

Structural and depth to basement evaluation of parts of Brass and Olobiri, Bayelsa STATE, Nigeria, using airborne magnetic data

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Abstract

The usage of potential field data in studying basins has gained recently despite being a reconnaissance tool. High-resolution aeromagnetic data from Niger Delta's Brass and Oloibiri regions were used in this study to qualitatively and quantitatively: examine structures, identify the extension/occurrence of the chain and oceanic fracture zone traversing from the Gulf of Guinea, delineate basement morphology, delineate basement lineament/tectonic trends and then determine depth to basement. On the aeromagnetic map, geomagnetic and diurnal corrections were applied by the Nigerian Geological Survey Agency to remove the effects other than that due to local geology. A project file was created as the gridded data was imported into the Oasis Montaj environment in X (x-coordinate), Y (y-coordinate), and Z (main) channels. Regional-residual separation was initiated on the Z channel for signature decomposition into anomalies of regional and residual extent. Subtle structural signatures were revealed as the residual was filtered further. This resulted in other field channels from which qualitative maps were generated. Various qualitative grid maps were generated. Faults, folds, dykes, and fracture zones in the ENE-WSW and E-W directions were visible on the qualitative maps. These lineaments hugely affect the area as they act as conduits, synclines, and anticlines, possibly improving economic viability. Fast Fourier Transform (FFT) was applied. This discriminated the signal into its energy and wavenumber component. Consequently, the Log of energy against wavenumber was plotted, and then a line was visually fit unto the high and low spectral energy curves. This art called 2D spectral depth estimate modeled two structural depth sources, D_a and D_b . The depth to deeper sources, D_a , varies from 3 km to 6.8 km, with a 4.5 km average depth, actually the shallow sources are found between 1.5 km and 3.2 km, but with a 2.2 km average depth. D_a was imported into Surfer 20 for the depth to the basement map to be generated. The basement map depicts undulations linked to the area. The average depth of 4.5 km emanating from the deeply seated sources is the sedimentary thickness value of the region. The NE-SW and NW-SE lineaments indicate extended Chain/Charcot fracture zones towards the Nigerian Niger Delta region. Due to the appropriate sedimentary thickness discovered and the recessive, NE-SW and NW-SE lineaments traversing from the Biafra Bight towards the region, this suggests that the area still holds a promise and thus hydrocarbon exploration can still be fostered if other conditions are met.

Keywords: Fracture zones, lineament, Fast Fourier Transform (FFT), anomalies

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1 Introduction

According to Anyanwu and Mamah (2013), in the last ten years, the understanding of aeromagnetic data evolved from analyzing basement structures to lithological gaps in sedimentary sections. The location and shape of individual joints, faults, folds, veins, and lithology, all of which may indicate the location of a particular economic deposit, are only established by mapping lineaments. Establishing lines linking subsurface structures may be possible using the magnetic method. A lineament is a linear feature of a landscape that represents an existing geological structure beneath the surface of the earth. A fault-aligned hill, valley, or linear shoreline makes up a lineament, according to Whitten and Brooks (1972) and Attoh and Brown (2008). On aeromagnetic maps, linear features typically represent geologic structures that may be a site of specific mineral deposits.

These geologic lineaments especially the fracture zones can extend for thousands of several kilometers along the ocean floors towards continental margins and can be mapped on aeromagnetic maps. Magnetic anomalies over the sedimentary formation, usually arise by the earth existing basement rocks or by intrusive anomalies are discovered over the sedimentary formation, usually arise by the earth's existing basement rocks or by intrusive plugs, lava flows, dykes, sills, and various igneous structures and volcanic centers (Gunn 1997). Most magnetic anomalies on sedimentary basins are caused by secondary mineralization along fault planes, which appear visible as linear patterns on aeromagnetic maps.

Five (5) oceanic fracture zones that trend NE-SW are known and have been mapped (Benkheli et al. 1989). Other fractures include the Ascension Fracture Zone, which defines the Guinea Ridges southern limit, and the Fernando Po Fracture Zone, which borders the Guinea Ridge to the north. Benkheli et al. (1989)

stated that among all the fracture zones, only the Chain/Charcot lineament Zone extends towards the Niger Delta region. Most fractures seen in continental southern Nigeria are an extension of these oceanic fracture zones.

Several exploration techniques are known to geophysicists and have been used reliably to map possible economic deposits beneath the earth. Adedapo et al. (2014) opined that seismic data has been used majorly in estimating hydrocarbon-bearing sequences of the region. We support such an assertion as little or no information on hydrocarbon exploration using high-resolution aeromagnetic data exists, especially within the study area. Sunday and Samuel (2013) used low-resolution aeromagnetic data to determine the basin architecture and hydrocarbon prospect of some parts of the Niger Delta, Nigeria. Okiwelu and Ude (2012) modeled the basement tectonics of some regions in the Niger Delta, using low-resolution aeromagnetic data. Recently, researchers are now diving into the application of potential fields in unearthing the hydrocarbon potential of the Niger Delta sedimentary basin using the recently acquired high-resolution data from the Nigeria Geological Survey Agency (NGSA), Abuja. The aeromagnetic method can decipher the subsurface as it relates to the structural disposition and basement morphology of a region.

The Niger Delta zone is known for its hydrocarbon exploration potential due to the large volume of deposited and accumulated sediments. This height of sediment negatively impacts the application of methods like the borehole and seismic methods. The sediment height makes it difficult for a borehole to drill the bottom of basement rocks. Also, the low resolution of reflection data and the sudden disappearance of energy due to attenuation at greater height during seismic survey has made it difficult for basement information

to be provided. These inadequacies make the aeromagnetic survey more appropriate as it can penetrate at greater depths and it can also access any geological landform irrespective of location since it is airborne.

Spectral depth analysis is a quantitative forward modeling approach that helps to estimate the depth and dimensions of anomalous sources as it characterizes the frequency content of the dataset. According to Spector and Grant (1970), this technique has been used to calculate the depth of source ensembles on a moving window basis by selecting the steepest and deepest portion of the spectral energy curve. This technique is advantageous in that the data transformed from the space domain to the frequency domain will be easier to handle also noise linked to potential field data is often of a high frequency and by limiting interpretations to low frequency components/deeply seated sources, major improvement in interpretations is made.

Basement depth is an important exploration parameter, especially in areas having mature hydrocarbon. According to Reeves (2005), he enunciated that magnetic susceptibility is a basic parameter in magnetic prospecting as sedimentary rocks have the subtlest susceptibility contrast on average since they are non-magnetic. He went further to state that this is the basis for the use of aeromagnetic survey since magnetic sources are found below the sedimentary section, thus allowing for rapid identification and delineating of subtle sediments and magnetic basements.

This study seeks to: (i) determine the basement depth to provide an understanding of the sedimentary thickness and morphology, (ii) interpret some structures, to identify, if any, the extension of the chain and Charcot fracture zone (iii) delineate lineaments and infer their influence on basin dynamics within the area.

2 Geology area

Brass is an island in Bayelsa State, Nige-

ria. Brass is bounded within the geographical location of latitude $4^{\circ} 15' - 4^{\circ} 30' N$ and longitude $6^{\circ} 15' - 6^{\circ} 30' E$. The area is covered by two Aeromagnetic maps spanning an area of about 1404 km².

This region is an extraordinary basin located in the Bight of Biafra/Gulf of Guinea. Its formation and evolution are controlled by the Chain and Charcot fault zones, linked to the outlet of the Atlantic Ocean. It is situated at the southwestern end of the Benue Trough, bordered in the south by the Cretaceous tectonic framework of Anambra Basin, Abakaliki Anticlinorium, and Afikpo syncline in the north.

Regionally, the Niger Delta sedimentary Basin is located between Latitude $3^{\circ} N$ and $6^{\circ} N$ and Longitude $4^{\circ} E$ and $9^{\circ} E$ (Masle, (1976), Whiteman, (1982), Wright et al. (1985), Reijer, (1996), Nwajide, (2013).

Three formations have been identified within the zone. They signify depositional facies and stratigraphic successions as shown in Figure 1. These are the Akata formation, the Agbada formation, and the Benin formations.

Away from the South American-African plate guided the creation of the region. The start of the South Atlantic also caused the structuring of the basin. Following such separation, several faults were built. The Akata with Agbada were then deposited sequentially owed to large transgression (Fatoke 2010). The shale Akata Formation seen below was squeezed into the shale anticlinal fold during the Eocene. The Agbade and Benin Formations were then deposited till today during the Oligocene (Michele et al. 1999).

Three major depobelts mark Niger Delta sedimentary fill. The cycles express the movement of sediments as they change mud grains of deep origin to fluvial denser-sized grains. The changes experienced by the lithologies found within the locality are attributed to many factors. The nature of sediment is a contributing factor.

Also, sediment nature is reliant on the environment deposited (Haack et al. 2000).

Three Formations are differentiated on the ratio of sand shale within the province. These formations represent deposited prograding facies. These three Formations (Fig. 2) include the Akata, Agbada, and Benin Formations (Michele et al. 1999; Fatoke, 2010; Tuttle et al. 2015).

Dated behind Eocene is the Agbada

Formation. Freshwater and sea features are contained in the Formation. The basic oil bearing facies is the Agbada Formation. It has a 3700-meter thickness value. Younger and Oligocene in age is the Benin Formation. It contains deposition of alluvial and plains of a continental flood. 2000 meters is the Formation thickness (Short and Stauble 1967).

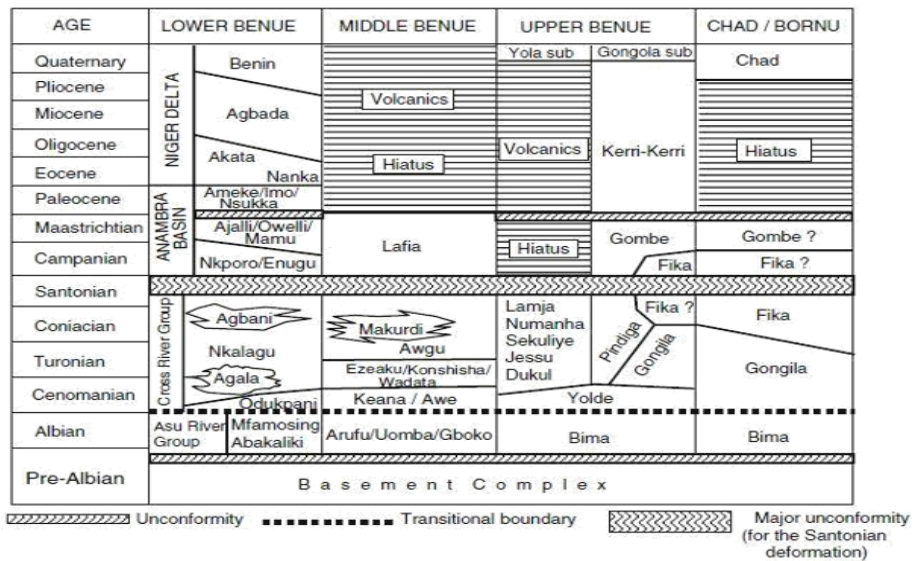


Figure 1. The study areas Stratigraphic Successions (Obaje 2009)

The area is an elongated rift basin established in the western Nigeria continental margin (Michele et al. 1999). The Province or Basin has suspected entrance to Cameroon, Equatorial Guinea, with Sao Tome. The basin is economically viable because of its quantity of petroleum. The sedimentary thickness varies between 9-12 km (Fatoke 2010). Various geologic formations that depict how the basin has been formed are evident within the province. The basin falls within the southwesternmost area of Benue Trough. The Volcanic Cameroun Line bound the Niger deltas other side (Michele et al. 1999).

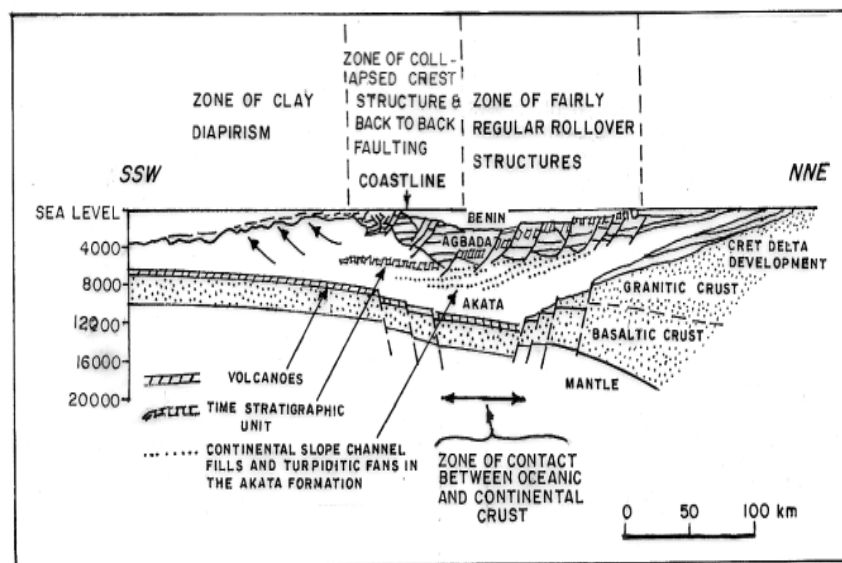


Figure 2. Niger Delta stratigraphy with its dip (Doust and Omatsola 1990)

Consisting of thick shales, sands with small amounts of silt and clay, and also Paleocene in age is the Akata Formation. A thickness of 7000 meters is affiliated with the Formation.

3 Materials and Methods

Nigerian Geological Survey Agency (NGSA), provided the digitized aeromagnetic data in Geosoft grid file format as sheets 324 (Fig. 3) and 327 (Fig. 4). The data with 324 and 327 sheet numbers cover Brass and Olobiri areas of Bayelsa state, Nigeria, respectively. The high-resolution datasets were obtained at a ground

clearance of 80 meters, tie of 2 km interval, and flight line direction of NE-SW at 500m line spacing. Qualitative and quantitative analyses were done using Oasis Montaj and Surfer 10. *Knitting* of the two sheets was undertaken before the isolation of magnetic anomalies linked to various magnetic sources. The overall magnetic intensity composite map for the research area is shown in Figure 5.

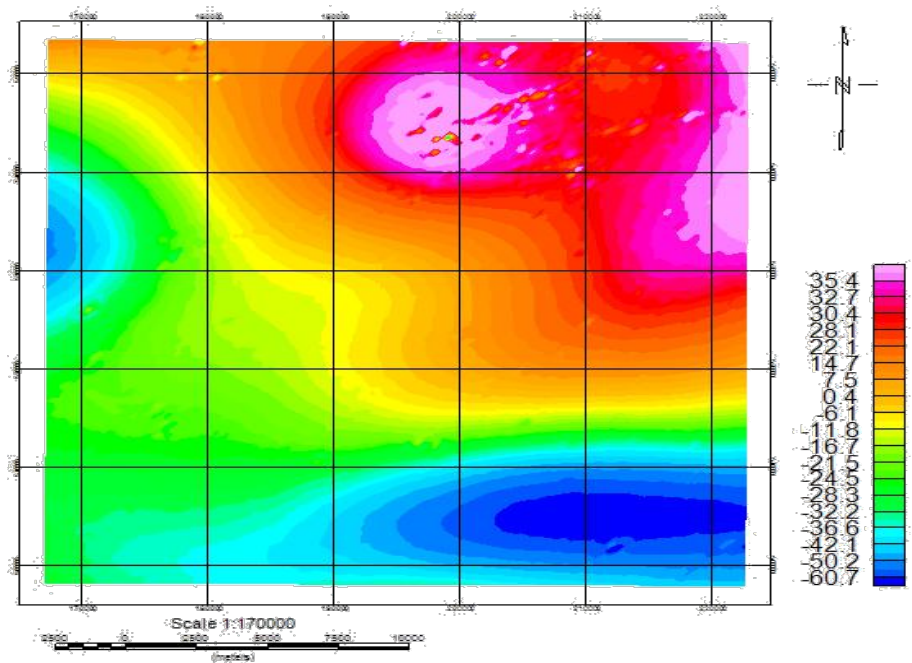


Figure 3. Aeromagnetic map with sheet number 327 covering Olobiri (nT).

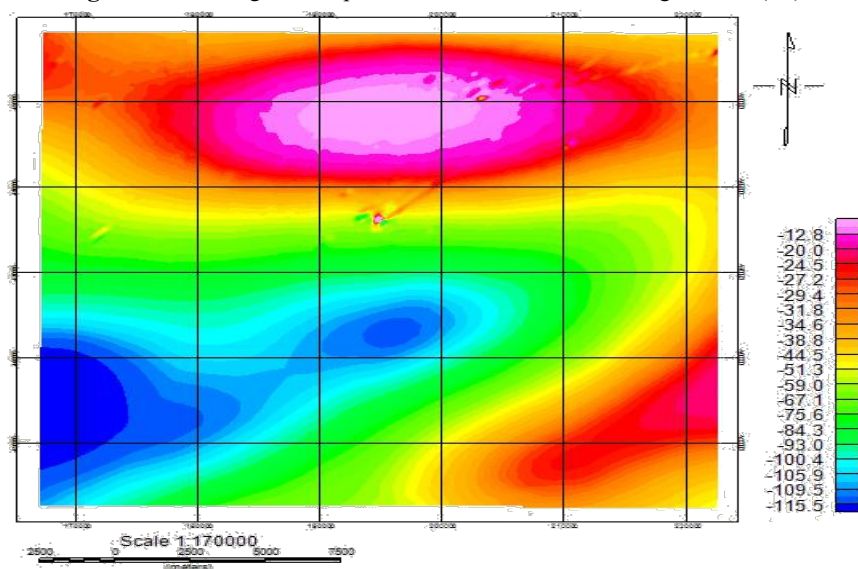


Figure 4. Aeromagnetic map with sheet number 324 covering Brass.

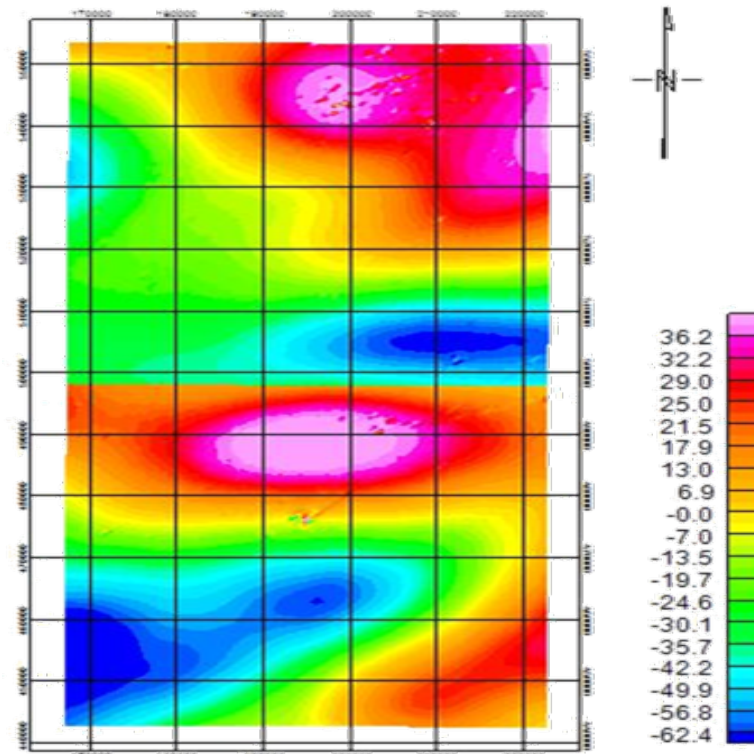


Figure 5. Knitted Aeromagnetic map of the study area.

Data reductions, like diurnal and International Geomagnetic Reference Field (IGRF) corrections, were employed by the agency for proper geological/structural interpretation. The obtained sheet maps are the results of these reductions/modifications. The knitted data were loaded into the Oasis Montaj environment and thus converted into X, Y, and Z channels. While the Z channel displays the primary field, the X and Y channels represent the coordinates. Applying polynomial fitting of the first degree, magnetic anomalies were isolated as regional-residual separation was applied on the Z channel. Qualitative filtering/enhancement techniques were applied to the digitized residual channel generating filtered channels like the first vertical derivative channel, Second vertical derivative channel, and first horizontal derivative channel. Other channels generated are the second vertical derivative channel, upward continuation channel, and reduction to pole channel. This enhancement was vital to improve the visual quality of anomalies of interest.

Each of these channels was transformed into qualitative field maps from which structural interpretations were made.

3.1 Qualitative analysis

For visual inspection of the map, the following separation and filtering techniques were applied.

3.1.1 Regional-residual separation

This is the art of decomposing the deep sources from shallow sources. In this research, this separation is paramount as a result of the data being a resultant contribution of all underground anomalies. The underground anomalies are made up of deep anomalies that are basement-related masking the shallow anomalies found at shallower depth. Empirically, the separation was undertaken by applying the least square polynomial degree of degree one (1) using the X-Utility module of Oasis Montaj.

3.1.2 FIRST VERTICAL DERIVATIVE (FVD)

This filter was executed on the residual data to make apparent high wave number components at the expense of low wave-number components. According to Luis (2009), equation 1 governs the filter.

$$F\left[\frac{d^n \varnothing}{dz^n}\right] = K^n F(\varnothing) \quad (1)$$

Where

$n = 1$, the nth-order vertical derivative

\varnothing = field potential

F = Fourier transform

3.1.3 SECOND VERTICAL DERIVATIVE (SVD)

This derivative improves the visualization of near-surface anomalous impact at the detriment of the effects emanating from deep origin. This filtering was important because those features not seen as FVD was applied were made apparent. This filtering relies on equation 1 as $n = 2$.

3.1.4 UPWARD CONTINUATION (UC)

The earth's field was transformed to a higher datum level as this filter was applied. When this transformation was applied, deep-seated causative sources were discriminated from shallow ones. In this study, residual data were continued upwards at 5 km. Blakely (1996) stated that the filter measured on a level $z = z_0$ at point $P = (x, y, z_0 - \Delta z)$ is governed by the equation:

$$U(x, y, z_0 - \Delta z) = \frac{\Delta z}{2\pi} \iint_{-\infty}^{\infty} \frac{U(x^l, y^l, z_0)}{[(x-x^l)^2 + (y-y^l)^2 + \Delta z]^{\frac{3}{2}}} dx^l dy^l, \quad (2)$$

Applying Fourier convolution to equation 2, we obtained

$$F[U_u] = F[U]F[\psi_u] \quad (3)$$

Where

U_u = Upward continuation at the initial

level

ψ_u = New level upward continuation given as

$$\psi_u(x, y, \Delta z) = \frac{\Delta z}{2\pi(x^2 + y^2 + \Delta z^2)^{\frac{3}{2}}} \quad (4)$$

$F[\psi_u]$ is expressed analytically as in equation 4

$F[U_u]$ = Fourier transform is given as:

$$F[U_u] = e^{-\Delta z|k|} \quad (5)$$

where

$$\Delta z > 0$$

4 Quantitative analysis/processing

Quantitatively, spectral depth modeling was undertaken. The usage of spectral modeling is based on the postulate made by Spector and Grant (1970) that the method is based on the radially averaged power spectrum. Before the power spectrum is computed, the magnetic data has to be transformed using a 2D Fast Fourier Transform. According to Spector and Grant (1970), statistical estimation of the depth to the top and bottom of the magnetic source can be estimated using the power energy spectrum. The Fast Fourier Transform of a potential field data $f(x, y)$ is given by

$$F(k_x k_y) = \iint_{-\infty}^{\infty} f(x, y) n e^{-i(k_x x + k_y y)} dx dy \quad (6)$$

where $k_x x$ and $k_y y$ are wavenumbers in x and y directions respectively measured in radians per unit of x and y.

Quantitative analysis in this research began by windowing the residual into twelve overlapping spectral sections upon which *Fast Fourier Transform (FFT)* was performed. The windows were made to overlap to ensure that no part of the anomaly was missing. Consequently, the signatures were divided into their energy and

wavenumber components as the FFT algorithm was initiated. Log of energy was derived and then used in plotting against wavenumber. From the spectral energy curve, two lines were visually fit based on the steepest and least steep portion of the curve. The first steepest portion represents the depth to the basement while the second but the least steep portion represents the shallow depth. Slopes M_1 and M_2 were obtained as the tangents to the energy curves were taken.

The average depth to magnetic sources is computed from the gradient using equation 7

$$h(f) = \frac{m}{2} \quad (7)$$

where $h(f) = \text{depth value}$

$m = \text{slope}$

The slope is taken after visually fitting the line on the energy curve. Equation 7 gives approximate depth values D_a and D_b , for each of the windows. The M_1 line emplaced on the deepest portion gives a measure of sedimentary thickness within the region. The depth values associated with the steepest portion of the curve are thereafter imported into the surfer environment for the depth to basement contour map to be generated. Thereafter, geological interpretations were read.

5 Results

The composite contour format (Fig. 6) was created from the raster aeromagnetic data (Fig. 5). The consequence of regional-residual separation as polynomial fitting was used is the regional map (Fig. 7) and residual map (Fig. 8). Numerous filtering techniques were used on the residual data qualitatively to expose fine details of the subsurface, and as a result, Figures 9 through 13 were produced. Figure 14 depicts the raster residual map sectioned

into twelve overlapping windows. Upon each of the windows, the Fast Fourier Transform (FFT) was initiated and this generated various spectral energy curves (Fig. 15). Based on the spectral energy plots, two source depth models due to deeper and shallow sources were observed. The deeper depth sources D_a and shallow-depth sources D_b are obtained respectively from M_1 and M_2 . These values are presented in Table 1 which shows the sedimentary thickness values for each window obtained after spectral analysis was performed. By importing D_a into Surfer 10, a basement depth map (Fig. 16) was generated.

6 Discussion

Colour differences showing full and decreased amplitude anomalies can be found on various qualitative grid maps. The full/high anomalies are associated with yellow, magenta, and red colours whereas reduced/low anomalies are linked to the colours, green and blue. On sheet 324, the colour alternates between yellow, magenta, and red in the northern zone and green and blue in the center and southwest region. Immediately after the green and blue amplitude anomalies are the yellow and red anomalous sources. Similarly, colour differences are apparent on sheet number 327. These colour contrasts depict magnetic dominant and recessive zones. Yellow, magenta, and red colours are connected to magnetic high/dominant zones. They are visible on the northern side of the map, whereas magnetic low/recessive anomalies tied to blue and green colours are observed on the southwestern and southern sides. Hence these contrasts in colour indicate that the area is distributed into high (yellow, magenta, and red) and low (blue and green) amplitude zones.

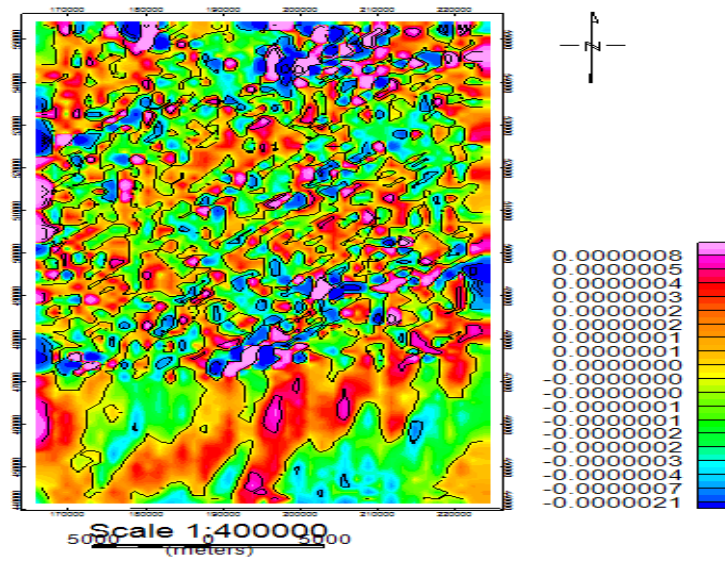


Figure 12. Second horizontal derivative map (nT).

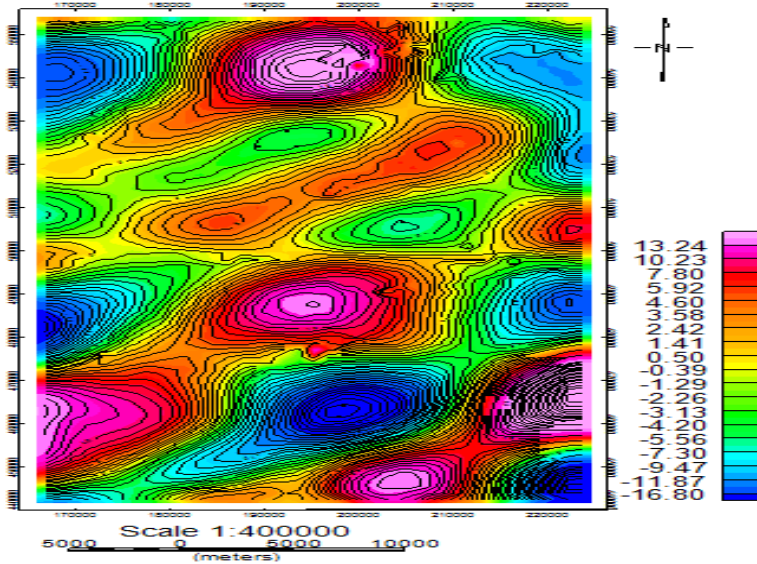


Figure 13. Upward continuation map (nT).

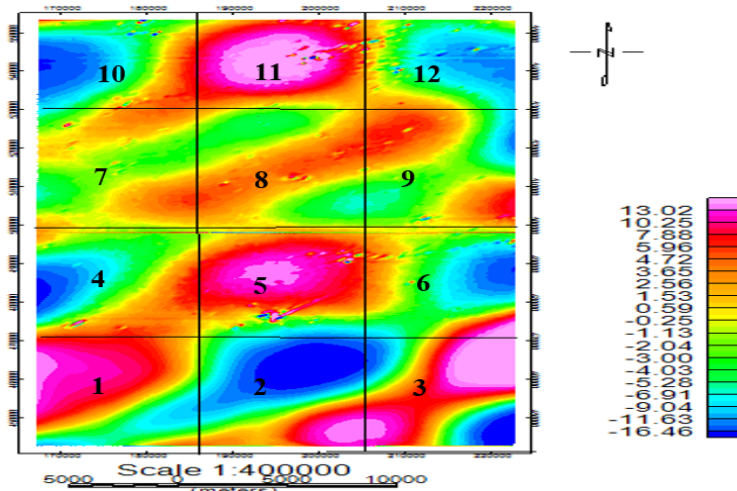
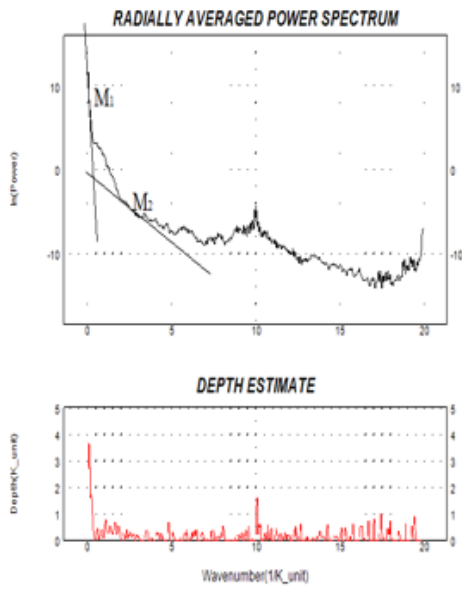
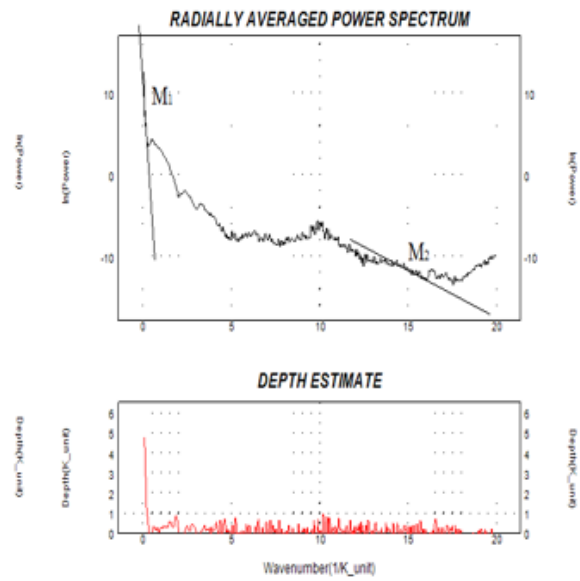


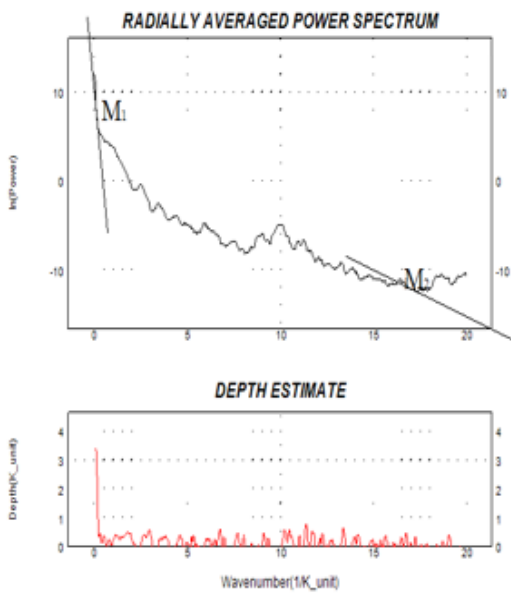
Figure 14. Windowed residual map (nT).



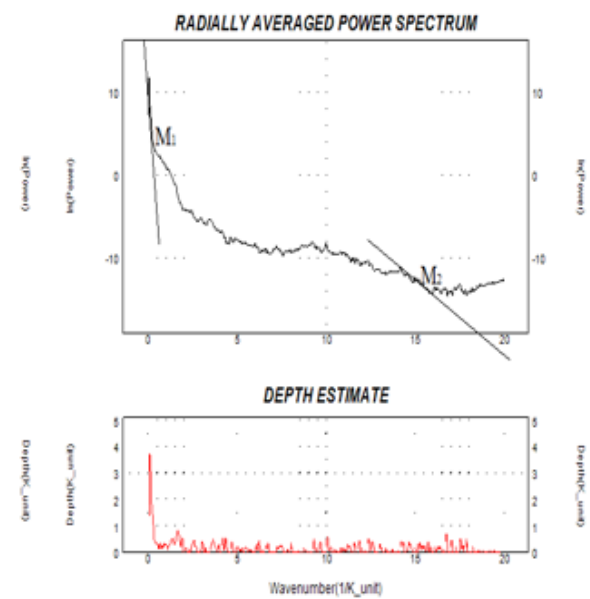
Spectral energy curve for window 1



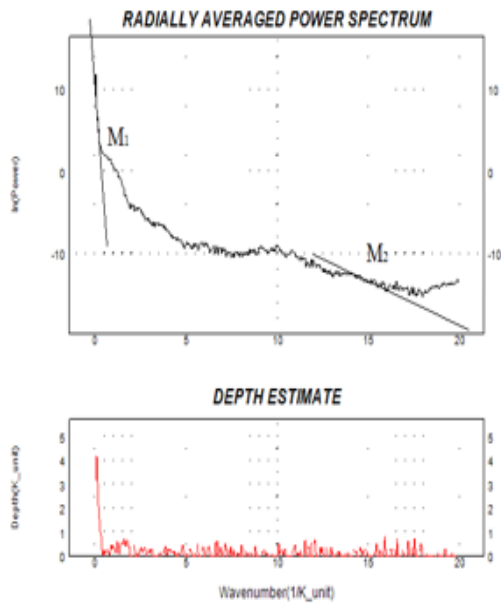
Spectral energy curve for window 2



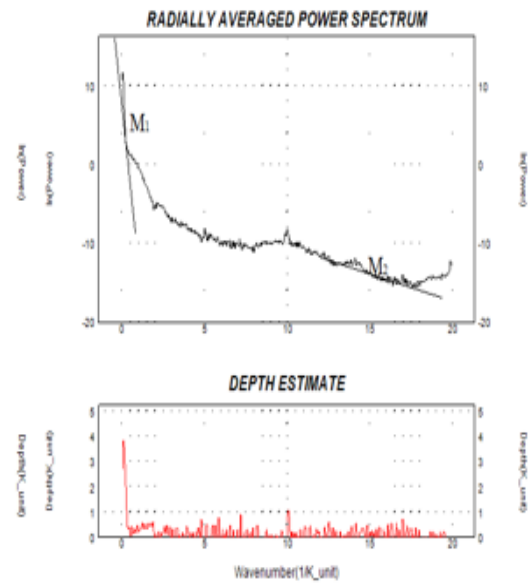
Spectral energy curve for window 3



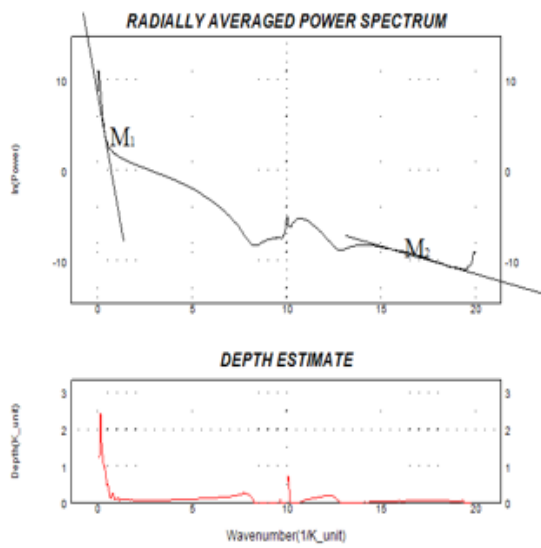
Spectral energy curve for window 4



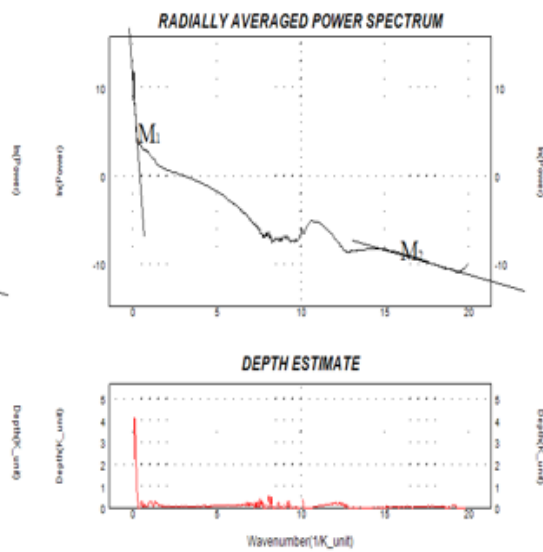
Spectral energy curve for window 5



Spectral energy curve for window 6



Spectral energy curve for window 7



Spectral energy curve for window 8

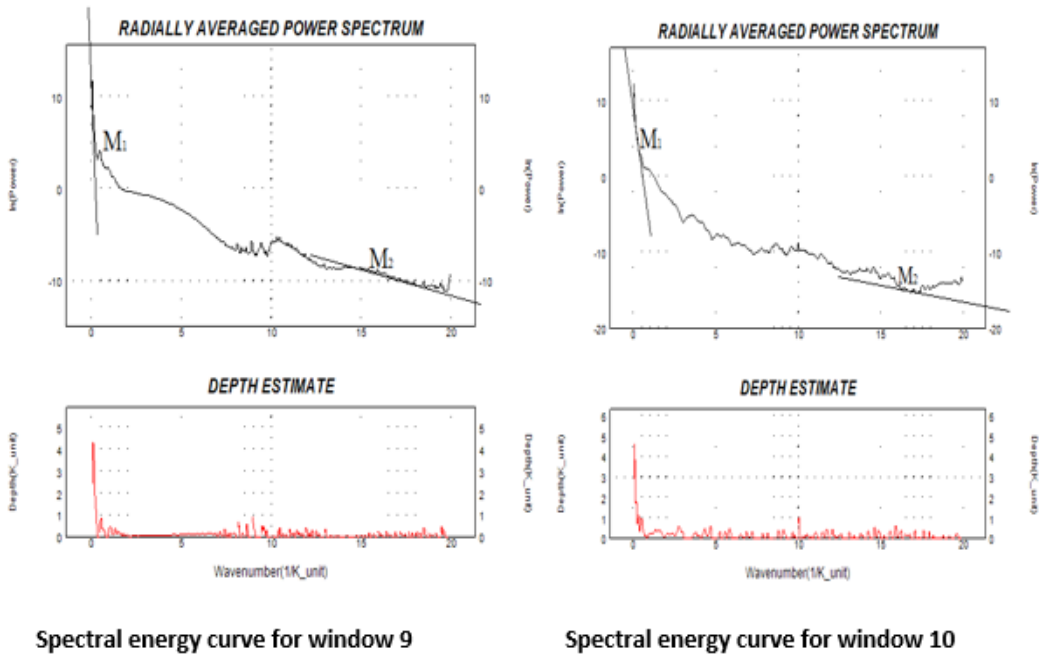


Figure 15. Spectral energy curves for various windows.

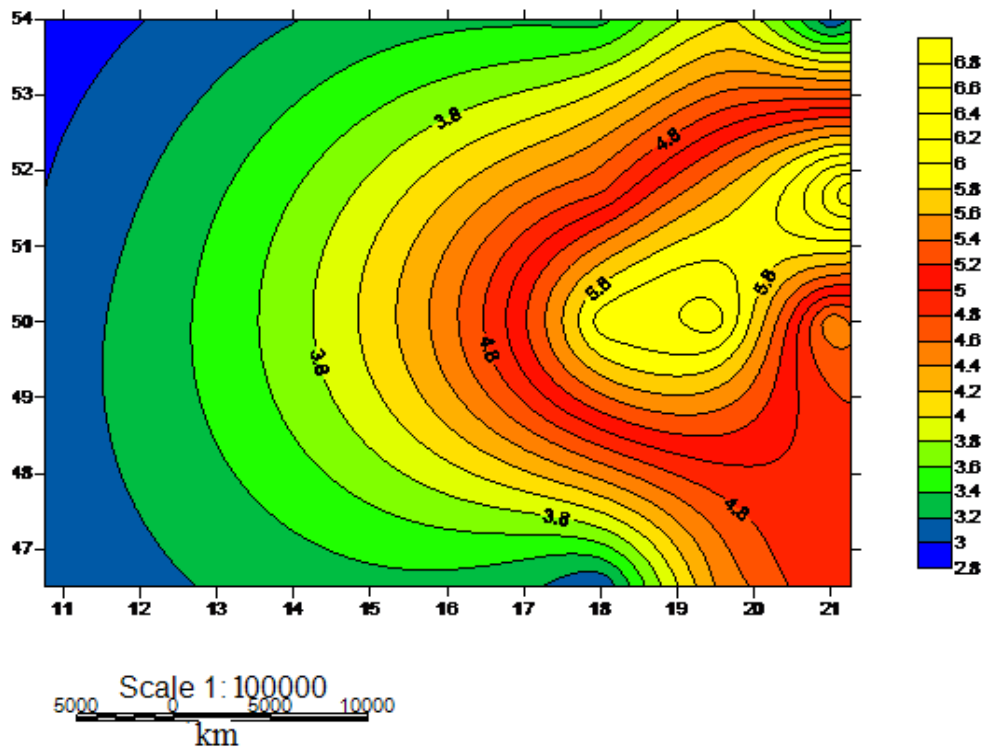


Figure 16. Depth to basement contour map (km).

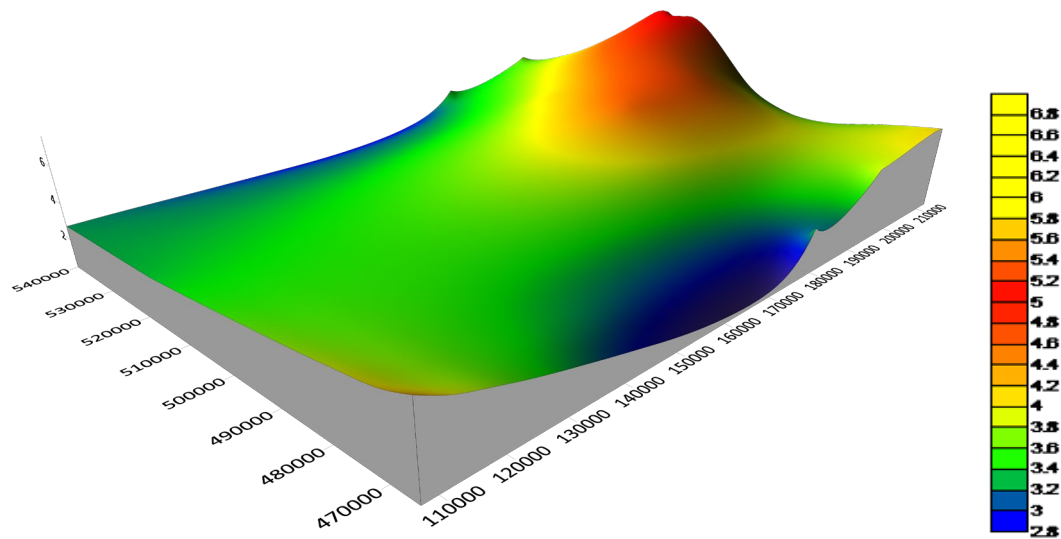


Figure 17. 3D basement depth map.

Table 1. Spectral depth estimates.

WINDOWS	X	Y	SLOPE		DEPTH (km)	
			M_1	M_2	D_a	D_b
1	180000	540000	6.66	2.5	3.33	1.25
2	197500	540000	8	3	4	1.5
3	210000	540000	6	4	3	2
4	180000	517500	9.5	5.6	4.75	2.8
5	107500	517000	9	4.6	4.5	2.3
6	212500	517000	13.6	6.4	6.8	3.2
7	180000	500000	12.2	5.4	6.1	2.7
8	195000	500000	12.6	5.2	6.3	2.5
9	210000	500000	8.86	3.52	4.43	1.76
10	180000	465000	9	4.1	3	2.05
11	195000	465000	8.82	4.3	4.41	2.15
12	210000	465000	9.99	4.8	4.99	2.4

Ali et al. (2012) opined that regions with low amplitude anomalies are sedimentary whereas areas with high amplitude anomalies are related to intrusive/extrusive igneous rocks. It can be inferred therefore that the low amplitude magnetic zones with blue and green colours are magnetically quiet while the regions with high amplitude anomalies are magnetically respondent. These inferences are derived as sedimentary regions have low magnetic sources while igneous zones contain high amounts of magnetic sources.

Magnetic values in sheet 324 range from -115.5 nT to -12.8 nT. These extremely low magnetic values show that the area could be dominated by limestone and shale.

In sheet 327, magnetic intensity readings range from -60.7 nT to 35.4 nT. Comparing this location to the Brass region, the magnetic levels are higher. This is owed to the occurrence of possible igneous intrusive. However, after joining the two data sets covering the research area, it was found that the magnetic anomalies have values ranging from -62.4 nT to

36.2 nT. The knitted aeromagnetic data been the composite data was transformed into its corresponding contour format so that the influence of structural features inside and close to the basement could be examined. The transformation of the raster also aided the identification of deformation patterns linked to the zone. Numerous signatures having elliptical, circular, closely parked, linearly elongated, and spaced geometry are apparent on the map. The majority of the anomalies or signatures have short wavelengths, whereas the remaining ones have extensive wavelengths. While the spaced signatures imply that the sources are located around the basement, the tightly parked signs/contours hint that the sources leading to such signatures are of shallow origin. Signatures having elliptical, circular, and linear elongated orientations hint at the possibility of dyke, seal, and fault fracture zones being found within the area. These sources furnished the magnetization contrast spotted on the map but in the words of Onuba et al. (2011), they stated that Nsikak et al. (2000) opined difference in magnetic susceptibility arises due to the magnetite oxidation to haematite. He further stated that the emplacement of dyke like sources in fractured zones can lead to such magnetization contrast. These features with distinct orientations typify geologic lineaments. The lineaments are ENE-WSW and E-W tectonic trends, with minor NW-SE and NE-SW tendencies. Charcot and the oceanic fracture zone that passes through the Benue Trough itself from the Guinea Gulf are in agreement with the NE-SW and NW-SE tendencies, notwithstanding their slightness.

The anomalous trend is a reflection of subsurface lineaments guiding geologic activities. These trends do serve as a conduit for fluid migration. Positive and negative anomalies are evident beside the legend of the composite map. Negative values show that the zone in question is mag-

netically subdued while the positive values show that the zones are magnetically operational. Nsikak et al. (2000) hinted that positive anomalies mean that the field strength is thus, higher than the regional, hence the presence of hidden ore, while the negative values suggest that the field strength is lower than the regional. The shallowly connected sources or residuals that are positioned on the regional or deeply rooted features make up the composite knitted map. Consequently, the regional-residual separation was necessary. Conspicuous on the regional map is smoothed and long wavelength anomalies whose values are from -66.4 nT to 34.6 nT. The smoothness and long wavelength of the anomalies/signatures trending E-W, and ENE-WSW suggest that the sources causing these anomalies are of deep origin. On the southern and eastern sides of the regional map, a nearly oval blue contour can be noticed. The regional map center shows linear elongated characteristics. Linear elongated signatures are seen in the central area of the regional map. The residual data are the results of subtracting the regional values from the total field values. Closely packed signatories are visible on the residual data. This proves that the anomalies with values ranging from -16.5 nT to 13.0 nT emanate from sources that are of shallow origin. The configuration of anomalies/contours is majorly elliptical, hence the dominating occurrence of dykes that foster the entrapment of economic fluids. Recessive NE-SW and NW-SE tectonic trends symbolize lithology boundary patterns linked to the Charcot fracture. Half of the residual map towards the south is smooth, unlike half of the data towards the north. This is an indication of high basement undulation comprising synclines and anticlines within the north. Also, noisy geologic sources that are of deep origin occurring shallower can cause the anomalies to be irregular. The tectonics of the region, fault lines, and lineament zones are all clearly expressed on

the map by signatures with ENE-WSW, E-W, NE-SW, and NW-SE lithologic boundary trends. Anomalies with positive and negative numbers are obvious on the legend beside the map. The positive values denote volcanic rocks while negative values express sedimentary rocks/zones.

The first vertical differential map depicts closely positioned signatures/anomalies that are broadened and relatively irregular. The closeness of the signatures indicates that the causative signatures are shallowly related whereas the broad nature implies that the sources are of a large extent. The relatively irregular nature indicates little differential in the basement. However, the anomalies are between -0.002240 nT and 0.001747 nT. The second vertical-derived map shows blurred anomalies with values between 0.000012 nT and 0.000006 nT. The anomalies are oriented NE-SW.

The close-parking of signatures makes it difficult to distinguish irregularities in the horizontal direction at first glance. On the first horizontal derivative map, the anomalies range from -0.002397 nT to 0.001993 nT, while on the first vertical differentiation map, they are configured similarly. When the anomalies' derivative was horizontally taken from the first order to the second order, short wavelength contours and anomalies were clearly visible. The NE-SW-oriented anomalous values range from 0.000002 to 0.000001 nT. In contrast, the continued upward map shows smooth near contours, similar to other qualitative field maps listed above. At 10 km, the upward continuation map pronounces anomalies that are relatively deeply seated. Nevertheless, the anomalies have NE-SW directional trends. This is seen within the northwestern and south-eastern portions.

The depth due to the deeper sources varies from 3 km to 6.8 km but with a 4.5 km average depth however the shallow causes are emplaced between 1.5 km and 3.2 km, with a 2.2 km true depth. The

depth to deeper sources measures the true sedimentary thickness within the area while the shallow depth sources are connected with igneous intrusions, adjacent disparities in susceptibilities of the basement, and intra-basement structures like faults and fractures. The thickest sediment can be located in window 6 while the thinnest sediment is found in windows 3, 5, and 10. The result obtained conforms to the hydrocarbon exploration implication of the region, in that the thickness values encountered make hydrocarbon exploration feasible if other conditions are met. In a recent study, Eke et al. (2022), significantly obtained an average sedimentary thickness of about 6.6 km using Source Parameter Imaging (SPI) and spectral analysis of aeromagnetic data covering the Niger Delta eastern domain in Nigeria. Lebo and Obi (2017) undertook sedimentary thickness estimation using spectral analysis, Euler Deconvolution, and Horizontal Gradient Method (HGM). They discovered depth values of 4.2 km using spectral analysis, 6.421 km using Euler Deconvolution, and 4.0 km using HGM. Eke and Okeke (2016) obtained basement depth using 3D Euler Deconvolution. Their results showed that the maximum basement depth is between 9.6 km to 10.6 km. Keen inspection of the basement depth map indicates that the maximum thickness is discernible in the eastern region while the minimum thickness appears toward the western portion of the map. Thus, the thickness of sediments thins from the east towards the west. This suggests that the eastern part has greater plausibility of hydrocarbon exploration when other conditions are taken good care of. The hydrocarbon exploration ability of the eastern region is further justified by the presence of almost elliptical and semi-elliptical signatures identified in the region. These signatures are possible dykes that trap hydrocarbon or any other mineralized fluid within the areas. On the 3D basement map showing the basement

shape and size, magnetic highs and lows are apparent. A hollow magnetic low which is a possible exploration site is formed within the southeastern region. Complex basement undulation is absent due to the region being a sedimentary terrain.

6 Conclusion

NE-SW, NW-SE, and E-W lineament patterns were qualitatively observed to characterize the architectural framework of the area. The NW-SE and dominant NE-SW are onward extensions of the oceanic fracture zones traversing from the Bight of Biafra. The tectonic trends show that the area is characterized by faults, folds, dykes, and oceanic fracture zones. These features foster hydrocarbon migration and entrapment. These trends also explain the occurrence of magmatism and rifting during Pan African Orogeny.

Two depth models D_a and D_b quantitatively exist in the area. The D_a relates to the basement and thus identifies sedimentary thickness. D_b shows depth to possible shallow intrusive and regional faults within the area. D_a lies between 3 km and 6.4 km with 4.5 km average depth whereas D_b lies from 1.25 km to 3.2 km with an average depth of 2.3 km. The sedimentary thickness is similar to that of the boarding segment which is important to hydrocarbon generation potential. The obtained depth values fall within the acceptable thickness favorable for hydrocarbon accumulation or presence within an area. There should be more focus on hydrocarbon investigation in the Oloibiri zone of the area as the thickest sediments were found there. This study by using the aeromagnetic method was able to justify the existence of appropriate sedimentary thickness within the area. These results validate the results of other researchers who applied seismic and borehole techniques within the area.

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Statements and declaration

Competing of interests: The authors declare that no competing interest of any kind will the publication of this work.

Authors Contribution

NCN and EJM conceived the initial idea of the study, prepared the manuscript, and made corrections after proofreading. OCC did the analysis and interpretation. All authors read and approved the final manuscript.

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