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Basin Model of Oloibiri and Environs, Bayelsa State, Nigeria Deduced from Magnetic Data

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Abstract:
***Background**: Oloibiri is a community in Bayelsa State, in the Niger Delta region of Nigeria. The first commercial oil discovery in Nigeria was in the community. Oloibiri Oilfield produced oil for 20 years and production finally stopped in 1978 and the field was abandoned. There was growing interest in identifying new petroleum prospects within Bayelsa State, as expressed when the State hosted the National Council on Hydrocarbon Summit in 2020. This research focused on the application of magnetic method in delineation of structures and sediment thickness underlying the area; hence, highlighting the basin's structural and sedimentary endowments favourable for hydrocarbon generation, accumulation and migration in the place. The geologic features that enhanced the drying or accumulation of oil within Oloibiri Area were highlighted in this study.*
***Materials and Methods**: The aeromagnetic data covering the area were used in delineating the geologic structures and sediment thickness within the area. Data enhancement techniques involving analytic signal filter, upward continuation and source parameter imaging were applied to the magnetic data.*
***Results**: Low magnetic field intensity characterises the northeastern part of the area at depth due to the depletion in magnetism by the thermal activities that accompany the subsurface volcanic bodies of the region. The other parts of the area reflect gradational increase in magnetic intensity southwards, indicating an increase in both ferruginization of sandstone sediment and sediment thickness. The sediment-basement contacts in the area are located at depths between 0.1 km and 19.1 km with an average of about 1.0 km.*
***Conclusion:**Most places within the area have both the sediment thickness and structural complexity favourable for hydrocarbon generation and accumulation and the northeastern part of the study area is more deformed than other places in the area.*
***Key Word**:Structural Complexity, Structural Faults, Intrusive Activities, Ferruginization of Sandstone, Sedimentary Thickness.*

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I. Introduction

Seismic remains the primary method for exploring hydrocarbon prospects. However, it is rational to implement inexpensive geophysical exploration methods before seismic detailing (Hendra 2015). The use of magnetic techniques for basin delineation at a regional scale, especially in hydrocarbon exploration, is well-known (Peirce et al. 1998; Chapin and Ander 1999; Oruç et al. 2013). Hydrocarbon exploration applies a magnetic method in detecting faults and igneous intrusions, forming structural traps for hydrocarbon. Magnetics is commonly used with gravity as low-cost methods for mapping out structures and delineating the sediment thickness during the beginning phases of exploration. Evaluation of structural systems aims to target structural traps and sediment thickness to assess the maturity of the sediments within the target basin. The magnetic method is non-unique, meaning that multiple geologic models can fit the data; hence, indicating its validity in basin studies (Henry 2016).

There was growing interest in identifying new petroleum prospects within Bayelsa State, Nigeria as expressed when the State hosted the National Council on Hydrocarbon Summit in 2020 (Ibe 2021). The goal of this research was to evaluate the structural complexity and model the sediment thickness within the oil-producing Oloibiri Area and environs, to identify other petroleum prospects within the place.

Oloibiri is a community in Ogbia Local Government Area located in Bayelsa State, in the eastern Niger Delta Region of Nigeria. Oil was discovered at Oloibiri in the Niger Delta Area on Sunday 15 January, 1956 by Shell Darcy. It was the first commercial oil discovery in Nigeria; this discovery ended fifty years of unsuccessful oil exploration in the country by various international oil companies (Chuks 2018). Appraisal of the oil field commenced immediately after the discovery and this led to the drilling of development wells in 1958. The field started oil production in 1958 and the first oil production from the field came at the rate of 4,928 barrels per day (Chuks 2018). The Oloibiri oilfield produced over 20 million barrels of oil during its 20 years life cycle. Oil production finally stopped in 1978 and the field was abandoned the same year.

With the growing interest in new hydrocarbon prospects within Bayelsa Area of Niger Delta Basin by the State government as the major driving force, this research focused on the application of magnetic method in delineation of structures and sediment thickness underlying Oloibiri Area and environs; hence, highlighting the basin's structural and sedimentary endowments favourable for hydrocarbon generation, accumulation and migration. The geologic features that enhanced the drying or accumulation of oil within Oloibiri Area were highlighted in this study. The results obtained enhance the generation of the basin model for Oloibiri and environs.

II. The Study Area

The study area is located in the south-south part of Nigeria. It is bounded by Latitudes 4° 30′ 00″ N and 5° 00′ 00″ N and Longitudes 6° 00′ 00″E and 6° 30′ 00″ E and covers a total surface area of about 3,025 km^2. The major towns within the place include Oloibiri, Akenfa, Yenagoa, Topopiri, and Otuoke (Figure 1).

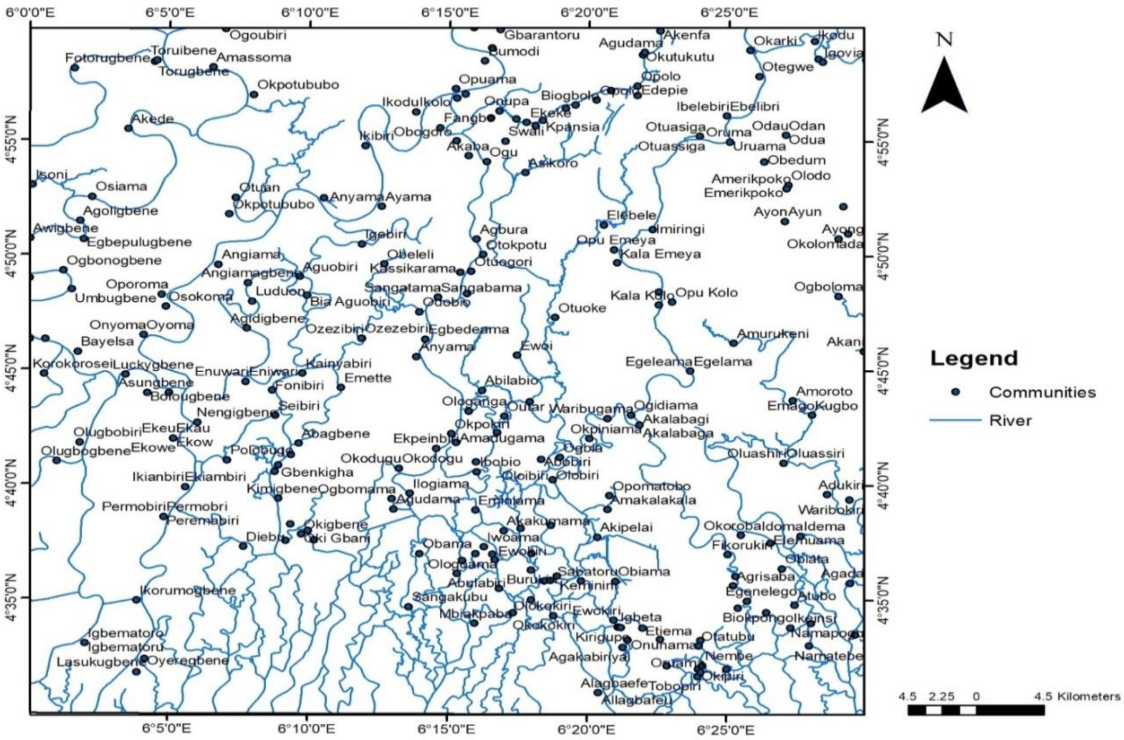

Figure 1: Geographic Map of the Study Area

The study area falls within the eastern part of the Niger Delta Sedimentary Basin. Many researches on the geology of the Niger Delta Basin have been carried out by Reyment (1965), Short and Stauble (1967), Murat (1972), Nwajide (2013) and the exploration activities of oil and gas companies. Oil of commercial quantity and quality was discovered by Shell Darcy at Oloibiri, at a depth of 3.6 Km. This implies that a similar sediment thickness range was targeted in this research.

III. Material, Method, Data Processing And Enhancement

The magnetic dataset used for this study was acquired by Fugro Airborne Survey and the Nigerian Geological Survey Agency. The data were acquired along NW – SE flight lines at 500 m line spacing and 80 m terrain clearance. The study area is covered by airborne magnetic Index Sheet 327 – Oloibiri. The acquired total magnetic field intensity data were processed, and the data grid was developed by employing a minimum curvature algorithm at 100 m grid cell size.

Data enhancement techniques involving analytic signal filter, upward continuation, and source parameter imaging were applied to the magnetic data.

Roest et al. (1992) define the analytical signal as a function that relates the magnetic field by the derivatives. The analytical signal (AS) transformation is independent of the direction of the magnetization of its source; therefore, it places the magnetic anomaly directly over its causative body (Silva et al. 2003; Asadi and

Hale 1999). Analytic signal (AS) is given as the square root of the sum of the squares of the derivatives in the x, y and z directions.

$$AS = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2} \qquad (1)$$

Where $T =$ Magnitude of the total magnetic field

Upward continuation is a filter which transforms the total magnetic field on a surface to a higher level. It is a mathematical technique used to separate the anomaly of the deeper geology from shallower geology (Hailemichael et al. 2020). It was used to estimate the large scale or regional (low frequency or long wavelength) trends of the data; hence the transformation reduces the effect of shallow bodies with respect to deep causative sources. Upward continuation is a method used in oil exploration and geophysics to estimate the values of a gravitational or magnetic field by using measurements at a lower elevation and extrapolating upward, assuming continuity. The upward continuation filter reduces noise and enhances the signal-to-noise ratio of the observed data (Salem et al. 2004).

Source Parameter Imaging (SPI) is a profile or grid-based method for estimating magnetic source depths, and for some source geometries, the dip and susceptibility contrast. The method utilizes the relationship between source depth and the local wave number (k) of the observed field, which can be calculated for any point within a grid of data via horizontal and vertical gradients (Thurston and Smith 1997). The SPI method estimates the depth from the local wave number of the analytical signal.

IV. Result

The total aeromagnetic intensity map (Figure 2) reflects magnetic signatures from both the regional magnetic field variation and the local (residual) magnetic field of interest. To separate the regional and residual magnetic field, International Geomagnetic Reference Field (IGRF) Model of 2010 Epoch was subtracted from the total magnetic intensity data and reduction to the equator carried out to produce the residual magnetic intensity map (Figure 3). The residual magnetic field intensity enhances the shallow structures within the study area.

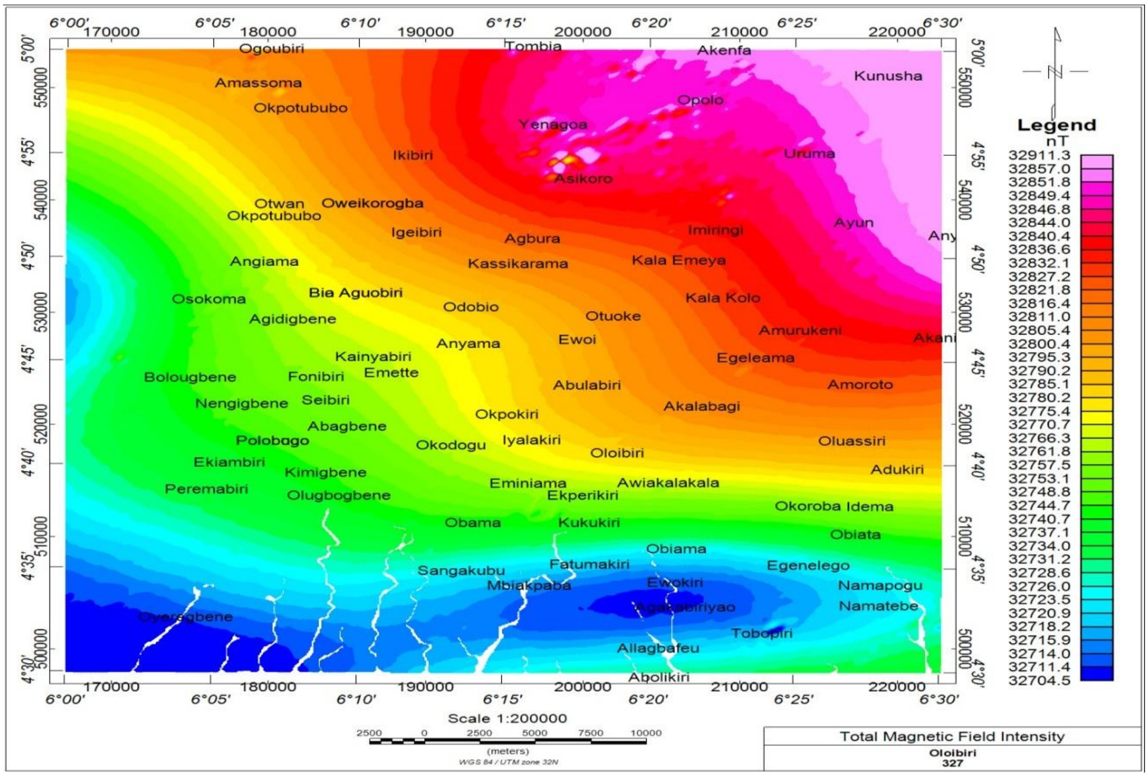

Figure 2: The Total Aeromagnetic Field Intensity Map of the Study Area

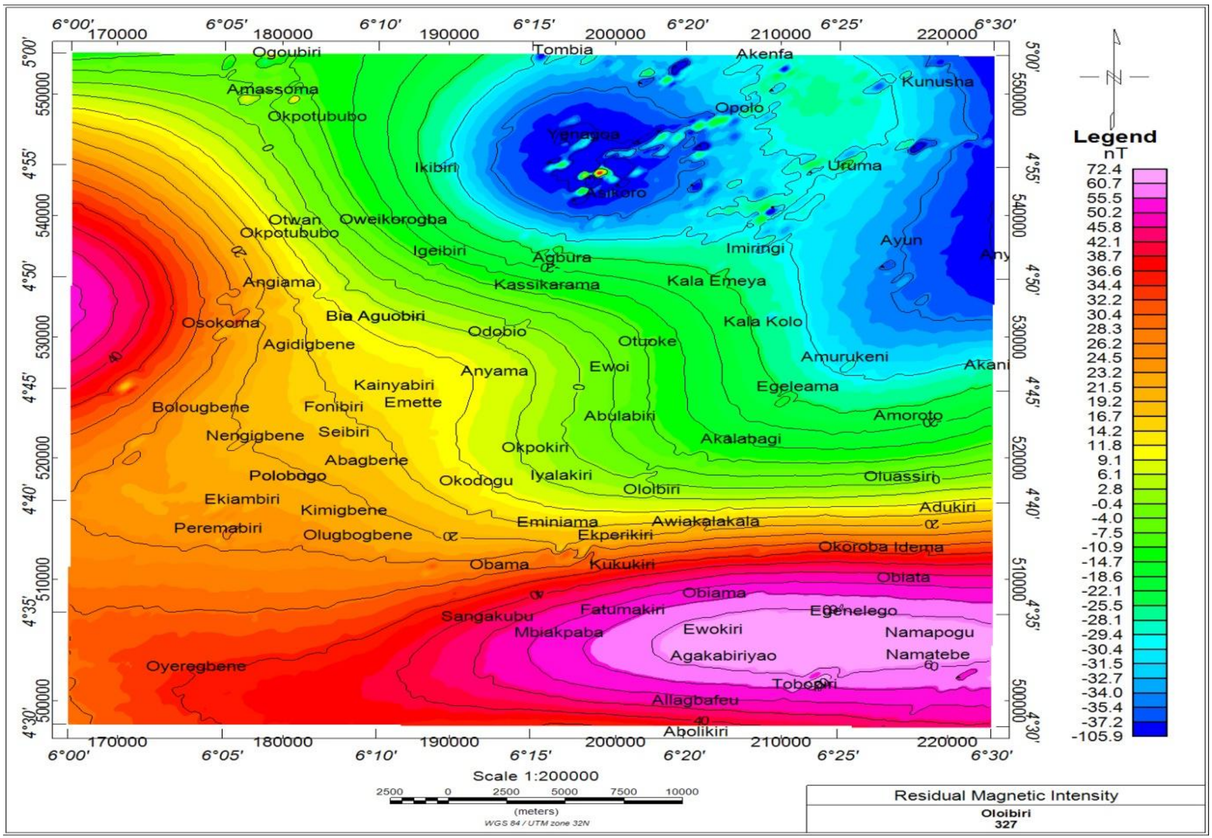

Figure 3: The Residual Magnetic Field Intensity Map of the Study Area Reduced to the Equator

The analytic signal of the aeromagnetic anomalies map (Figure 4) determines the causative source parameters (location of boundaries). It reduces the aeromagnetic data to peculiarities whose maxima mark the edges of magnetized bodies (Silva et al. 2003; Asadi and Hale 1999). Thus, the boundaries/contacts within the study area were better highlighted in the analytic signal map, with maxima values of magnetization contrast outlining the shallow anomalies.

Figure 5 shows the Residual magnetic intensity (grid) upward continued to 3000 m. The result obtained is enhanced effect of deeper anomalies relative to shallower ones. That is, high-frequency anomalies were suppressed, leaving only the long wavelength (deeper responses) for interpretation.

The source parameter imaging filter was applied on the residual magnetic data of the study area to show the locations and the corresponding depth estimations of geologic sources in the place. The source parameter imaging map (Figure 6) determined the positions and depths of contacts between the sedimentary and the basement rocks within the study area.

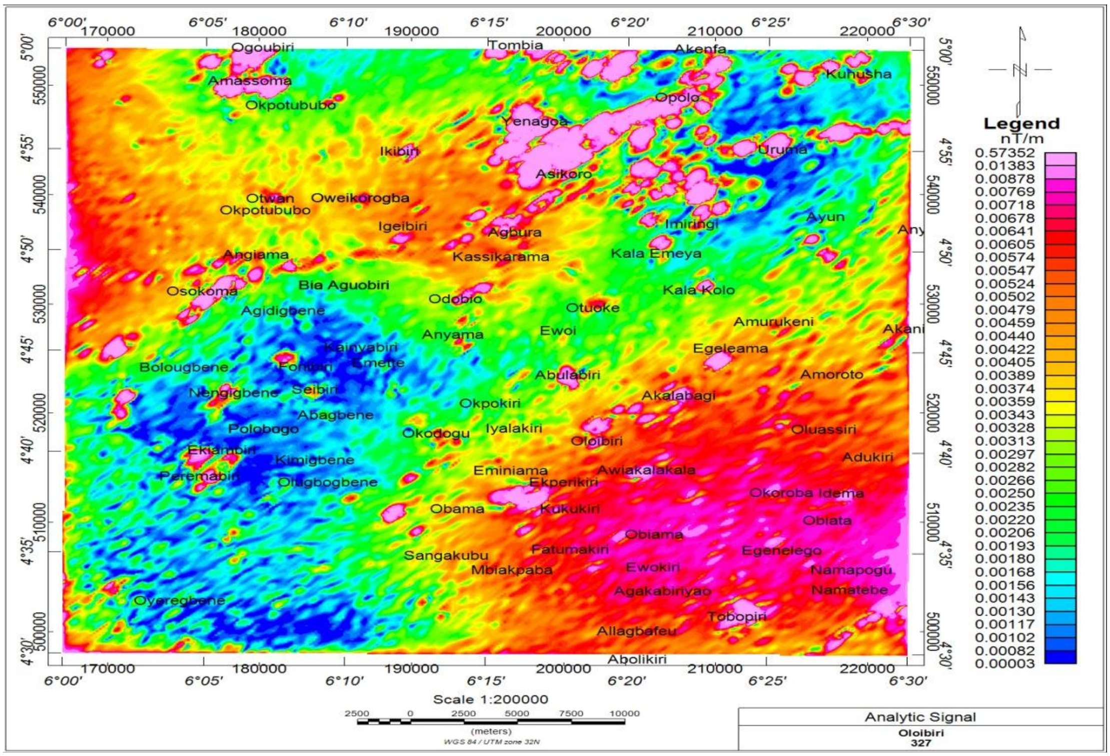

Figure 4: The Analytic Signal Map of the Study Area

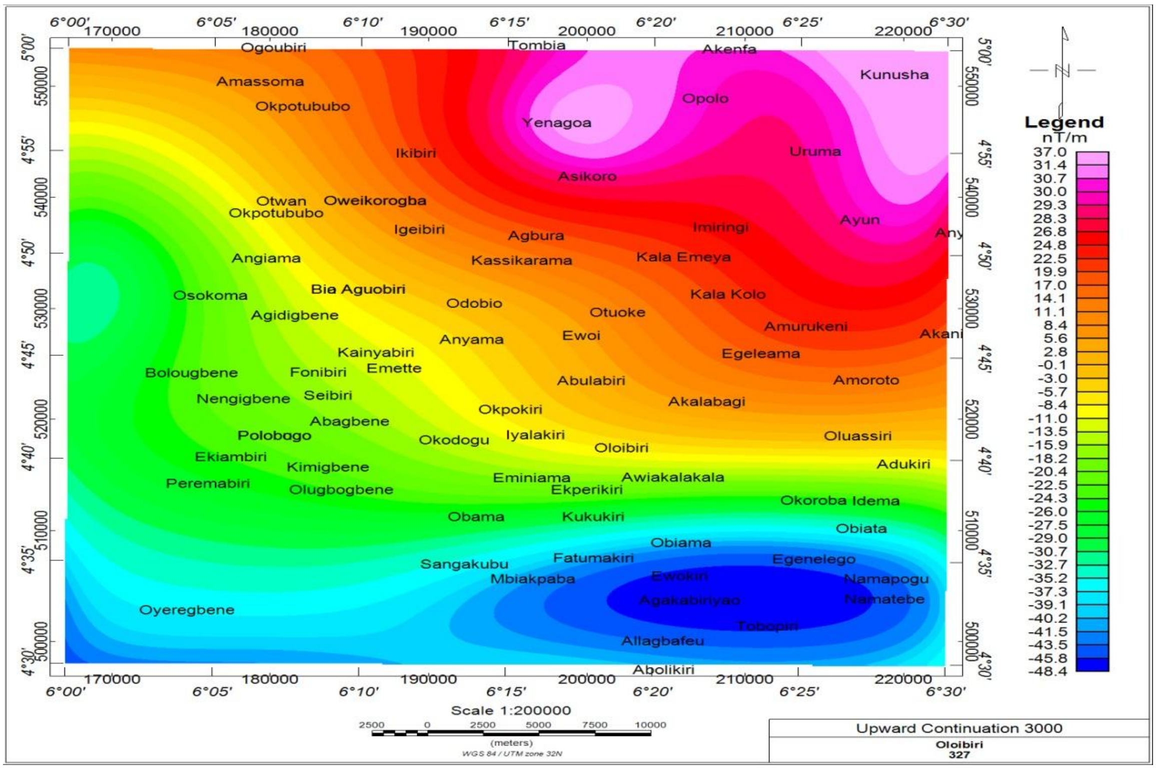

Figure 5: Residual Magnetic Intensity Map of the Study Area Upward Continued to 3000 m

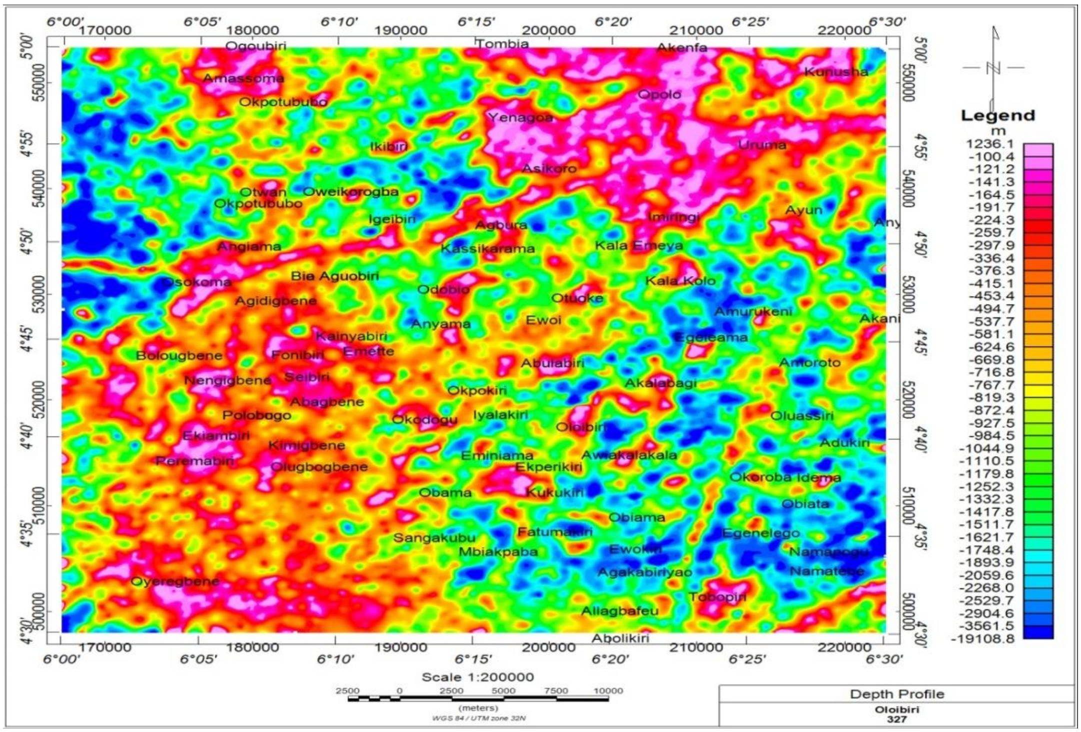

Figure 6: The Source Parameter Imaging Depth Map of the Study Area

V. Discussion

The residual magnetic intensity reduced to equator maps (Figure 3) shows low magnetic anomalies (-105.9 nT to -31.5 nT) at the northeastern part of the study area (Yenagoa, Asikoro (Azikoro), Opolo, Kunusha, Ayun, Amurukeni and Akeni). These low magnetic intensities anomalies have a NE-SW trend and are characterised by long wavelength (low frequency) and short-wavelength bodies (high frequency). The short wavelength bodies dominate Yenagua, Asikoro (Azikoro), Opolo, Uruma and Imiringi and most likely resulted from subsurface intrusions of high magnetic contents at different depths. Also, the differences in magnetic relief between two adjacent magnetic highs and lows suggest a comparable variation in lithology. The central part of the study area (Oloibiri, Otuassiri, Amoroto, Otuoke, Kassikarama, Anayama, Okodogu, Otwan, Igeibiri, Okpotububo and Amassoma) is dominated by intermediate magnetic intensities ranging from >-31.5 nT to -16.7 nT. Qualitative interpretation of contour lines defined numerous structural faults within Oloibiri, Odobio, Akalabagi, Bia Aguobiri, Angiama, Igeibiri and Amassoma. The central part of the study area is also characterised by long-wavelength bodies, indicating great depth to the magnetic basement (thick sediment cover). The southern, western and southwestern parts of the study area are characterised by high magnetic, long-wavelength anomalies ranging from>-16.7 nT to 72.4 nT. The high magnetic intensity observed at the southern and southwestern parts (Allagbafeu, Tobobiri, Ewokiri, Namapogu, Obama, Kimigbene, Ekiambiri, Bolougbene, Fonibiri, Oyeregbene and Osokoma) most likely resulted from thick ferruginised sandstone belonging to the Benin formation.

Extensive regional fault systems were delineated from the qualitative interpretation of the residual magnetic field map. These regional faults predominantly have NE-SW trend. The relationship between the orientation of the regional structures and the subsurface intrusives at the northeastern part of the study area (Yenagoa, Asikoro (Azikoro), Uruma, Opolo and Imiringi) suggests that the study area underwent two major tectonic events. The NE-SW trend is associated with the opening of the Gondwanaland Supercontinent, which led to the formation of the Benue Trough during the Albian; while the intrusives in the northeastern part of the study area were emplaced during the Santonian Orogeny that majorly affected the southern portion of the Benue Trough and the Anambra – Afikpo Basin.

The upward continuation map (Figure 5) shows that low magnetic field intensity characterises the northeastern part of the study area (Yenagoa, Asikoro, Opolo, Akenfa, Kunusha, Uruma and Ayun) at depth. This magnetic low is mostly due to the depletion in magnetism by the thermal activities that accompany the subsurface volcanic bodies of the region. The other parts of the study area reflect a gradational increase in magnetic intensity southwards, indicating an increase in both ferruginization of sandstone sediment and sediment thickness.

The analytic signal map (Figure 4) lends support to the existence of anomaly peaks (due to intrusive), and it outlines the position of the signature over the relative positions of the source bodies forming the anomalies. The highlighted edges of the high analytic signal defined at the northeastern, southeastern and western parts of the study area indicate contacts of high magnetic intensity bodies at varying depths within the subsurface. These bodies correlate with the magnetic structures delineated within Yenagoa, Asikoro (Azikoro), Opolo, Kuhusha, Uruma, Imiringi and Akanfa in the residual magnetic intensity map (Figure 3). The analytic signal map (Figure 4) further delineated magnetic bodies within Otuoke, Abulebiri, Oloibiri, Egeleama, Amoroto, Obiama, Egenelego, Tobopiri, Kukukiri and Obama at the southeastern part of the study area; Osokome, Angiama and Otan at the western part of the study area; Ogoubir, Amassoma and Okpotububo at the northwestern part of the study area. Based on structural complexity, the northeastern part of the study area is defined as heavily deformed place with high occurrences of magnetic bodies (intrusives); the southeastern part of the study area is moderately deformed, while other parts have low deformed sediments, especially at the southwestern part of the area (within Oyeregbene).

The interpretation of the residual field and analytic signal maps shows that the study area is structurally controlled sedimentary basin with both regional and minor faults associated with fracture systems and intrusive activities. The fracture systems developed due to stress imposed on the crust. Fracture gaps representing discontinuities are favourable areas for hydrocarbon accumulation. Such fracture systems were delineated within the central/southeastern parts of the study area (Otuoke, Abulebiri, Oloibiri, Egeleama, Amoroto, Obiama, Egenelego, Tobopiri, Kukukiri and Obama) and northwestern part of the area (Ogoubir, Amassoma, Okpotububo, Otwan, Ikibiri and Oweikorogba).

The 2D source parameter imaging map (Figure 6) shows the variation in depth to magnetic sources within the study area. The maximum depth obtained for the magnetic sources is about 19.1 km, whereas the shallowest magnetic source depth is approximately 0.1 km. An average depth of about 1.0 km was delineated for the entire area. Otuoke, Abulebiri, Oloibiri, Egeleama, Amoroto, Obiama, Egenelego, Tobopiri, Kukukiri, Obama, Namapogu, Adukiri and Amoroto Areas have basement depth range of >1.0 km to 19.1 km. The western part of Otwan, Okopotububo Angiama and Osokoma also recorded high depth to basement >1.5 km. Both the northeastern and southwestern parts of the study area have sediment thickness <1.5 km.

Interpretation of Depth Profiles within the Study Area

Five depth profiles were taken across the source parameter imaging map for modeling in order to develop a depth model of the study area. Figure 7 shows the interpreted profiles and the sediment–basement contact model of the profile lines are presented in Figures 8 to 12. Profile 1 has NW-SE trend; the profile has a total length of 30.1 km and extends from Tombia to Ayun Area. Profile 2 has NW-SE orientation with a total distance of 65.0 km. The profile begins at Amassoma and terminates at Amoroto Area. Profile 3 extends from Osokoma to Obiata Areas, with a length of 61.2 km. Profile 4 has a length coverage of 50.5 km and runs from Peremabiri to Tobopiri Area. Profile 5 has a NE-SW trend, running from Oyeregbene to Akanfa Area.

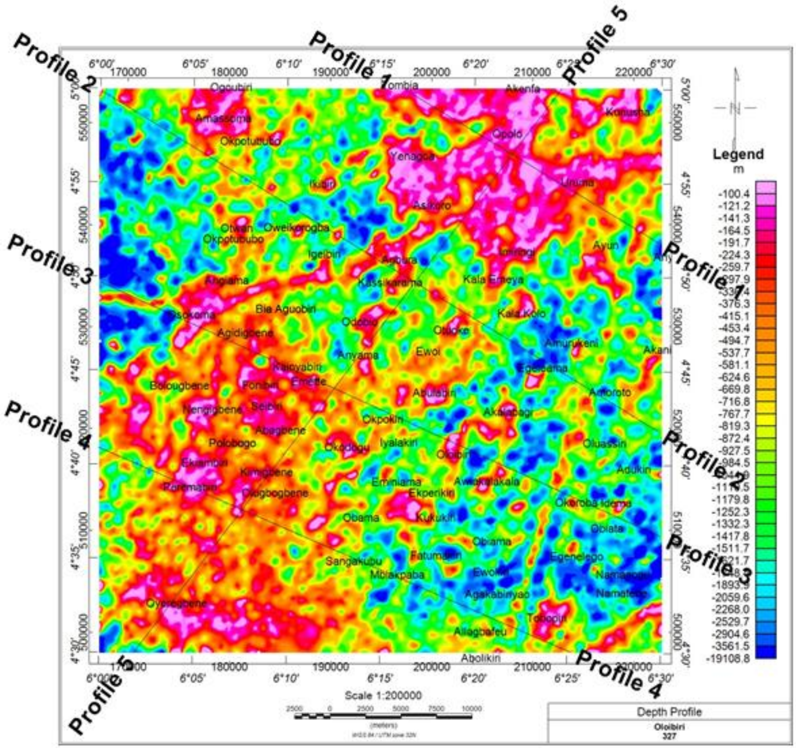

Figure 7: Profile Lines across the Source Parameter Imaging Map for modeling

Profile 1 (Figures 8) shows that the depths to shallow magnetic sources around Opolo and Uruma Areas range from 0.1 km to 0.5 km. The near-surface structure along the profile could have resulted from thick ferruginized sandstone bodies and intense faulting. The highest depth across the profile occurs within Ayun. The shallowest depth range along the profile is from 0.1 km to 0.5 km and the range for the deepest sources is from 1.5 km to >2.5 km.

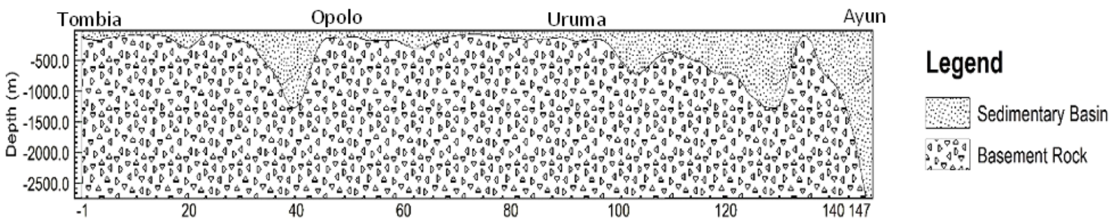

Figure 8: Sediment–basement Contact Model for Profile 1

Profile 2 shows that the depth to shallow magnetic sources within Amassoma, Okpotububo and Ogoubir Areas range from 0.1 km to 1.0 km, while deeper sources have depth >2.0 km. The depth to magnetic basement within Otuoke Area and environs ranges between about 0.5 km and 1.8 km. Oweikorogba and Igeibiri Areas have depth to magnetic basement within the range of about 2.0 km to 6.0 km.

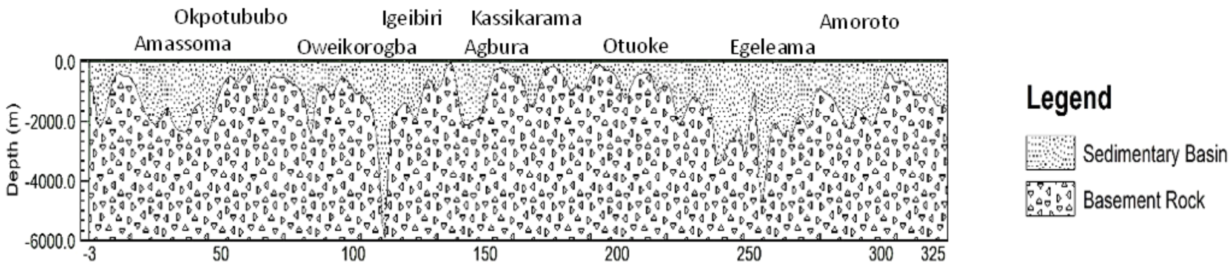

Figure 9: Sediment–basement Contact Model for Profile 2

Profile 3 (Figure 10) has NW-SE trend and runs from the west of Osokoma to Obiata Areas. Osokoma, Agidigbene, Kainyabiri and Emette Areas have shallow depth to the magnetic basement with a range of 0.1 km to 0.7 km. The deepest point along the profile was delineated at the northwestern part of the modeled profile. The highest depths across the profile has a range of 2.0 km to >3.5 km.

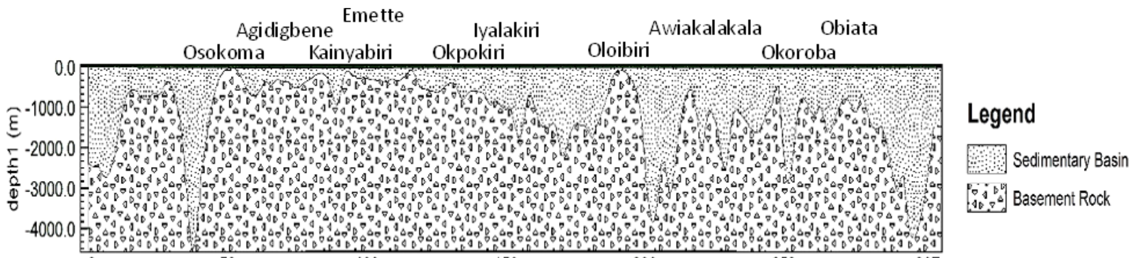

Figure 10: Sediment–basement Contact Model for Profile 3

Profile 4 (Figure 11) also has NW-SE trend and extends from Peremabiri to Tobopiri. Shallow sediment thickness within Peremabiri and Ekiambiri Areas ranges from about 1.0 Km to 1.2 Km, while the thickest sediment around the area is about 2.5 Km, as observed at the beginning of the profile. Shallow magnetic basement characterises Olugbogbene Area with a depth range of about 1.0 Km to 1.4 Km. Mbiakoaba Area has the highest depth range of about 2.0 Km to 3.5 Km. Allagbafeu and Agakabiriyao Areas have basement depth of about 1.0 Km to 2.5 Km, while, Tobopir Area has a relatively shallow sediment thickness with an average of about 1.2 Km.

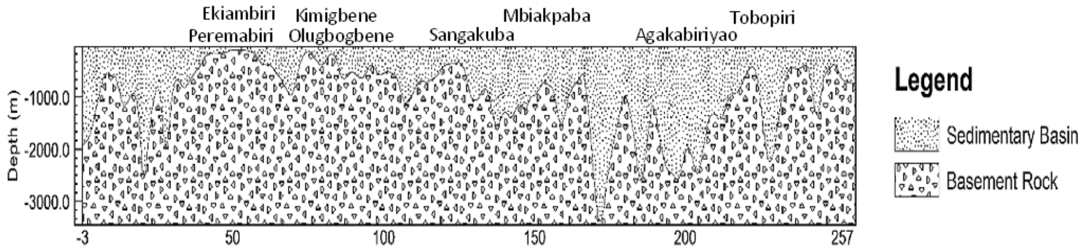

Figure 11: Sediment–basement Contact Model for Profile 4

Profile 5 (Figure 12) shows that Oyeregbene Area has an average sediment-basement depth range of about 0.7 Km to 2.5 Km. Ologbogbene, Kimigbene, Abegbene and Emetite Areas have relatively shallow sediment thickness with an average of about 1.0 Km. Kassikarama and Agbura Areas have sediment thickness range of about 1.5 Km to 3.2 Km, while the northeastern end of the profile within Asikoro (Azikoro), Opolo and Akenfa Areas are characterised by relatively shallow sediment thickness range of 0.5 Km to 1.6 Km.

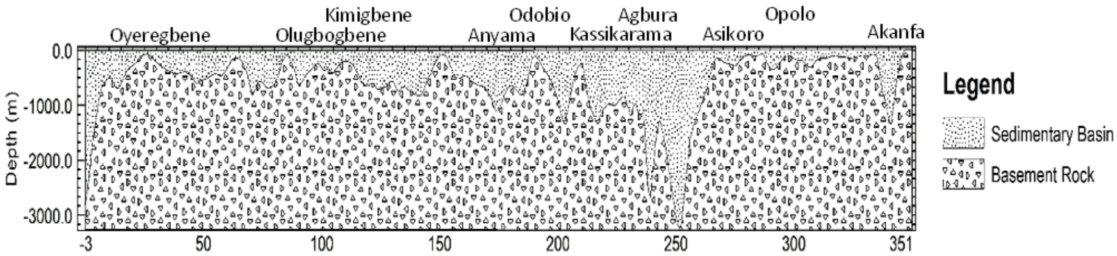

Figure 12: Sediment–basement Contact Model for Profile 5

VI. Conclusion

This study shows that the sediment-basement contacts in Oloibiri and environ are located between 0.1 km and 19.1 km with an average of about 1.0 km. The area is structurally controlled sedimentary basin with both regional and minor faults associated with fracture systems and intrusive activities. The fracture gaps representing discontinuities are favourable areas for hydrocarbon accumulation. Such fracture systems were delineated within the central/southeastern parts of the study area, including Otuoke, Abulebiri, Oloibiri, Egeleama, Amoroto, Obiama, Egenelego, Tobopiri, Kukukiri and Obama and northwestern part of the study area including Ogoubir, Amassoma, Okpotububo, Otwan, Ikibiri and Oweikorogba. These places have both the sediment thickness and structural complexity favourable for hydrocarbon generation and accumulation. Northeastern part of the study area is heavily deformed with high occurrences of magnetic bodies; the southeastern part is moderately deformed, while other parts have low deformed sediments, especially at the southwestern part of the area.

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