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Structural and Depth Model of Bayelsa State, Nigeria Deduced From High Resolution Aeromagnetic Data

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Abstract:
Background: *Bayelsa State, Nigeria is located in the Niger Delta Basin. The basin is very rich in oil and gas. In November 2020, Bayelsa State hosted the National Council on Hydrocarbon Summit, where the government revealed its interest in identifying new petroleum prospects in the state. The growing interest in new hydrocarbon prospects by the government is a major driving force of this research. The research focuses on the application of magnetic method in delineating the basin's sediment thickness and structural models within the state; hence, highlighting features with potentials for hydrocarbon generation and migration.*
Materials and Methods:*High resolution airborne magnetic data covering Bayelsa State were used in delineating the structures and sediment thickness within the area. Data enhancement techniques involving upward continuation, analytic signal filter, first vertical derivative and source parameter imaging were applied on the magnetic data. These helped in the delineation of the structural and depth models of the area.*
Results: *The structural map shows a dominant NE-SW fault with minor NW-SE fault systems. The thickest sediment was delineated within Atalaweigbene, Aziama, Batagbene, Akede, Azatuta, Ogidikoro, Gbaran, Apoi and Tobobubo Areas with a range of 11.9 Km to 26.8 Km. The shallowest depth was delineated within Ekpikakiri, Goldsmithkiri, Tobopiri, Allagbafeu, Abolikiri, Galubakiri, Lasukugbene, Egbomatoro, WeisonKinbogbene, Olugbogbene, Ogbogbene, Korugbene, Ezeotu-Zion and Kogbene Areas with thickness range of 2.0 Km to 4.3 Km.*
Conclusion:*The sediment thickness and structural endowment of the study area prompted the classification of Brass, Fantuo, Gold Coast, Namatebe, Emele, Pokokiri, Aganatoku, Ekpikakiri, Owon, Bokubokiri, Ekpikakiri, Bumodi, Akenfa, Okpotububo and Amassoma Areas as zones of very viable potentials for hydrocarbon generation and migration.*
Key Word:*Bayelsa State, Structural Model, Depth Model, Hydrocarbon Generation, Hydrocarbon Migration.*

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I. Introduction

Nigeria is a member of Organization of the Petroleum Exporting Countries (OPEC). In 2020, the country was rated the world's eleventh (11th) and Africa's first largest producer of crude oil (U.S. Energy Information Administration 2021), which is deep buried in her sedimentary basins. Current production of all Nigeria's crude oil is mostly derived from the Niger Delta Basin (Whiteman 1982;Obaje 2009; Nwajide 2013). The study area, Bayelsa State, Nigeria is geologically located in the Niger Delta Basin. The Niger Delta Basin has attracted the attention of geoscientists worldwide, owing to the discovery of crude oil in commercial quantity in Oloibiri, Bayelsa State in 1956. Oil and gas were later discovered in commercial quantities in other parts of the basin and in the neighbouring basins (Anambra and Afikpo) that have similar characteristics with it.

Most studies on Niger Delta Basin dwelt on search for oil (Wright et al. 1985;Adedapo et al. 2014;Emujakporue and Ekine 2014) and groundwater (Amajor 1991; Ophori 2007; Nwankwoala and Ngah 2014). Most of these studies lacked wider coverage; they are limited to areas of interest. In November 2020, Bayelsa State, Nigeria hosted the National Council on Hydrocarbon Summit, where the government displayed its interest in identifying new petroleum prospects in the state. Structural and depth model of all parts of Bayelsa State is scarce. The few that are available made use of obsolete methods, low resolution airborne magnetic data, one-dimensional profiles for depth modelling or high spectral grid cell size to generate results. Forward and inverse modelling of one-dimensional profiles for depth modelling is less accurate, as the three-dimensional effects of geologic bodies are not considered and high spectral grid cell size yields low resolution results.

One of the fundamental features that affects the formation of hydrocarbon in a basin is the thickness of the sediment (Wright et al. 1985;Anyanwu and Mamah 2013; Ibe and Uche 2021). Another fundamental feature that affects the formation of hydrocarbon in a basin is the structural endowment of the basin (faults and fractures) which could serve as migratory pathway for hydrocarbon or hydrothermal fluid (Uche et al. 2020).

There was need to produce the depth and structural models of Bayelsa state with high resolution geophysical data. This study used high resolution aeromagnetic data to appraise the hydrocarbon potential of the study area. This was accomplished by the determination of the depth to magnetic sources, sediment thickness, basement topography and structures within the basin.

The growing interest in new hydrocarbon prospects within Bayelsa area of Niger Delta Basin by the State government is a major driving force of this research. The research focused on the application of magnetic method in delineating the basin's structural and depth models of Bayelsa Area; hence, highlighting sediment thickness suitable for the generation or commencement of the formation of hydrocarbon. This research therefore identified new suitable prospect areas for localized studies.

II. The Study Area

The study area is located in the south-south Nigeria. It is bounded by Latitudes 4°16′30″N and 5°22′53″N and Longitudes 5°22′00″E and 6°36′26″E (Figure 1). The major towns within the study area include Yenagua, Oloibiri, Brass and Otuoke. The study area is bounded to the north by Delta State, to the east by Rivers State and to the west and south by the Atlantic Ocean.

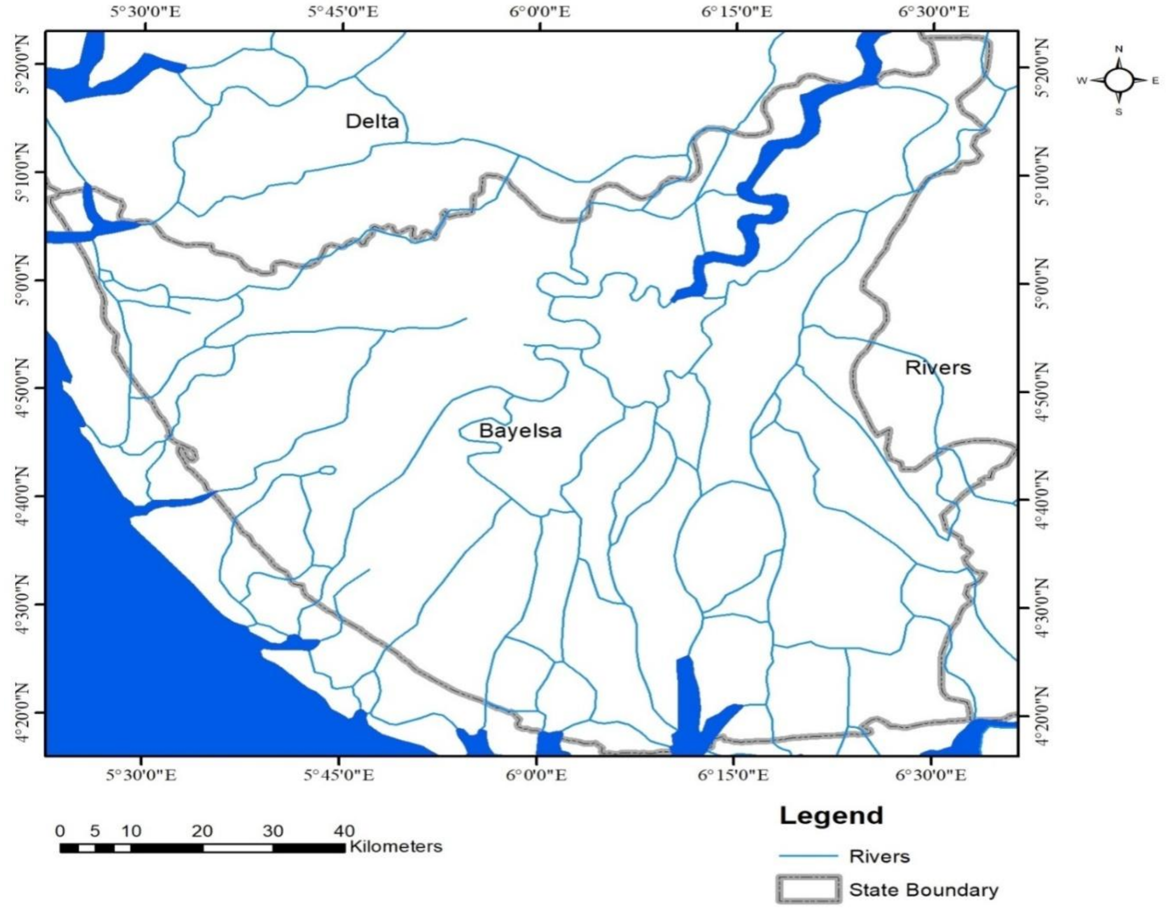

Figure 1. Geographic Map of the Study Area.

The Niger Delta Basin is an extensional rift basin located in the Niger Delta and the Gulf of Guinea on the passive continental margin near the western coast of Nigeria (Tuttle et al. 1999) and partly extends to Cameroon, Equatorial Guinea and São Tomé and Príncipe. The basin occupies a total area of about 300,000 km^2. Oceanic basement rock of pre-rift time period and basaltic in composition is the oldest rock in the basin. Also, closer to the coast is the Precambrian continental basement. This basin was formed in the Tertiary period from the interplay between subsidence and deposition arising from a succession of transgressions and regressions of the sea (Hosper 1965). It was formed by a failed rift junction during separation of the South American plate and the African plate, as well as the opening of the South Atlantic.

The formation of the present Niger Delta started during Early Paleocene as a result of the built up of fine grained sediments eroded and transported to the area by the River Niger and its tributaries. Three lithostratigraphic units are distinguishable in the Tertiary Niger Delta (Short and Stauble 1967). The basal

AkataFormation of about 7000 m in thickness, which is predominantly marine prodelta shale, is overlain by about 3700 m thick paralic sand/shale sequence of the Agbada Formation (Tuttle et al. 1999). The Akata Formation is the source rock in the sedimentary basin. The topmost section is the continental upper deltaic plain sands – the Benin Formation, estimated to be about 2000 m in thickness (Tuttle et al. 1999). A separate member of Benin Formation, the Afam Clay Member, is recognized in the Port Harcourt Area which is interpreted to be an ancient valley fill formed in Miocene sediments (Short and Stauble 1967). These Formations are underlain by various types of Quaternary deposits. According to Osakuni and Abam (2004), these Quaternary sediments are largely alluvial and hydromorphic soils and lacustrine sediments of Pleistocene age. The Quaternary geologic units of the Niger Delta Area are shown in Table 1.

Table 1: Quaternary deposits of the Niger Delta (Adopted fromIbe and Anekwe 2018;Uche et al. 2020)

Geologic Unit	Lithology	Age
Alluvium	Gravel, Sand, clay, silt	
Freshwater Backswamp, meander belt	Sand, clay, some silt, gravel	
Saltwater Mangrove Swamp and backswamp	Medium-fine sands, clay and some silt	Quaternary
Active/abandoned beach ridges	Sand, clay, and some silt	
Sombreiro-warri deltaic plain	Sand, clay, and some silt	
Benin Formation (Coastal PlainSand)	Coastal to medium sand; subordinate silt and clay lenses	Miocene-Recent
Agbada Formation	Mixture of sand, clay and silt	Eocene-Recent
Akata Formation	Clay	Paleocene

The depositional pattern which accompanied the accumulation of sediments during the formation of the delta, gave rise to structural traps (growth faults and roll-over anticlines) in the Agbada Formation (Nwankwoala and Ngah 2014). Virtually all the hydrocarbon accumulations in the Niger Delta occur in the sands and sandstones of the Agbada Formation where they are trapped by the rollover anticlines related to the growth fault development (Ekweozor and Daukoru 1994).

III. Materials, method, data processing and enhancement

The magnetic data used for this study was acquired by Fugro Airborne Survey and Nigerian Geological Survey Agency. The data were acquired along NW – SE flight lines at 500 m spacing, 20 km tie lines spacing and 80 m terrain clearance. The study area is covered by the magnetic data drawn from parts of eight airborne magnetic Index Sheets, comprising Sheet 318 (Burutu), Sheet 319 (Patani), Sheet 326 (Pennington River), Sheet 327 (Oloibiri), Sheet 328 (Degema), Sheet 333 (Sangana), Sheet 334 (Brass) and Sheet 335 (Kula). The entire Index Sheets cover about 24,200 km^2; the study area (Bayelsa State) was masked of the sheets with an area of about 10,322 km^2. The acquired total magnetic field intensity data were processed and the grid was developed by employing a minimum curvature algorithm at 100 m grid cell size.Data enhancement techniques involving Upward Continuation, Analytic signal filter, First vertical derivative and source parameter imaging were applied to the magnetic data.

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.

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.

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

Where $T =$ Magnitude of the total magnetic field

The Vertical Derivatives are used to delineate the anomalous source's boundaries. They can be used to delineate the contacts of lithologies of contrasting physical properties such as densities and susceptibilities. These contacts are reflected by inflation point in the potential field which, while difficult to locate on the anomaly map, are accurately traced by the zero contours of the vertical derivative map. First vertical derivative is physically equivalent to measuring the magnetic field simultaneously at two points vertically above each other, subtracting the data and dividing the result by the vertical spatial separation of the measurement points

(Nabighian et al. 2005). In accordance with Hendra and Darharta (2017), the First Vertical Derivative (FVD) was used to delineate the anomalous source's boundaries while limiting the high frequency amplification.
The basic equation for first vertical derivative is:

$$\frac{\partial T}{\partial z} = -\left(\frac{\partial T}{\partial x} + \frac{\partial T}{\partial y}\right) \qquad (2)$$

Where$T$ = magnetic anomaly field

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 1999). The SPI method estimates the depth from the local wave number of the analytical signal.

IV. Result and Discussion

The total magnetic intensity equals the Earth's magnetic field plus the residual/local field produced by magnetic bodies located at the subsurface of the study area. Figure 2 is the Total Magnetic Intensity (TMI) map of the study area. The Total Magnetic Intensity (TMI) field of the area has a range of 32540.9 nT to 32742.5 nT. The onshore zone at the northern part of the study area is characterized by high to moderate magnetic intensity anomaly, while the offshore areas are characterised by low magnetic intensity. The total magnetic intensity map is generally characterized by long wavelength bodies and they have a major NW-SE placement. The lithology is most likely the major control of the magnetic anomalies within the study area. Ekowe, Abari, Koloware, Ibia, Sagbama, Ofoni, Tubegbe, Kaiama, Yanagoa, Akenfa and Ayama Areas have magnetic intensities ranging from 32815.0 nT to 32887.5 nT.Ajamobri, Ozobo, Fougbene, Sanatobo, Ebikogbene, Kabiama, Ogoubiri, Batagbene, Akede, Ikibiri, Obeleli, Otuoke, Ewoi, Oloibiri, Emago, Odekiri, Okoroba and Pokokiri Areas have total magnetic intensities ranging from 32706.7 nT to 32742.5 nT. Brass, Spiff Town, Kirikakiri, Otokolopiri and Odioma Areas have total magnetic intensities within the range of 32619.0 nT to 32647.9 nT.

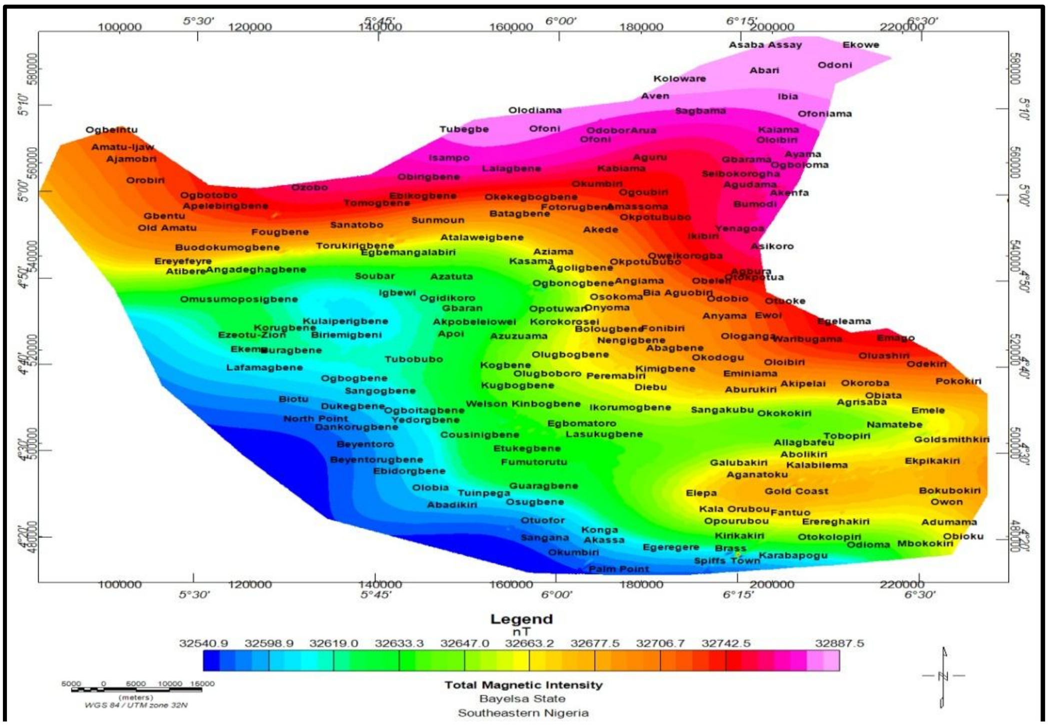

Figure 2. Total Magnetic Intensity, TMI Grid Mapof the Study Area.

International Geomagnetic Reference Field (IGRF) 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 intensity amplitude within the study area ranges from -102.0 nT to 121.2 nT with a mean value of -30.0 nT. The northern part of the study area is characterized by high magnetic intensity with range of 15.0 nT to 121.2 nT. This most likely resulted from thick ferruginised older sandstone sediments. Egbemangalabiri, Azatuta, Soubar, Igbewi, Gbaran, Apoi and Ogbonogbene Areas are characterized by both long wavelength and high frequency with low amplitude bodies. The long wavelength is indicative of deep sited basement and thick sediment accumulation, while the high frequency bodies are most likely due to tectonic activities within the sediments. The high frequency bodies predominantly have NE-SW trend.

Low amplitude - long wavelength bodies are also observed within Emele, Namatebe, Agrisaba, Obiata, Okokokiri, Tobopiri and Goldsmithkiri Area. Gabubakiri, Gold Coast, Elepa, Opourubou, Fantuo and Erereghakiri Areas are characterized by high amplitude – long wavelength and high frequency bodies. The high amplitude - long wavelength is indicative of shallow depth to basement and thin sediments of sandstone bodies. Brass, Spiff Town, Ereregere, Akassa, Palm Point, Otuofor, Abadikiri, Ebidorgbene, Bayentoro, Biotu and the entire regions along the coast and offshore areas recorded negative residual magnetism, indicative of deep sited basement and young sediment deposits.

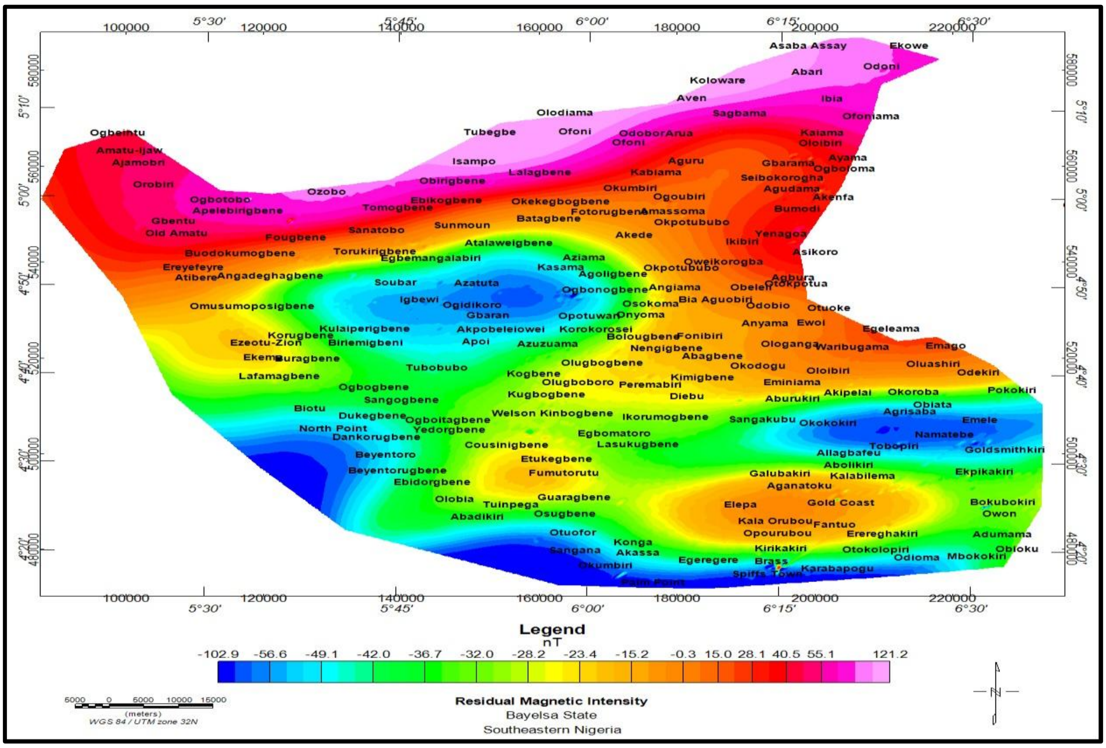

Figure 3. Residual Magnetic Intensity, RMI Grid Mapof the Study Area.

Figure 4 shows the Residual magnetic intensity (grid) upward continued to 1000 m. Upward continuation enhances the effects of deeper anomalies relative to shallower ones (Milligan and Gunn 1997). By carrying out the upward continuation, high-frequency anomalies are suppressed leaving only the long wavelength (deeper responses) for interpretation.

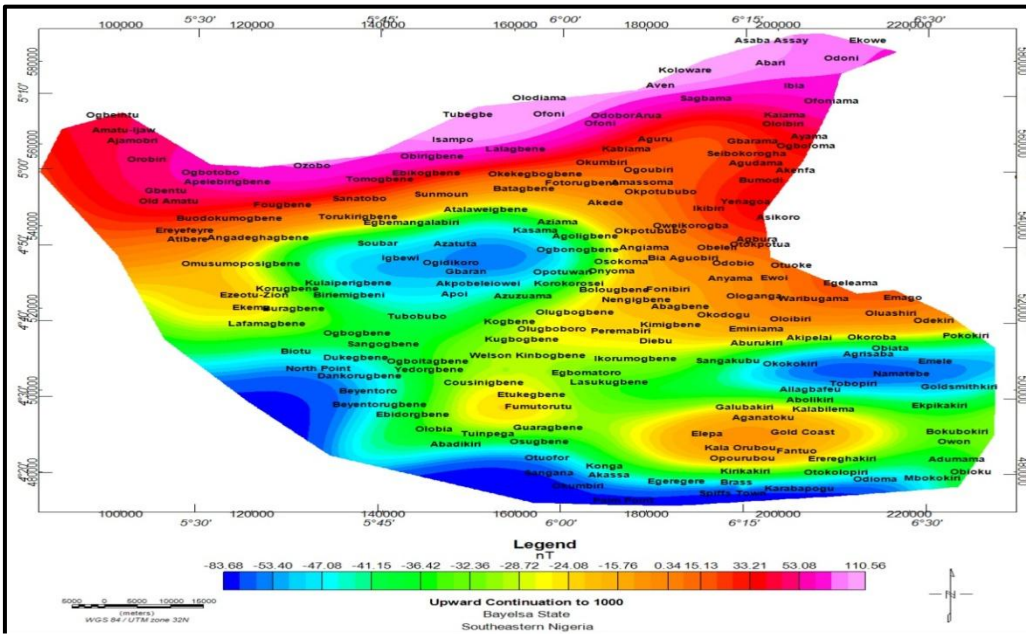

Figure 4. Residual Magnetic Intensity Map of the Study Area Upward Continued to 1000 m.

The high frequency bodies observed on the residual magnetic intensity map have been totally suppressed in the upward continued map, enhancing just the long wavelength (low frequency) bodies. This is best for depth to basement or sediment-basement boundary computation, as all effects of shallow structures have been removed.

Structural Interpretation

The analytic signal of the aeromagnetic anomalies over the study area is presented in Figure 5. The analytic signal determines the edges of the causative sources (location of boundaries) within the area. It reduces the aeromagnetic data to anomalies whose maxima mark the edges of magnetized bodies (Silva et al. 2003; Asadi and Hale 1999). The boundaries/contacts within the study area are well defined in the analytic signal map, with maxima values of magnetization contrast outlining the shallower anomalies. The first vertical derivative map of the aeromagnetic data over the study area is presented in Figure 6. The vertical derivative also enhanced the structures within the study area and major faults were defined within the area. The faults predominantly have NE-SW trend with minor NW-SE trend. These are correlated as structure formed during the opening of Gondwana Supercontinent in the Early Albian Age. The most prominent fault (F1) extends from Brass, through Fantuo, Gold Coast, Namatebe, Emele to Pokokiri Area. It is crossed by a younger fault (F2) that extends from Aganatoku, through Gold Coast to Ekpikakiri Area. The F2 fault terminates another fault, F3 which extends from Owon, Bokubokiri and terminates at Ekpikakiri. The structural relationship shows that the oldest is the F1 fault and the youngest is the F3 fault.

Another major fault extends from Cousinigbene through WeisonKinbogbene, Olugbogbene, Kogbene, Azuzuama to Ogbonogbene Area. There is a fault system delineated in the analytic signal map that is not visible in the first vertical derivative map; it extends from Torukirigbene through Sunmoun, Ebikogbene, Lalagbene to Olodiama Area. Many bipolar structures were delineated within Yenagoa, Akenfa, Agudama, Seibokorogba, Gbarama, Ibia, Odoni, Ogoubiri and Amassoma Areas which are indicative of shallow faults. Similar structures are observed around Brass, Spiffs Town and kirirkakiri area.

Center for Exploration Targeting (CET) Grid Analysis Module in Oasis Montaj was used to automatically extract lineaments from both first vertical derivative and analytic signal maps. The lineaments extracted from the two sources were then combined to produce the structural map of Bayelsa State (Figure 7).

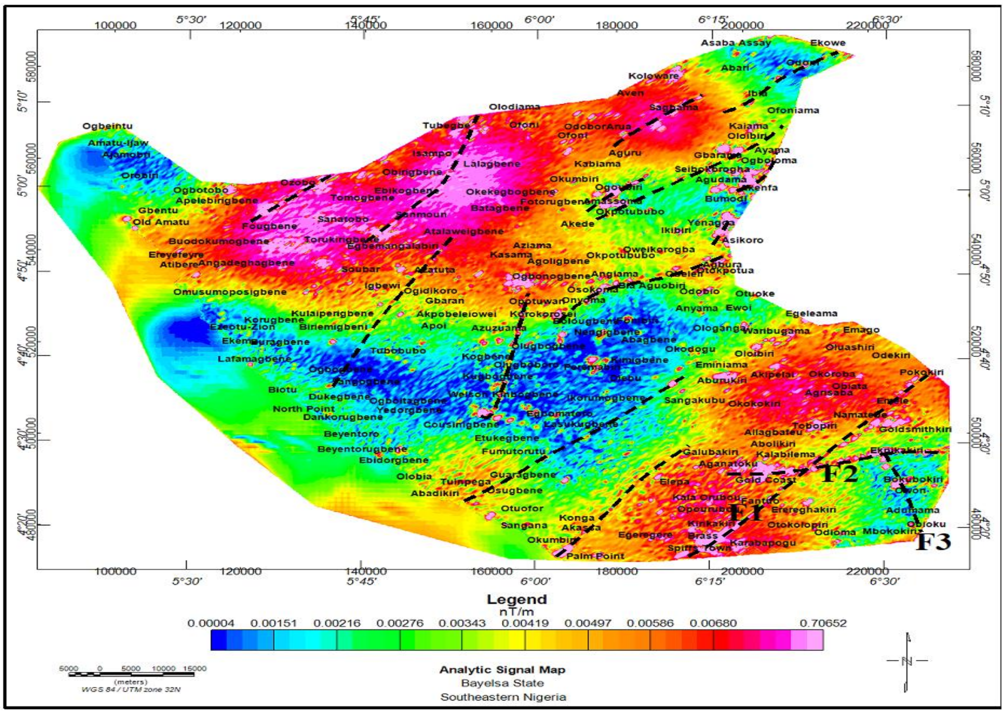

Figure 5. Analytic Signal Map of Bayelsa State.

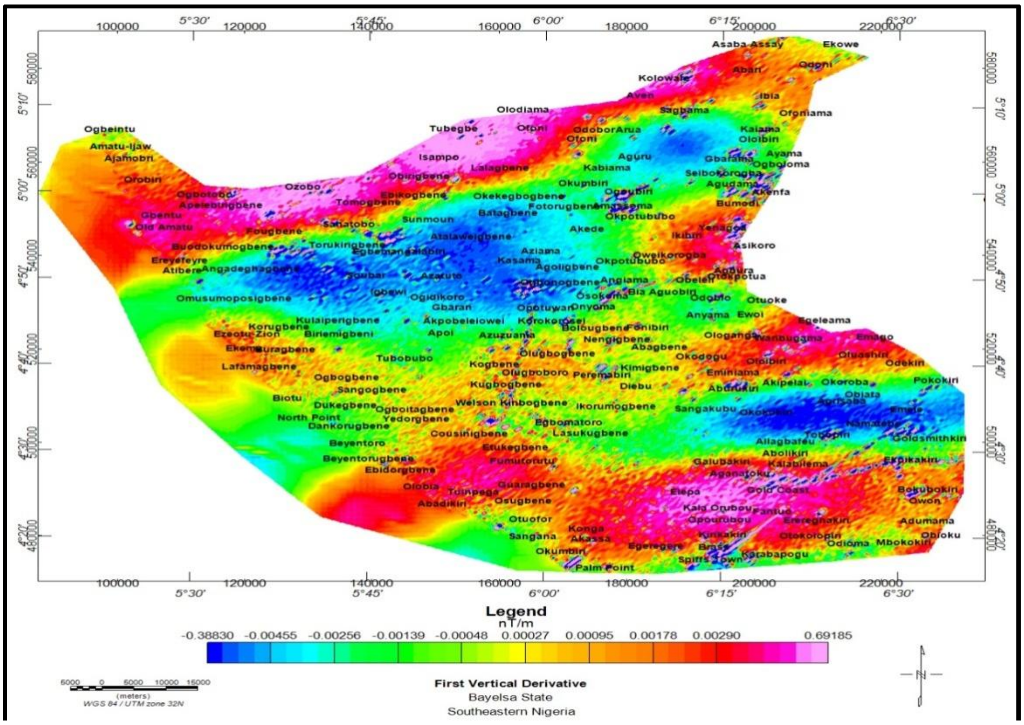

Figure 6. First Vertical Derivative Map of Bayelsa State.

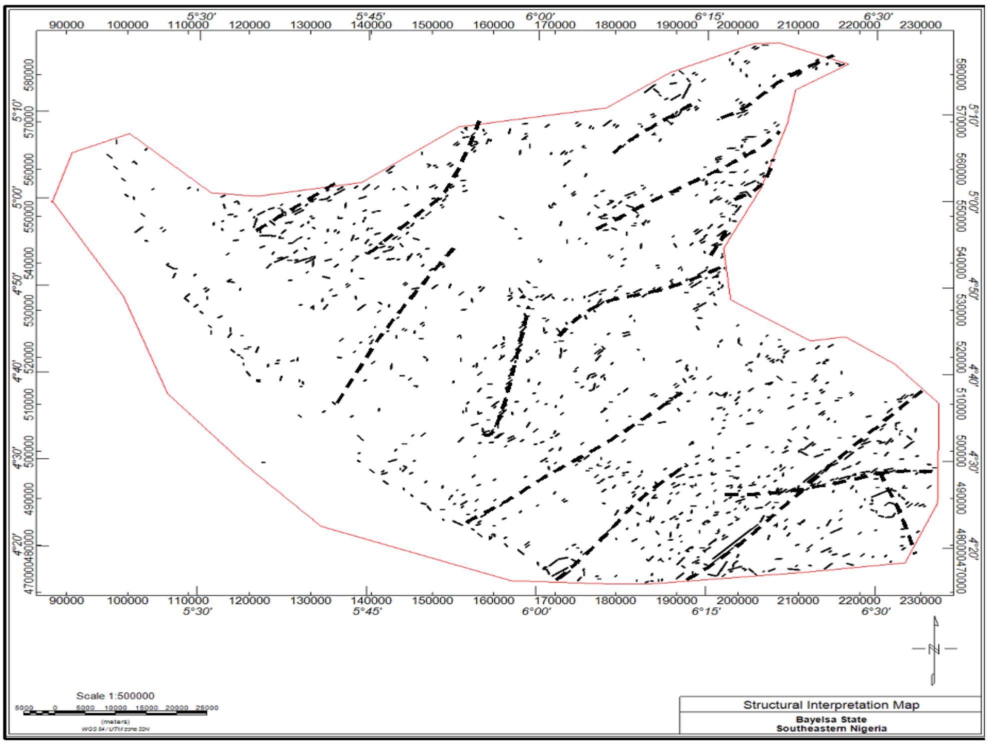

Figure 7. Structural Interpretation Map of Bayelsa State.

Depth Interpretation

The sediment thickness distribution within Bayelsa State was computed by calculating the depth to the top of the basement (sediment – basement contact). The depth was computed using the source parameter imaging filtering method. This method has an accuracy of about +/- 20% in tests on real data sets with drill hole control (Salako 2014). In other to compute the depth to long wavelength bodies (basement), the source parameter imaging was applied to the upward continuation map (Figure 4). This method is best for computing the depth to basement as all shallow bodies (high frequency bodies) have been eliminated from the solution, leaving the basement structures (low frequency). Figure 8 is the source parameter imaging depth result of the upward continued grid.

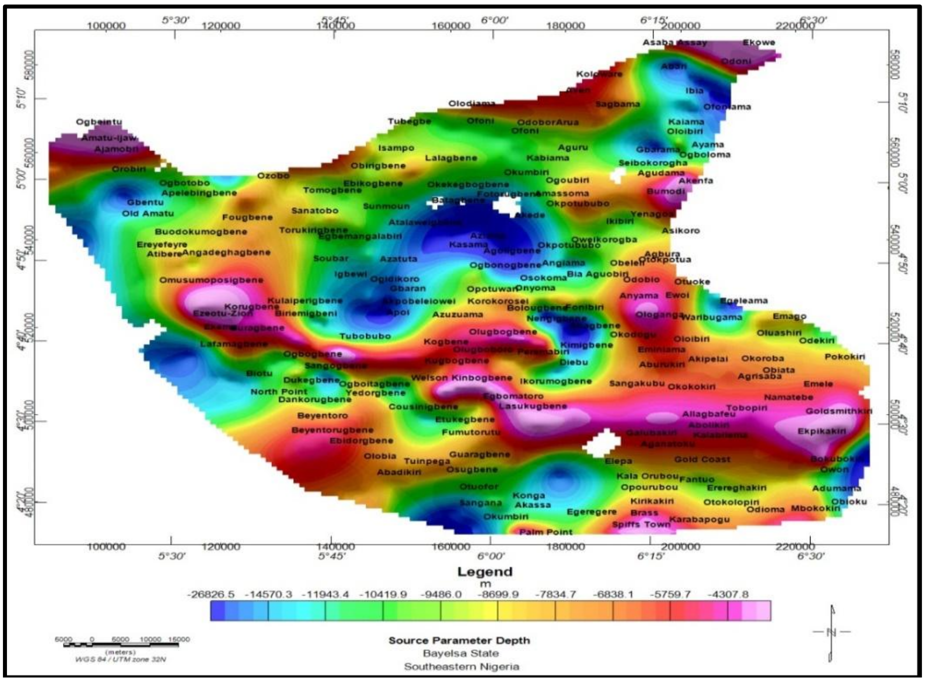

Figure 8. Source Parameter Imaging Depth Map of the Upward Continued Gridof the Study Area.

The sediment thickness varies from 2.0 Km to 26.8 Km with an average of 12.4 Km. This is closely in agreement with the works of Lucas and Omodolor (2018); Lucas and Odedede (2012); Murat (1972) which placed the Niger Delta sedimentary thickness at about 12.0 Km. The highest sediment thickness offshore was delineated within Atalaweigbene, Aziama, Batagbene, Akede, Azatuta, Ogidikoro, Gbaran, Apoi and Tobobubo Areas with a range of 11.9 Km to 26.8 Km. Abari, Ibia, Ofoniama, Kaiama, Ayama and Seibikorogha Areas also have sediment thickness range of 11.9 Km to 26.8 Km. Yenagoa, Bumodi, Akenfa, Okpotububo and Amassoma Areas have sediment thickness range of 4.3 Km to 6.8 Km. Otuoke, Ewoi, Anyama, Ologange, and Okodogu Areas have sediment thickness of 2.0 km to 5.7 Km. Oloibiri, Eminiama, Aburukiri, Akipelai, Okoroba, Obiata, Agrisaba and Sangakubu Areas have sediment thickness range of 5.7 Km to 6.8 Km. Pokokiri, Oluashiri, Emago and Egeleama Areas have sediment thickness range of 7.8 Km to 11.9 Km. Brass, Spiffs Town, Karabapogu, Kirikakiri, Odioma, Mbokokiri and Opourubou Areas have sediment thickness range of 3.0 Km to 7.8 Km. Akassa, Ereregere, Elepa, Konga, Okumbiri and Otuofor Areas have sediment thickness of 9.6 Km to 14.5 Km.

The shallowest sediment thickness was delineated within Ekpikakiri, Goldsmithkiri, Tobopiri, Allagbafeu, Abolikiri, Galubakiri, Lasukugbene, Egbomatoro, WeisonKinbogbene, Olugbogbene, Ogbogbene, Korugbene, Ezeotu-Zion and Kogbene Areas with thickness range of 2.0 Km to 4.3 Km. Figure 9 is the sediment thickness model for Bayelsa State, produced from the computed source parameter imaging map.

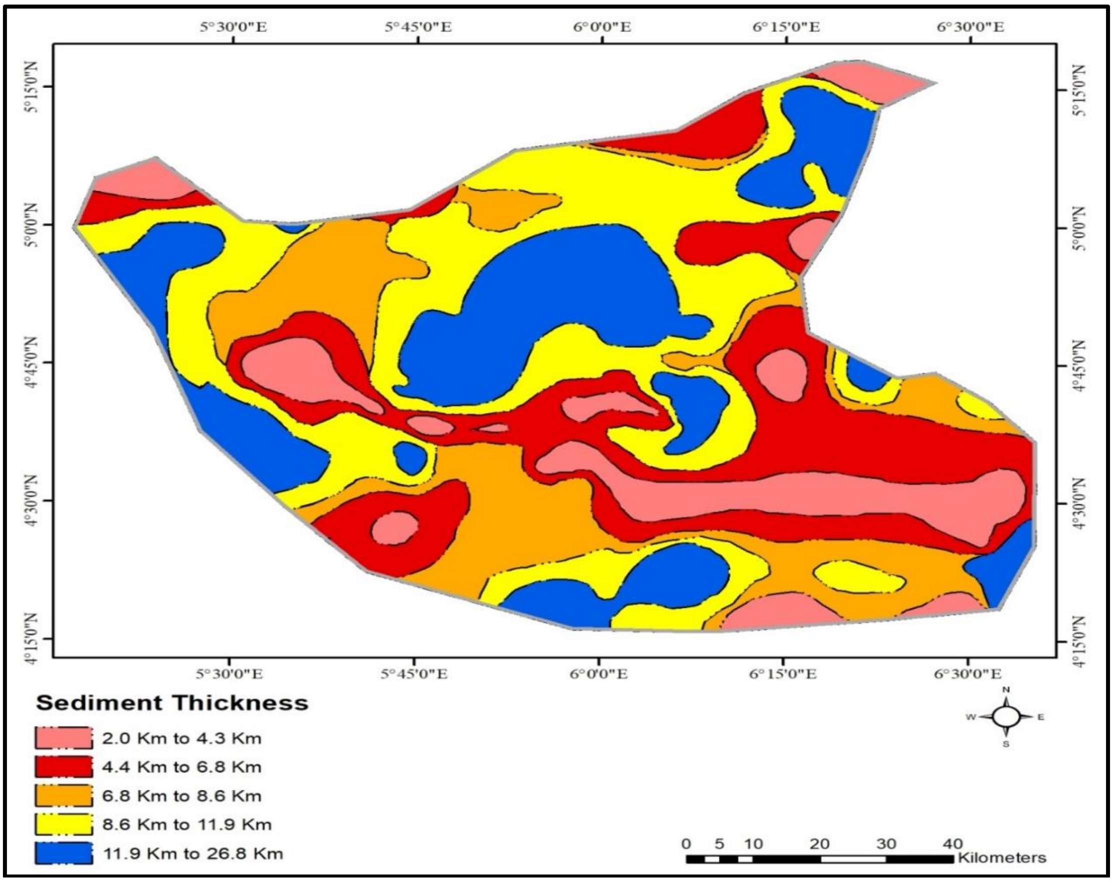

Figure 9. Sediment Thickness Model of Bayelsa State.

The depth to basement is synonymous with the thickness of the sediment and this is very significant to the hydrocarbon generation potential of a place (Nwosu 2014). It is known that the minimum thickness of sediment required to achieve the threshold temperature of 115°C for the commencement of oil formation from organic remains is 2.3 km when all other conditions for hydrocarbon accumulation are favourable and the average temperature gradient of 1°C for 30 m obtainable in oil rich Niger Delta is applicable (Wright et al. 1985). Hence, all the places with sediment thickness $\geq$ 2.3 km within the study area have potentials to achieve the threshold temperature of 115°C for the commencement of oil formation from organic remains. However, the sediment thickness, when compared to the thickness in the areas with existing oil wells, shows that regions with thickness range of 4.3 Km to 6.8 Km have more potentials for the commencement of hydrocarbon formation when other conditions necessary for the formation are present. Hence, considering the sediment thickness and structural endowment of the study area, Brass, Fantuo, Gold Coast, Namatebe, Emele, Pokokiri, Aganatoku, Ekpikakiri, Owon, Bokubokiri, Ekpikakiri, Bumodi, Akenfa, Okpotububo and Amassoma Areas have very viable potentials for hydrocarbon generation and migration.

V. Conclusion

The sediment thickness within Bayelsa state was delineated to range between 2.0 Km to 26.8 Km, with an average of about 12.4 Km. The thickest sediment was delineated within Atalaweigbene, Aziama, Batagbene, Akede, Azatuta, Ogidikoro, Gbaran, Apoi and Tobobubo Areas with a range of 11.9 Km to 26.8 Km. The shallowest depth was delineated within Ekpikakiri, Goldsmithkiri, Tobopiri, Allagbafeu, Abolikiri, Galubakiri, Lasukugbene, Egbomatoro, WeisonKinbogbene, Olugbogbene, Ogbogbene, Korugbene, Ezeotu-Zion and Kogbene Areas with thickness range of 2.0 Km to 4.3 Km. The sediment thickness and structural endowment of the study area prompted the classification of Brass, Fantuo, Gold Coast, Namatebe, Emele, Pokokiri, Aganatoku, Ekpikakiri, Owon, Bokubokiri, Ekpikakiri, Bumodi, Akenfa, Okpotububo and Amassoma Areas as zones of very viable potentials for hydrocarbon generation and migration.

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