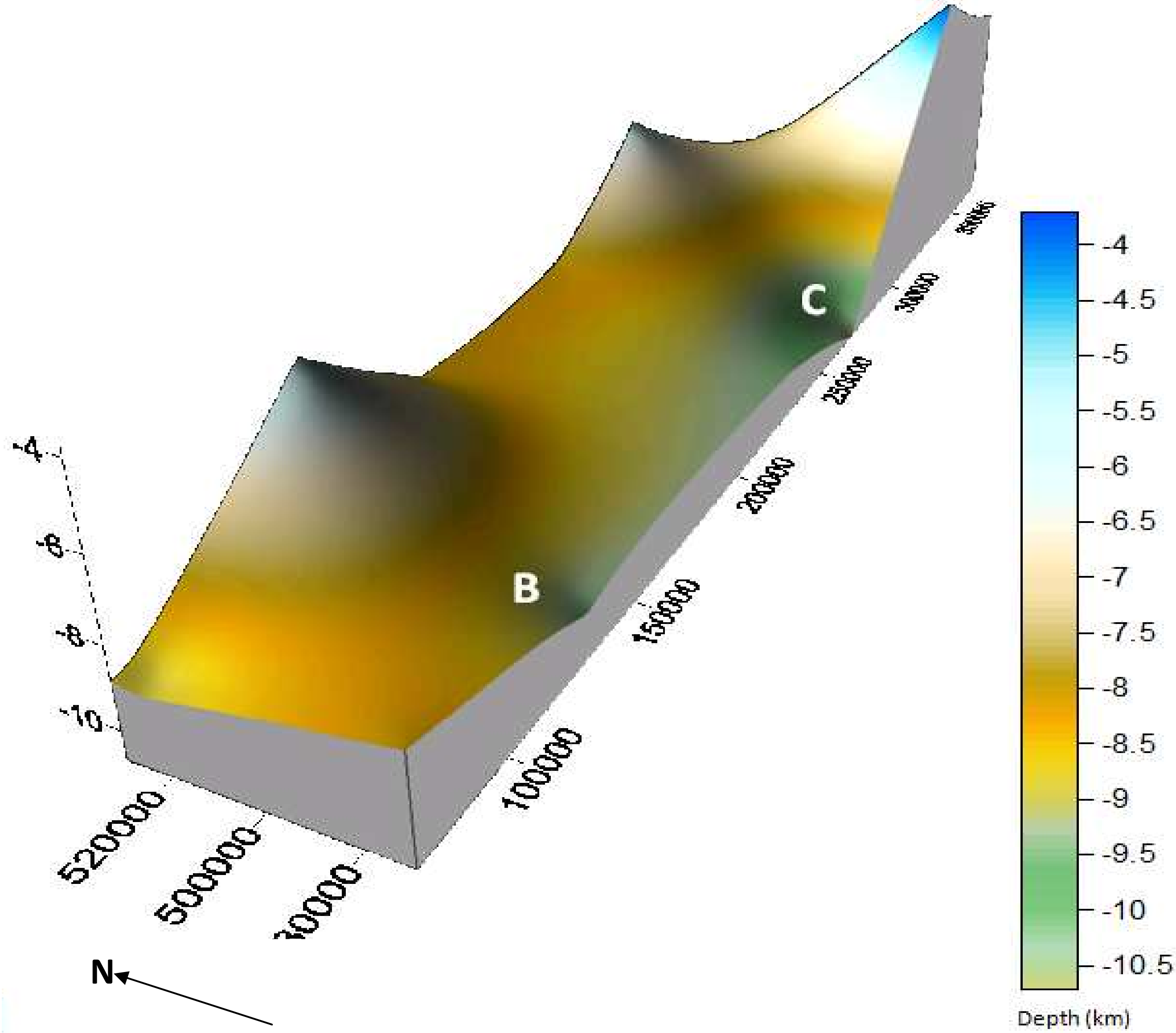

Fig. 11: Depth to the basement map for the second magnetic layer

Table 1: Modeling parameters

Profiles	Inclination (^{0})	Declination (^{0})	Total Field (nT)	No. of Basement blocks	Magnetic Susceptibility of sedimentary rocks (c.g.s)	Magnetic susceptibility of basement rocks (c.g.s)	No. of subsurface Intrusives
A-A'	- 18.5	-6.5	31,463.8	8	0.001-0.003	0.00001-0.001	4
B-B'	- 18.5	-6.5	31,463.8	8	0.001-0.003	0.00001-0.001	3
C-C'	- 18.5	-6.5	31,463.8	7	0.001-0.003	0.00001-0.001s	4

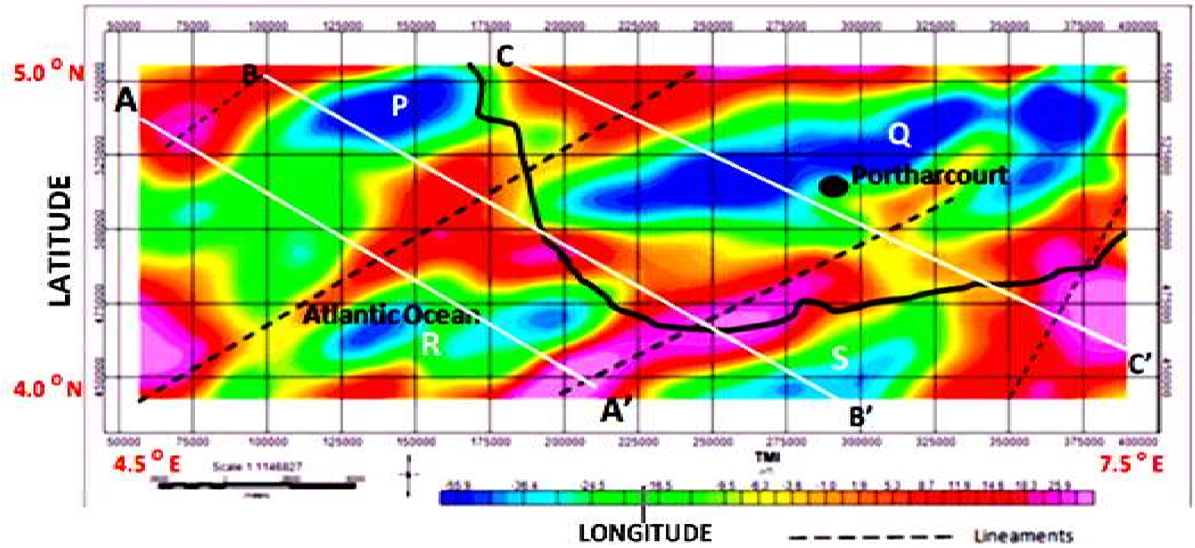

Fig. 12: Residual Anomaly Map Showing the three profiles

Table 2: Magnetic susceptibility of some selected earth materials (Modified from Ahamefula, 2005)

Rock (Mineral)	Type Susceptibility (c.g.s)
magnetite	0.3 to 0.8
Pyrrhotite	0.028
Ilminite	0.044
Iron Formation	0.056
Basalt	0.00295
Rhyolite	0.00112
Granite	0.00047
Other Acid Intrusives	0.00035
Slates	0.00005
Sedimentary	0.00001 to 0.001

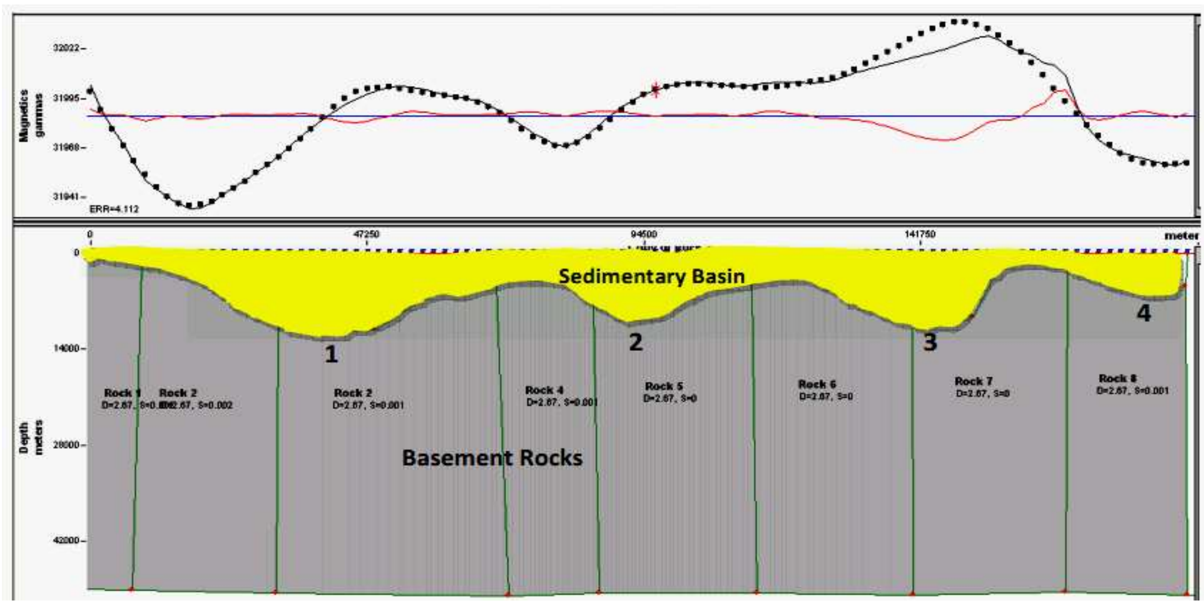

Fig. 13: 2.5D Forward and Inverse modeling for profile A-A'

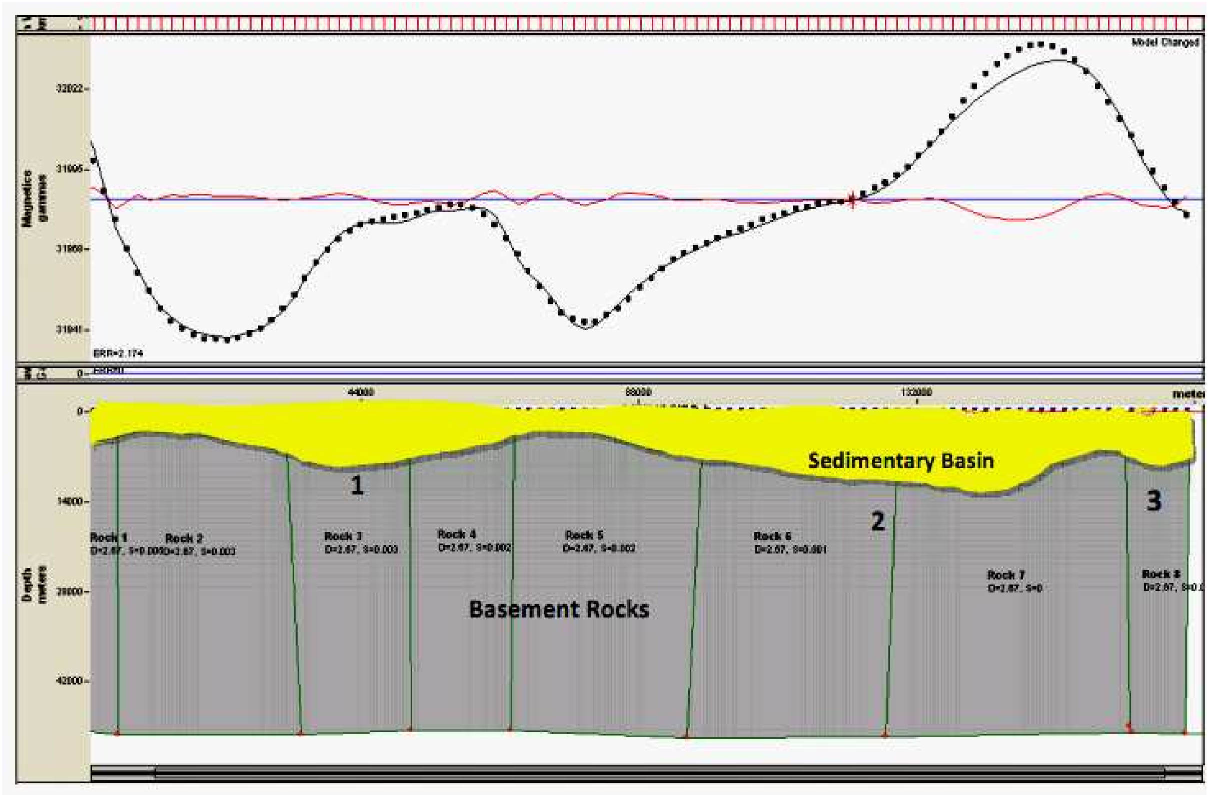

Fig. 14: 2.5D Forward and Inverse modeling for profile B-B'

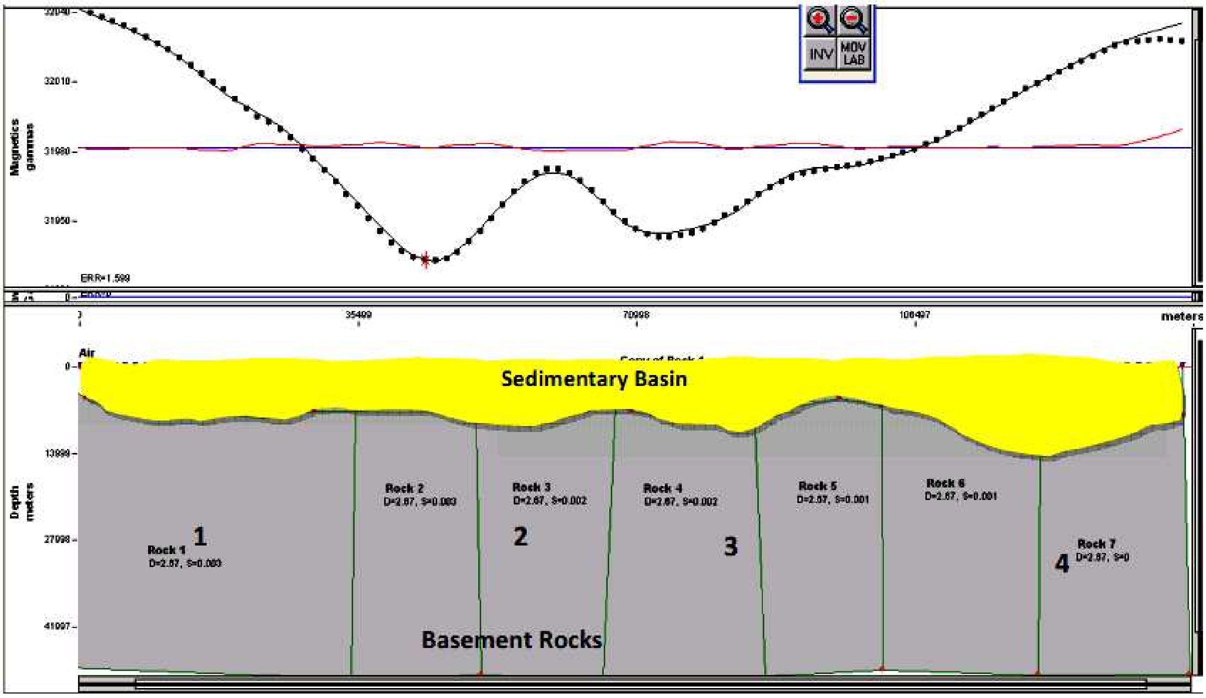

Fig. 15: 2.5D Forward and Inverse modeling for profile C-C'

CONCLUSION

There are four locations on the residual map (Fig. 8) labelled P, Q, R, S characterised by weak anomalies or a magnetic low. These are potentials traps for hydrocarbon or local relief on the basement surface. Point Q, extending from the north central to the north eastern part, correlated with part of the Miocene sands of the Niger delta, explored for direct hydrocarbon indicators (Fig. 2) [14].

Altogether , eleven intrusives were mapped (Fig. 13, Fig. 14, and Fig. 15) respectively and their lateral extents range from 1.5 km to 6 km. Due to their presence, part of the study area are less favourable for hydrocarbon exploration especially the northern and north central parts. Also southwest, southeast and parts of the south are dominated by these features. In essence, the more the intrusives, the more the geothermal energy to be released to the source rocks and the more likelihood for them to become over – matured as the geothermal temperature window for their maturation is exceeded. Consequently part of their organic matter contents such as kerogen will be destroyed which will invariably affect the quantity of hydrocarbon to be generated.

Careful and thorough comparison of both the residual (Fig. 8) and the depth to the basement maps (Fig.10 and Fig.11) respectively, along the longitude in the southern parts, revealed some interesting correlations. The positions of magnetic low areas R and S on the residual map correlated favourably with those of the structurally low areas A, B, C (Fig. 10 and Fig. 11) respectively. More also, it was reported that several oil producing fields were reportedly situated around the structurally low areas of the Niger Delta basin e.g. Bonga Field [2]. In view of this, the structurally low areas are therefore recommended for detailed prospecting in 'the new frontiers' using seismic methods.

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