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EVALUATION OF SUBSURFACE STRUCTURES FOR HYDROCARBON POTENTIALS WITHIN SOME PART OF THE NORTHERN ANAMBRA BASIN NIGERIA, USING AEROMAGNETIC DATA

Chibuko Chukwuebuka and Gabriel N. Egwuonwu
Department of Physics and Industrial Physics, Nnamdi Azikwe University Awka, Anambra State Nigeria.

Abstract: *The aeromagnetic data of some part of the northern Anambra basin has been procured and analyzed to evaluate it subsurface structures in order to assess the hydrocarbon potentiality of the area using the depth weighting techniques of source parameter imaging (SPI), Euler deconvolution and 2D modeling technique which is a better way of mirroring subsurface structures, topography and depth to the top of magnetic body. The results of 3D Euler and SPI ranges from -55.9 to 4197 m and -135.0 to 3926 m respectively. More so, the modelling techniques estimated various hydrocarbon maturation depths within the models at 2.4, 3.2, 4.8, 5.6 and 6 km respectively. The both depth of 3D Euler and SPI correlates well with each other and to some extent with the modeling results. In summary the study area showed possible potentials for hydrocarbon prospecting.*

Keywords: *2D modeling, SPI, Anambra basin and hydrocarbon prospecting*

Introduction

In massive hydrocarbon exploration projects, magnetic method is used as a reconnaissance tool for hydrocarbon exploration prior to seismic surveys to provide more preliminary information about the subsurface, particularly the basement rocks. A series of seismic reflection surveys are then conducted to offer more comprehensive imaging of the subsurface, which is more useful for hydrocarbon development (Reynolds, 2011). Magnetic data can be employed to solve a variety of exploration challenges, depending on the geological context and rock properties (Okiwelu *et al.*, 2013). Magnetic data give a low-cost technique to filter huge areas while also constructing essential alternative models to characterize underlying features and gain a better understanding of geology.

The purpose of magnetic survey is to identify and describe regions of the earth’s crust that have unusual or anomalous magnetization which might be associated with local mineralization that are of commercial interest. The anomalies could be due to sub-surface structures that have bearing on the location of oil or hydrocarbon deposits (Lowrie, 2004). These magnetic anomalies come from the magnetization contrast between rocks with different magnetic properties

The Current advancement, development and improvements on the technological aspects of airborne geophysical data acquisition, processing, analyzing and interpretations have provided new possibilities in defining petroleum systems of any area of interest (Nnaemeka *et al.*, 2024). In order to determine the thickness of the crust and the thickness of the sedimentary covers of the basement surface for hydrocarbon exploration, magnetic data are often used and also in mapping lithology, structures such as faults, contacts, dykes or sills.

Magnetic data also provides insight into mapping basement surfaces and distinguishing shallower volcanoes and, in some cases shale or salt diapers. Recent studies has engaged this potential field method (magnetic data) in hydrocarbon investigation across the country as reconnaissance survey tool. The search for hydrocarbons in Anambra basin started many years ago with the use of magnetic and gravity data, employing techniques such as spectral depth analysis, source parameter imaging, and Euler deconvolution, and 3D modelling technique to determine the depth to the top of the geologic bodies, sedimentary thickness and geological structures for possible hydrocarbon maturation and accumulation. Therefore, this study attempts to evaluate the subsurface structures controlling hydrocarbon maturation and accumulation within the Anambra Basin using 2D structural and magnetic depth modelling of aeromagnetic data compared to previous studies. This is because, the 2D structural and magnetic depth modelling is a better method that provides a clearer picture of the subsurface structures, sedimentary thickness, topography and hydrocarbon indicator rocks in the area.

Location and Geological setting of the Study Area

The study area is located between latitude $6^{\circ}30'$and $7^{\circ}30'$ North and longitude $7^{\circ}00'$ and $8^{\circ}00'$East within the anambra basin, it has a coverage area of around 12,100 km^2. The Anambra Basin is one of the Nigeria intracratonic basins that trends in a NE-SW direction, with a folded, and abortive rift basin that extends obliquely across the country. As a result, its origin was related to the tectonic processes that occurred during the Early Cretaceous period, when the African and South American plates separated (Murat, 1972; Burke, 1996). The rift model was supported by structural, geomorphic, stratigraphic, and paleontologic data (Burke *et al*., 1972; Benkhelil, 1989). The sedimentary basin fill includes the Imo Shale Ajali Formation, Nsukka Formation, Lower Coal Measures, Bassange Formation, Nkporo, Agwu, Eze-Aku, Groups and Asu-River Group. The formations consists of clay, shale, limestone, false-bedded sandstone, coal, sandstone, ironstone, mudstone, siltstone, and black shale. They are also exposures of fractures, faults and anticlinal structures inferred from the geology map which may serve as traps or path ways for hydrocarbons within the sedimentary beds as seen in Fig. 1.

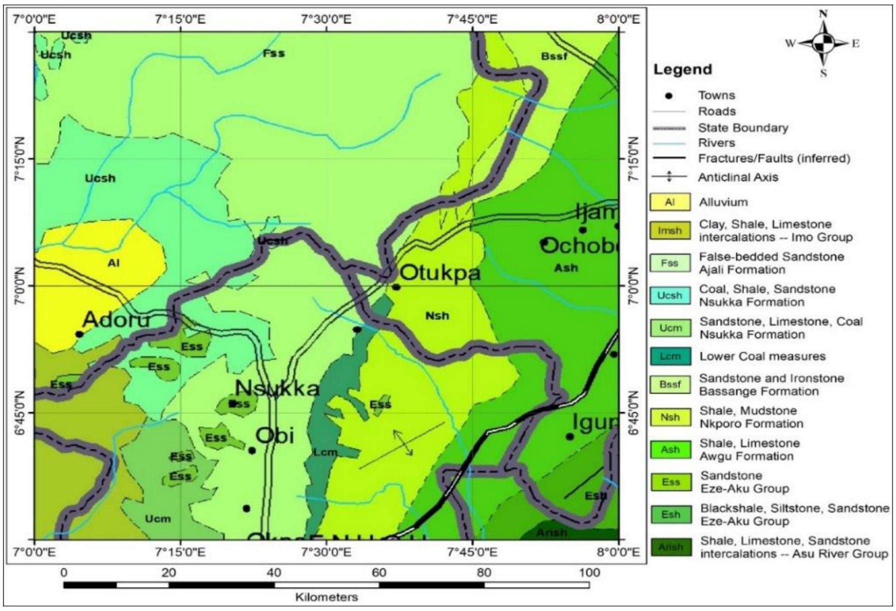

Fig. 1: The geological map of the study area.

Methodology

The proposed data sheet numbers for this study are 268 (Agba), 269 (Anka), Nsukka (287) and Igumale (288) was carried out in Nigeria between the years 2005-2009 by Nigeria geological survey agency (NGSA). The airborne data was obtained at flight altitude of 0.08 km, tie and flight line spacing of 2 km and 0.5 km respectively. The digital data acquired was made available on on a scale of 1:100,000 and half-degree sheets contoured mostly at 10nT intervals. The geomagnetic gradient was removed from the aeromagnetic data using the International geomagnetic Reference Field (IGRF) of 2005.

Theory of Methods of data analysis

Reduction to Magnetic Equator

Reduction to the pole is a commonly used approach for removing the effects of inclination and declination and centering the anomaly over the body. The reduction-to-the-pole method has long been acknowledged to be ineffective for anomalies occurring in low magnetic latitude regions. The approach adds errors and erroneous trends to the lowered anomalies. A different technique for mitigating the effects of inclination and declination is proposed. The new method reduces anomalies to the magnetic equator (0 degrees of inclination). The reduction to the magnetic equator has been applied to actual data from low magnetic latitude places.

Reduction to the equator has an amplitude component (**sin (I)**) and a phase component (i **cos (I) cos (D-θ)**). The algorithm used for reduction to magnetic equator is expressed mathematically as equation (1)

$$L(\theta) = \frac{[\sin(I) - i.\cos(I).\cos(D-\theta)]^2 \, X(-\cos^2(D-\theta))}{[\sin^2(Ia) + \cos^2(Ia).\cos^2(D-\theta)] X [\sin^2(I) + \cos^2(D-\theta)]}, if (|Ia| < |I|), Ia = I \qquad (1)$$

Where,

I Geomagnetic Inclination in °

D Geomagnetic declination in ° azimuth

Ia Inclination for amplitude correction

Depth Estimation Techniques

This involves making material estimations of depths and dimensions of the sources of anomalies (Revees, 2005). The quantitative interpretation adopted in the present study include; Source Parameter Imaging (SPI), Euler Deconvolution and 2D modeling

Source Parameter Imaging (SPI)

Thurston and Smith (1997) and Thurston *et al*. (1999) developed the source parameter imaging (SPI) technique, based on the complex analytic signal, which computes source parameters from gridded magnetic data. The technique is sometimes referred to as the local wavenumber method. The local wavenumber has maxima located over isolated contacts, and depths can be estimated without assumptions about the thickness of the source bodies (Smith *et al*., 1998). Solution grids using the SPI technique show the edge locations, depths, dips and susceptibility contrasts. The local wavenumber map more closely resembles geology than either the magnetic map or its derivatives. The technique works best for isolated 2D sources such as contacts, thin sheet edges, or horizontal cylinders.

The Source Parameter Imaging (SPI) technique is expressed mathematically as equation 2 below (Thurston and Smith, 1997):

$$Depth = \frac{1}{K_{\max}} = \frac{1}{\left(\sqrt{\left(\frac{\delta Tilt}{\delta x}\right)^2 + \left(\frac{\delta Tilt}{\delta y}\right)^2}\right)_{\max}} \qquad (2)$$

Where the tilt is given as

$$Tilt = \arctan \frac{\frac{\delta T}{\delta z}}{\left(\sqrt{\left(\frac{\delta T}{\delta x}\right)^2 + \left(\frac{\delta T}{\delta y}\right)^2}\right)} \qquad (2.1)$$

$$Tilt = \frac{\delta T / \delta Z}{HGRAD} \qquad (2.2)$$

Where HGRAD is horizontal gradient,
T is total magnetic intensity (TMI), $\delta T/\delta x$, $\delta T/\delta y$, $\delta T/\delta z$ are the first order partial derivates of the total magnetic intensity (T) in x, y and z coordinates.

This method will be used in this study to determine the discrete magnetic basement depth beneath the study area (Anambra Basin) to assess the presence of hydrocarbon potentials.

Euler Deconvolution

The 3D Euler deconvolution has proven to be a reliable interpretation tool for magnetic data because it requires no prior knowledge of the geometry of the magnetic sources. Another advantage of this technique is that it requires no knowledge of the magnetization vector (Thompson, 1982; Reid *et al.,* 1990). As a result, it can be used in areas where causal magnetic sources are buried and the geology of the site is unknown. The technique has been widely utilized to highlight the boundaries and forms of sources in potential field images (Salawu *et al.,* 2019). The 3D Euler deconvolution equation is expressed as seen in equation 3 below (Reid *et al.,* 1990).

$$(x - x_0)\frac{\partial T}{\partial x} + (y - y_0)\frac{\partial T}{\partial y} + (z - z_0)\frac{\partial T}{\partial z} = N(B - T) \qquad (3)$$

where,

(x_o, y_o, z_o) is the position of a source whose total field T is detected at any point (x, y, z)

B is the background value of the total field

N is the degree of homogeneity interpreted physically as the attenuation rate with distance and geophysically as a structural index (SI).

Modelling of Aeromagnetic Anomaly

Modeling is an inverse method for interpreting magnetic field data in which models are created from which synthetic magnetic signatures are formed and statistically fitted to the observed data. The level of information (depth to a certain magnetic body, shape, size, and magnetism) acquired from the created models can be ascribed to the quality and quantity of accessible data, as well as the sophistication of either manual methods or computer software that can be employed.

In this work, a two-dimensional (2D) modeling technique will be employed with the program Gravity/Magnetic System (GMSYM), an extension available in Oasis montaj version 8.4. The application is an interactive forward modeling program that calculates gravity and magnetic reaction based on a user-defined hypothetical geology model. Any disparities between the model response and the measured gravity and/or magnetic field are decreased by improving the model structure or attributes (for example, density or susceptibility of model components).

Results and discussions

Total Magnetic Intensity (TMI) and Reduction to the Equator (TMI_RTE)

The total magnetic map (Fig.2a) is characterized by intensities ranging between -117.3 to 140.5 nT which are high, moderate and low in magnitude (magnetically heterogeneous). This is clearly represented by the colour variations, aiding the visibility of wide range of anomalies and their intensities. While Reduction to the magnetic equator (Fig. 2b) revealed similar signatures of anomaly strike at the southeastern part observed in the total magnetic intensity map, but appeared smoother and defined the high and low centers better than the TMI map because the reduction processes have been carried out on the TMI data and magnetic intensities ranging between -107.3 to 131.1 nT corresponding to lows and high. The both maps showed areas with magnetic high zones (pink-red colours) which may be due to shallow basements/structures or areas of intrusions and areas with low magnetic anomalies (green- to blue colours), depicting deep structures or sedimentary terrains.

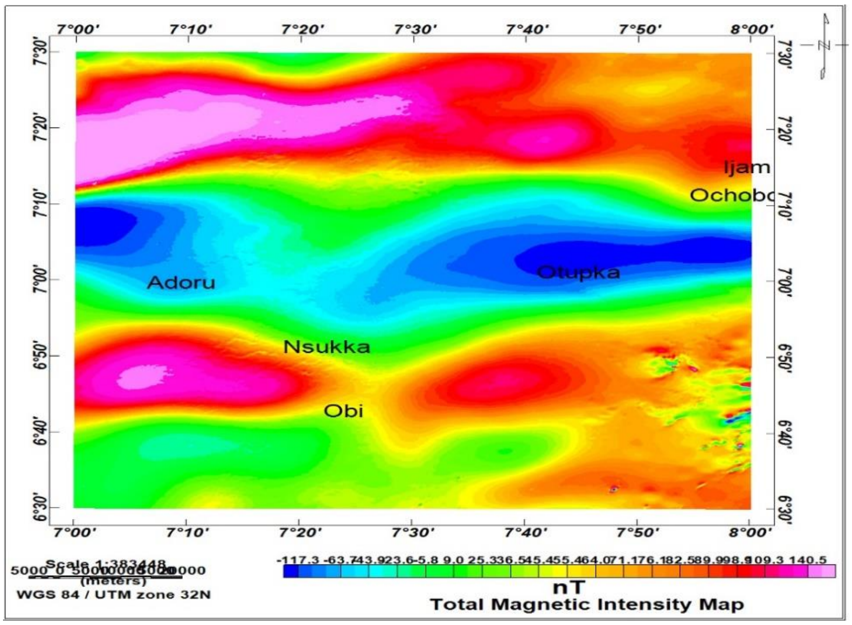

Fig. 2a: Total Magnetic Intensity Map of the Study Area

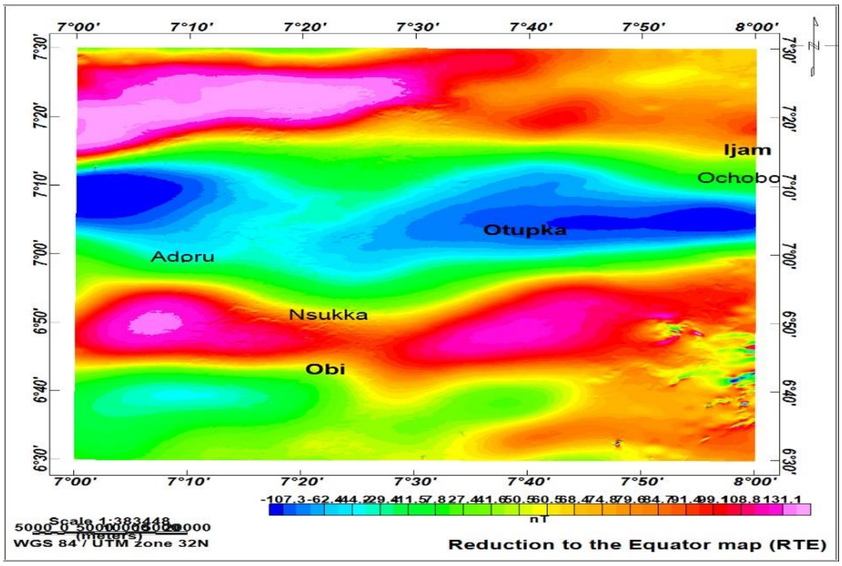

Fig. 2b: Reduction to Equator Map of the Study Area.

Depth Estimations Techniques

Source parameter imaging (SPI)

The SPI depth weighting solutions (Fig. 3) revealed negative depth values ranging between -135.0 m to -3926 m signifying shallow and deep magnetic sources. The negative values depict the depths of buried magnetic bodies, which could be deep sedimentary rocks or near surface intrusive. The shallow magnetic bodies are occupied with (pink to shaded red areas) while the blue colour depicts areas of deep magnetic bodies. The maximum depth of -3926 obtained from SPI is sufficient enough for hydrocarbon generation if other conditions are met.

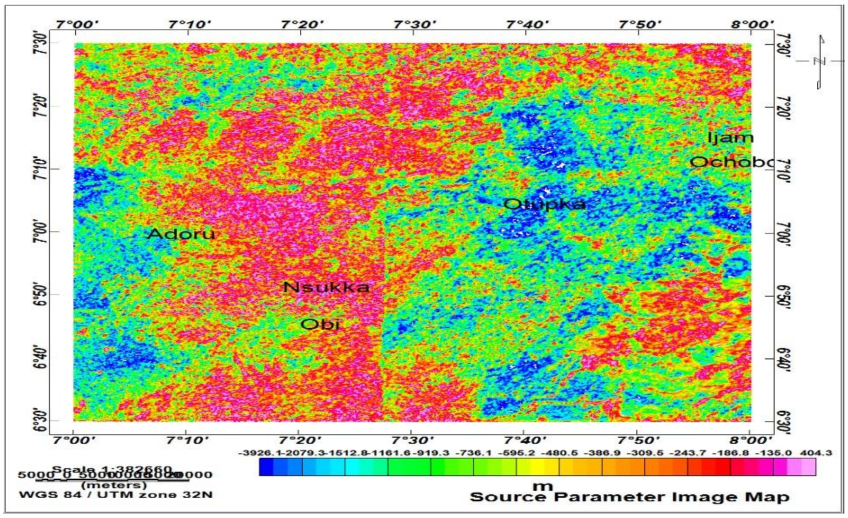

Fig. 3: Source Parameter Image (SPI) Map of the Study Area.

3D Euler deconvolution

Depth estimation solotions of 3D Euler depth analysis using structural indexes of (SI = 1) obtained depth values ranging from -55.9 m to 4197 m. The pink colour indicates shallow magnetic bodies, while the blue colour indicates deep lying magnetic bodies (Fig. 4). The northeastern parts of the study (Ijam, Ochobo and Otukpa) showed sufficient depth for hydrocarbon maturation.

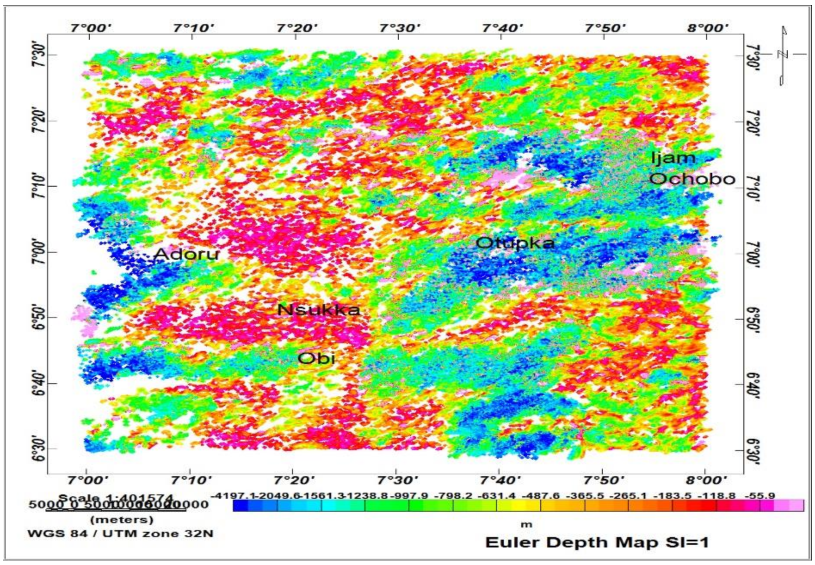

Fig.4: Euler 3D Map of the study area(SI=1)

2D Modeling of aeromagnetic anomalies

In modeling, three profiles (A-A', B-B' and C-C') were taken at different locations (Fig. 5) to determine topography, sedimentary thickness and subsurface structure. The results from the first Profile (A-A') (Fig.5a), taken at NNE-SSW direction cuts across Agwu formation (shale and limestone) petroleum source rock at the northeastern parts Ijam and Ochobo, with a sedimentation depression of about 3.2 – 5.6 km deep, stretching a distance about 32 km long to the central area where an uplift of 0.8 km was noticed cutting through Npkoro formation and lower coal measures to the southwestern part corresponding to Obi with depth of 3.2 km deep and geology of Ajali formation. The depths of 3.2 km and 5.6 km obtained from the model is adequate to mature hydrocarbons in the area.

The profile (B-B') (Fig.5b) taken in the NW-SE direction, cuts across Adoru at the northwestern part to the central area (Nsukka) with sedimentation of about 1.8 to 2.4 km deep stretching a distance of 68 km long. The deepest sedimentary thickness of 2.4 km which is sufficient to mature hydrocarbon was observed at Nsukka area cutting through geology of Ajali formation and streching towards the southeastern part with depth of 1.8 km cutting through Ezeaku sandstone, lower coal measure, Nkporo and Agwu formations.

The profile (C-C') (Fig.5c) taken across NNW-ESE direction revealed an uplift of depth of 0.8 km stretching about 30 km at NNW part towards a depression of 6 km around Otupka at the central area of the study cutting the geology of Nkporo formation stretching towards the southeastern part with depth of 4.8 km deep cutting across Agwu formation. The central portion to the southeastern part of the study met sufficient depth required for hydrocarbon maturation and accumulation.

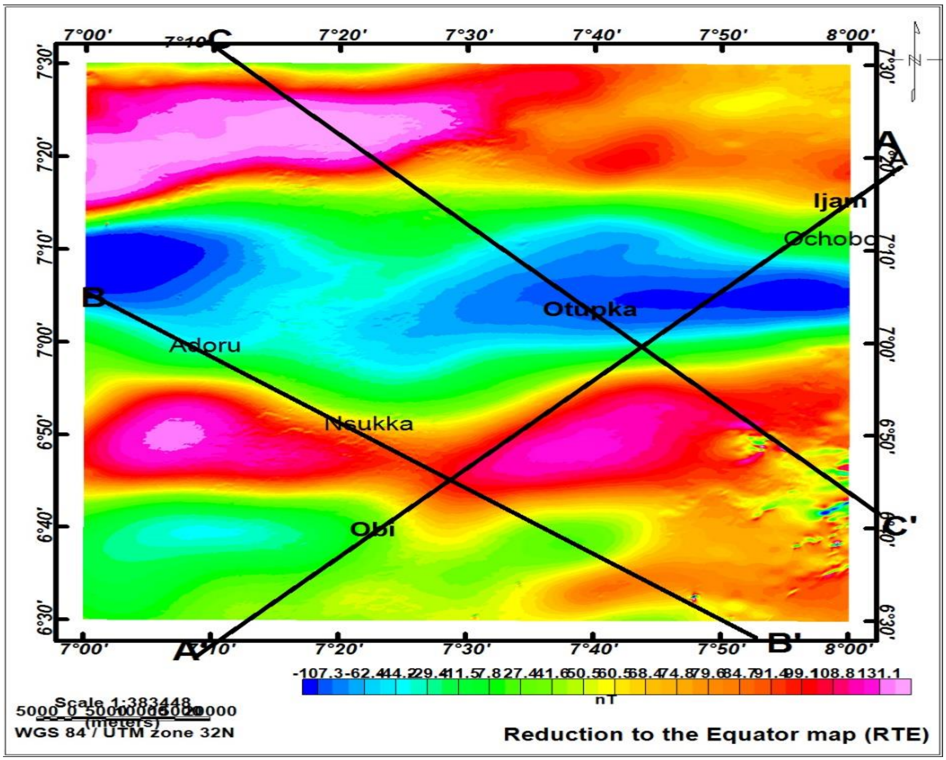

Fig. 5. Map showing profiles the models

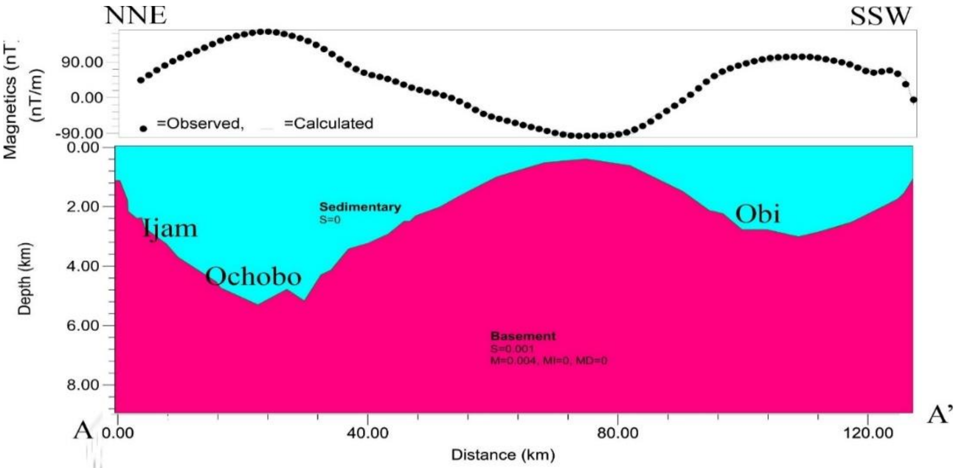

Fig.5a. Profile (A-A')

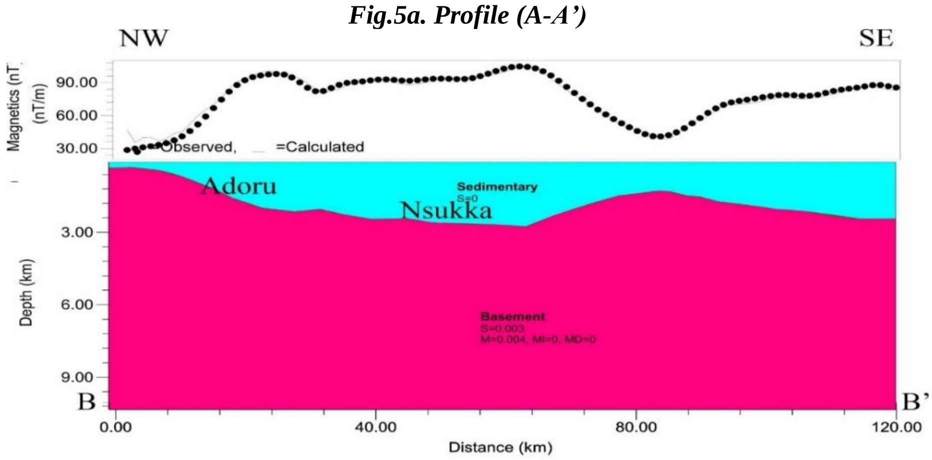

Fig.5b. Profile (B-B')

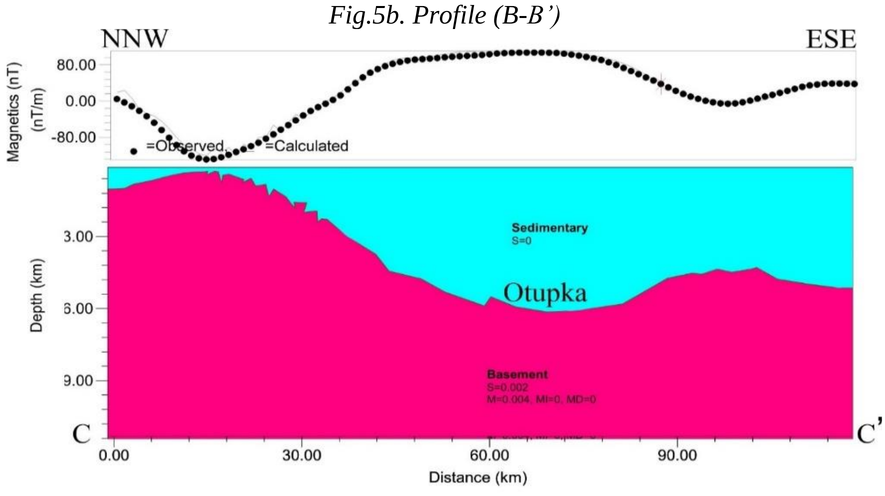

Fig.5c. Profile (C-C')

Conclusion

The total magnetic intensity and reduction to the equator maps showed areas with magnetic high zones which may be due to shallow basements/ structures or areas of intrusions and areas with low magnetic anomalies, depicting deep structures or sedimentary terrains. The average maximum depths of 3.9 m and 4100 m from the SPI and Euler techniques confirms feasibility for hydrocarbon maturation and accumulation in the area around Otupka, Ochobo, Ijam and part of Adoru. The 2D modeling techniques revealed deepest sedimentary thickness of 3.2 to 6 km with geology of Agwu formation with lithological composition of shale and limestone petroleum source rocks and Ajali formation (false bedded sandstone) around Otupka, Ochobo, Ijam of the area.

In terms of hydrocarbon prospect, the source parameter imaging and 3D Euler deconvolution and 2D modelling estimated the depth to the sedimentary thickness of more than 3000 m which is theoretically sufficient to favour hydrocarbon maturation and accumulation in the area if other conditions are met, particularly in the deep seated regional fractures/faults at the corresponding locations of Ijam Ochobo and Otupka areas. This area mentioned are recommended for follow up hydrocarbon exploration.

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