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ARTICLE

Aeromagnetic Interpretation of Basement Structures and Geometry in Parts of the Middle Benue Trough, North Central, Nigeria

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ARTICLE INFO

Article history
Received: 8 October 2022
Revised: 9 November 2022
Accepted: 18 November 2022
Published Online: 30 November 2022

Keywords:
Aeromagnetic data
Euler deconvolution
Basement structures
Hydrocarbon potentials
Middle Benue Trough

ABSTRACT

The research of an analysis of aeromagnetic data collected in the middle Benue Trough in north-central Nigeria is presented. A detailed analysis of basement structures is conducted in order to identify regions with high hydrocarbon potential that is different from those discovered by earlier researchers. Aeromagnetic data were filtered by using the Butterworth and Gaussian filters, transformed by engaging the reduction to the equator technique, and subsequently enhanced. To estimate magnetic basement depths at various places throughout the basin, the Euler deconvolution depth weighting approach was used. Eleven (11) sub-basins with depths ranging from –2000 m to –8000 m were also identified by Euler's findings. The sub-basins trend in the NE-SW direction while the average sediment thickness is found to be more than 3 km. The extracted structural features indicate areas like Kadi Blam and Kado areas in the southeastern part and Ogoja and Obudu in the southern part of the study area as regions with high structural densities. These areas coincide with the areas delineated as the sub-basins. The cross-sections generated reveal depressions caused by the action of some tectonic activities in the area. This study identified undulating basement topography believed to be due to tectonic activities as well as five areas that are possible targets for hydrocarbon exploration.

1. Introduction

Petroleum (oil and gas) has been discovered to be a major source of the nation's revenue generation since its discovery in large quantities in 1956. Abubakar [1] discovered that at least two potential petroleum systems may be found in Nigeria's Benue trough; namely (i) the lower cretaceous petroleum system which is capable of producing oil and

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DOI: https://doi.org/10.30564/agger.v4i4.5128

gas (ii) the upper cretaceous petroleum system which was inferred to generate mainly gas which made them very reliable in conducting future exploration research in the basin. The Benue Trough is an inland coal-bearing region with extensive hydrocarbon exploration. Despite geoscientists' tireless work over the last two decades to maximize the middle Benue Trough's hydrocarbon potential, there is still more to be found. This study intends to carry out a detailed interpretation of basement structures in parts of the middle Benue Trough in an attempt to discover areas of high hydrocarbon potentials different from the ones that have been discovered by earlier researchers. The aim is to assess the possible occurrence of fundamental hydrocarbon potential parameters (such as reservoir thickness) that could serve as a guide to further research and subsequent exploratory work in the basin. The aeromagnetic survey is an effective method for determining the regional geology (lithology and structure) of the buried basement area. When the geology of the examined area is well understood, the precise aeromagnetic map has proven to be quite useful [2]. Moreover, aeromagnetic surveys help to investigate the depth of magnetic basement rocks in the sedimentary basin. Major basement features are identified using an aeromagnetic survey, revealing promising exploration areas that can be further investigated using the more expensive but more concise and specific seismic approach of geophysical investigation. Intensive geophysical research has been conducted in various regions of the Benue Trough for quite some time. Falconer [3] was the first to report on work done in Nigeria's middle Benue Trough and also recently by Kasidi and Ndatuwong [4]. He wrote on the geology of the basement and the Chad basin nearby. According to him, the Asu River Group contains the middle Benue's earliest sediments. He later coined the term "Lower Shale" to describe this group. Cratchley and Jones [5] were the first to conduct a major geophysical survey in the Benue and also reported by Abubakar [1]. The majority of the articles published on the subject were regional. Many geologists, however, have mapped the area [6]. Ehinola [7] examined the middle Cretaceous black shales for hydrocarbon source potential, thermal maturity, and depositional environment using organic facies features. He also conducted detailed geological mapping and geochemical analyses of the Abakaliki anticlinorium's oil shale deposit to establish its extent, resource estimation, recovery strategies, and potential environmental consequences. Obi et al. [8] investigated the effects of subsurface intrusive on hydrocarbon appraisal in the Lower Benue Trough using aeromagnetic modeling. In the locations near Nkalagu, Abakaliki, IkotEkpene, and Uwet, they discovered 12 intrusive bodies with sediment thicknesses ranging from 1.0 km to 4.0 km. He concluded that these intrusives have adequate sediment thickness (more than 2 km) to generate hydrocarbons. To identify probable petroleum systems in the Nigerian Benue Trough and Anambra Basin, Abubakar [1] conducted an assessment of the geology and petroleum potentials of the basins. He discovered that the basins could have at least two potential petroleum systems: The Lower Cretaceous petroleum system, which could generate both oil and gas, and the Upper Cretaceous petroleum system, which could generate mostly gas. He observed that the systems are similar in temporal disposition, architecture, sources, reservoir rocks, and maybe generation mechanism to those found in Sudan's Muglad Basin and Niger and Chad Republics' Termit Basin. Likkason et al. [9] conducted a study on the Nigerian middle Benue Trough based on geological applications and analysis of the aeromagnetic data spectrum. The radial spectrum and the field's matched filtered output are compared, and the results of the plot of the log radial spectrum versus the frequency numbers revealed five discernible linear segments with depths corresponding to magnetic layers ranging from 20.62 km (highest) to 0.26 km (lowest). Patrick et al. [10] compiled a stratigraphic report for the middle Benue Trough in Nigeria, based on petrographic and structural analysis of the Abuni and environs formations, which are part of the late Albian-Cenomanian Awe and Keana formations. Bedding, lamination, huge bedding, graded bedding, mud cracks, cross-bedding, folds, and joints were among the formations they discovered on the field. The principal structural tendencies are directed in the following directions: NE-SW, NNW-SSE, WNW-ESE, and NW-SE. Hornblende, plagioclase feldspar, olivine, and accessory minerals, which include opaque minerals and are thought to be iron oxides due to the high concentration of iron in almost all of the samples, are among the mineral suites identified from the thin slice of the volcanic.

1.1 Location of the Study Area

The study region is located in Nigeria's middle Benue Trough, between latitudes 07°00'N and 09°00'N and longitudes 08°00'E and 10°30'E covering about 39027 km^2. It covers Markurdi, Tanka, Logo and Gboko towns in Benue State. The study area also includes the Wakuri and Donga areas of Taraba State. The study area also includes Nassarawa State's Lafia, Doma, and Awe regions (Figure 1). Bali is to the east, Apa is to the west, Bokkos is to the north, and Vandeky is to the south. The Gboko road in the southern section provides access to the research area. Other minor roads link the smaller interior villages to the major road. The major roads are tarred while the minor roads are best graded and may not be accessible at the peak of the rainy season.

1.2 Drainage

It is traversed by the Benue River, which is the largest in the study area (Figure 1). It comes from the Adamawa Plateau in northern Cameroon. It enters Nigeria from the south, passing through Garoua and the Lagdo Reservoir on its way to the Mandara Mountains. It then travels through Jimeta, Ibi, and Markurdi before arriving in Makurdi on the Niger. The NE-SW lineaments appear to direct its path. These rivers have a significant flow difference between peak flow (usually at the end of the rainy season) and ebb flow (at the end of the dry season), when they are reduced to a trickle. Their banks provide in the dry season, very good exposures of the shale units otherwise hidden in other locations. Other smaller streams are also controlled by the ridge and swale topography giving a rough trellis drainage pattern.

1.3 Climate and Vegetation

The study area has a warm tropical climate with relatively high temperatures (27 °C on average) all year and two seasons: The rainy or wet season, which runs from March to November in the south and May to October in the north, and the dry season, which runs the rest of the year. The rainy season is divided into two periods of high rainfall, separated by a brief time in August that is comparatively dry (the August break). The study area has evolved Guinea savannah with a relict forest as its vegetation. Originally, this region of the high woodland was the drier part. Most of the high forest trees were destroyed due to bush burning and overgrazing, cultivation, and hunting activities in the area over a lengthy period, and the forest was replaced with a mixture of grasses and dispersed trees.

1.4 Geologic and Tectonic Evolution of the Benue Trough

The Benue Trough is one of Africa's most significant rift structures, and it is thought to have been produced during the Cretaceous by rifting of the central West African basement. The circumstances that led to the development of the Benue Trough and its constituent subdivisions have been thoroughly chronicled [11-17]. The Nigerian Benue Trough (Figure 1) is an intracontinental basin that runs from north to south in Central Africa.

It has a length of over 1000 kilometers and a breadth of over 150 kilometers Its southern outcropping limit is the northern boundary of the Niger Delta Basin, while its northern outcropping limit is the southern boundary of the Chad Basin, which is separated from the Benue Trough by the "Dumbulwa-Bage High", an anticlinal structure [18]. The Benue Trough has up to 6 kilometers of Cretaceous deposits, some of which are volcanic. It's part of the West and Central Africa Rift System, a mega-rift system that spans the continent (WCARS). The WCARS includes Niger's Termit Basin and western Chad, southern Chad's Bongor, Doba, and Doseo Basins, the Central African Republic's Salamat Basin, and Sudan's Muglad Basin.

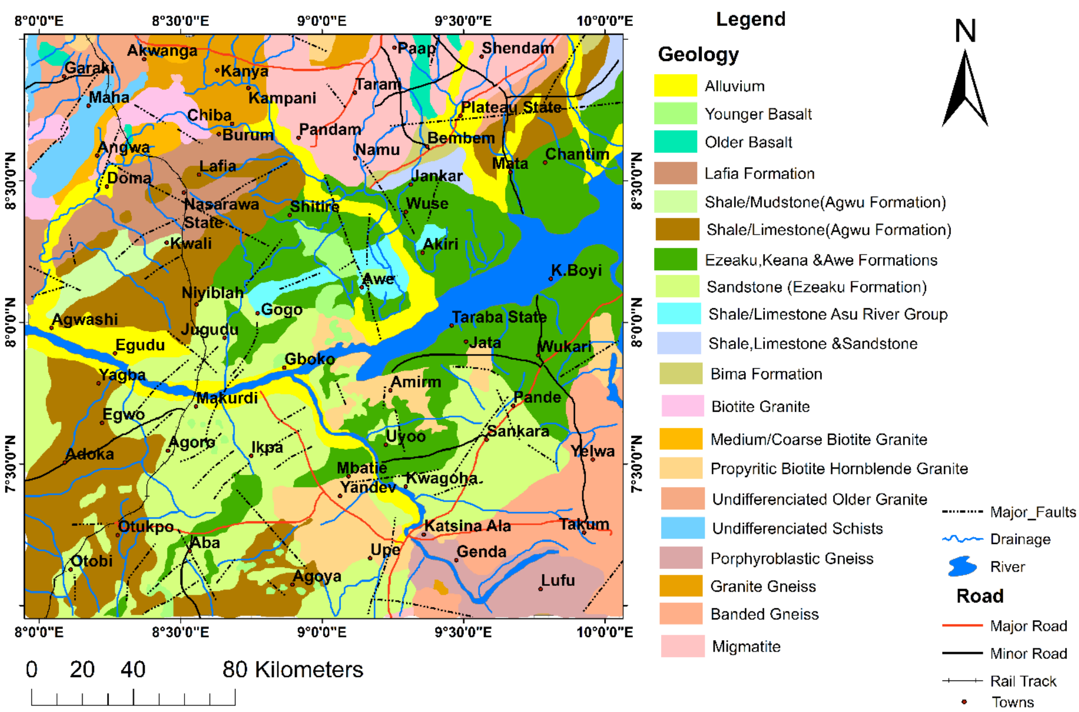

Figure 1. Geology map of Benue Trough.

1.5 The Middle Benue Trough

The Middle Benue Trough stretches northeastward as far as the Bashar-MutumBiyu border.

The Gombe and Keri-Keri Formations reach their southern limit at this point, while the Upper Benue Trough's earlier sediments undergo lateral facies shift.

1.5.1 The Structure of the Middle Benue Trough

The middle Benue Trough's axial basement high [19], (Keana ridge) coincides with the Keana anticline, which runs NE-SW. Benkhelil [13,20] used gravity and aeromagnetic data to locate the high sedimentary sub-basin on either side of the basement. A minor "Shendam Basin" and a more important "Kadarko Basin" with sediment thicknesses of 2.4 km to 5.3 km on the south-eastern flank, and a "Wukari" and a MutumBiyu Basin with inferred sediment thicknesses of 1.9 km to 3.8 km on the north-western flank. The Cretaceous era produced the middle Benue Trough (Figure 1).

1.5.2 The Stratigraphy of the Middle Benue Trough

The middle Benue Trough encompasses the research area. Several scholars have written about the geologic succession in the middle Benue Trough [5,6,21-23]. The middle Benue Trough is split into six (6) formations, according to these scholars.

1.5.3 Hydrocarbon Potential of the Middle Benue Trough

The Central Benue Trough is a valley in central Benue. The shales and limestones of the marine AlbianAsu River Group (Gboko, Uomba, and Arufu Formations) could be potential source rocks, the sandstones of the Cenomanian Keana and Awe Formations could be potential reservoirs, and the shales of the basal Ezeaku Formation could act as a regional seal in the possible Lower Cretaceous Petroleum System in the Central Benue Trough [24]. Because organic geochemical data on the potential petroleum source rock (Asu River Group) for this system is scarce to non-existent, the author was unable to obtain any raw data on organic matter quantity or quality. Obaje et al. [24] suggested that values over 1.25 percent indicate late gas window stage to over maturity on maturity. The Asu River Group could be up to 1800 meters thick on average [24]. Flaggy medium coarse-grained calcareous sandstones and fluvial-deltaic cross-bedded coarse-grained feldspathic sandstones, respectively, are prospective reservoir rocks in the Awe and Keana Formations. In certain locations, the Awe Formation can be 100 meters thick. These formations are particularly important to water aquifers surrounding Keana and Awe, despite the lack of reservoir quality data.

2. Materials and Methods

2.1 Data Acquisition and Instrumentation

Fugro Airborne Surveys Limited gathered aeromagnetic data on behalf of the Nigerian Geological Survey Agency as part of a nationwide high-resolution airborne geophysical survey aimed at supporting and promoting mineral exploitation in Nigeria (NGSA). The data were gathered methodically by dividing the country into segments (blocks) with different measurement parameters for each block, with the result being the creation of an aeromagnetic map of the entire country. Three Scintrex CS-3 Cesium Vapour Magnetometers were utilized to collect data during the survey. The data were obtained at a nominal flying altitude of 152.4 meters along two N-S flight lines that were about 2 kilometers apart. The magnetic data were compiled into 12-degree aeromagnetic maps with a scale of 1:100,000. For simple reference and identification, the maps were numbered, and place names and coordinates (longitude and latitude) were written. Before plotting the contour map, the real magnetic data were scaled down by 25,000 gamma. All of the maps have an epoch date of January 1, 1974, and a correction based on the International Geomagnetic Reference Field (IGRF). The National Geographic Society of America (NGSA) published a report in 1974 on the subject of Fixed-wing (Cessna) aircraft also took part in the survey, which covered a total of 235,000 line kilometers with a flight spacing of 200 meters and terrain clearance of 80 meters. The flight was headed NW-SE, with a 200-meter tie-line spacing and a NE-SW tie-line orientation. The flight line and tie-line trends were 135° and 45°, respectively, and the magnetic data recording interval was 0.1 seconds. Within UTM Zone 36S and using the Clark 1880/Arc 1960 coordinate system, a grid mesh of 50 meters was used in the World Geodetic System of 1984 (WGS84). The followings are the sources of information used in this study:

(i) Aeromagnetic grid covering sheets 209-213, 230-234, 250-254, and 270-273 making a total of 19 sheets.

(ii) Oasis Montaj Software;

(iii) Surfer 13 Software;

(iv) Geological map of Nigeria (soft copy) (iv) Lineament map of Nigeria (soft copy).

2.2 Data Processing

In a defined coordinate system, digitized data were gridded into an evenly spaced lattice. Interpolating data taken along with parallel profiles but at random places along the profiles was done using the minimal curvature gridding approach. Using Briggs' method, this method fits minimal curvature curves to the data point (which is the smoothest possible surface that would suit the supplied data values) [25]. Because the data collected in the field are a mix of signal and noise, it must be processed to remove the undesirable information that could lead to erroneous subsurface interpretation. Data processing's overall goal is to reduce noise and improve the signal-to-noise ratio. To achieve this purpose and obtain a refined dataset, the following filters were used.

2.2.1 Combined Gaussian and Butterworth

These two filters were used to reduce the impacts of the regional anomaly on magnetic bodies (a model of the earth's core field based on the I.G.R.F. epoch date of data acquisition: 1st January 1974) [26]. Following the I.G.R.F reduction technique, the Butterworth filter, which is a low-pass filter, was used. This was used to remove regional impacts from total magnetic intensity data by removing all frequencies over the cut-off frequency and leaving those below unaltered. The fitting method generates a surface (called the regional field) that has the best fit to the magnetic field.

2.2.2 Data Transform

Because the study area is at a low magnetic latitude, and the Earth's field intensity decreases from the poles to the equator, peaks of magnetic anomalies are likely to be incorrectly or improperly positioned over their sources, as well as skewed along a particular direction, usually visible as abnormal elongation of anomalies along the E-W direction, this filter was used in the Fourier domain to migrate the observed field from the observed magnetic inclination and the observed magnetic inclination. The study site has a low magnetic equator of about 150, which can make anomaly interpretation difficult if not corrected. The peaks of magnetic anomalies are centered over their sources in this operation.

Any asymmetry in the reduced-to-equator field can then be attributed to source geometry and/or magnetic properties, which helps with interpretation. With a declination of –3.50, an inclination of –14.70, and a field strength of 31533.7 nT, the data were reduced to the magnetic equator. Reduction to the magnetic equator filter was applied to the magnetic intensity data to center the peaks of the magnetic anomalies over their geologic sources by recalculating the total magnetic intensity data as if the inducing magnetic field had a 900 inclination and transforms dipolar magnetic anomalies to monopolar anomalies centered over their causative bodies, simplifying the resultant aeromagnetic map, which bears a simple and direct relationship with t [27].

2.2.3 Data Enhancement

Horizontal Derivative: To refine the edges of magnetic anomalies and better determine their positions, derivative filtering techniques are applied [28]. This filter was employed to increase deep-seated abnormalities to see a sharper picture of them, thereby isolating magnetic anomalies near the surface. This filter was used to construct two maps, one in the x-direction and the other in the y-direction. As a result, high-frequency variations in potential field data are amplified. Faults and/or geological unit borders could be the source of such fluctuations [29]. This technique employed an order of differentiation of 1 because higher values would result in noise amplification. This filter also decreases the intricacy of anomalies, allowing for better imaging of the causal structures. The upward continuation filter was employed to investigate the regional propagation of the inherent anomalies. At 2 km altitudes, the anomalies' trending trends were compared. The analytic signal was gathered to create an analytic signal map of the study area, which is normally determined by a combination of horizontal and vertical gradients of the magnetic anomaly [30]. The resulting map delineated the forms and boundaries of the geologic sources that caused the anomalies.

As a result, the magnetization map was utilized to pinpoint the magnetic bodies (as well as their boundaries) that were responsible for the observed magnetic anomalies as shown on the magnetic intensity map [30]. To map the shallow basement structures and mineral exploration sites, the tilt derivative was applied [31]. The tilt angle's amplitude is positive over magnetic sources, crosses through zero at the source's near edge, and is negative outside of the source. The signatures of the linear structures were used to identify them. The structures that were continuous were not were identified by a comprehensive examination of the structures. The orientations of the mapped lineaments were also detected by this filter. Where VDR and THDR are the first vertical and total horizontal derivatives of the total magnetic intensity T, respectively. In the initial stage of this process, the standard deviation approach was applied. The method creates a smoother representation of the degree of unpredictability, which eliminates the data's intrinsic noise.

$$\mathrm{TDR} = \tan^{-1}\frac{VDR}{THDR} \quad (1)$$

as proposed by Verduzco et al. [31], where VDR and THDR are the first vertical and total horizontal derivatives, respectively, of the total magnetic intensity T.

The standard deviation method was used in the first phase of this process. The method provides a smoother representation of the degree of randomness that overcomes the inherent noise in the data.

$$\sigma = \sqrt{\left[\frac{1}{N\sum(x_i - \mu)^2}\right]} \quad (2)$$

where σ is the standard deviation.

The smallest wavelength filter employed was 5, the robustness was 3, and the orientation was all-encompassing, with a total of five filter scales. The resulting map depicts the lineaments' orientation. The structural complexity map was created to help discover locations with a high density of junctions. It also uses the standard deviation principle to create a database with straight line segments. The localized junctions were chosen using a contact voting influence of 3 and the orientation entropy was then calculated for all directions.

The vectorized standard deviation grid was used as the input grid to create this map. The proximity was set to be within 5 cells, the angle of deviation was set to be greater than 300, the contact voting influence radius was reduced to 3 (to pick localized junctions), the window size was 20 cells, and the entropy bins were set to 6. The obtained map from the Euler deconvolution plot was used to identify the sub-basins in the study area.

The total magnetic field measured at a point (*x*, *y,* and *z*) due to a point/line source located at *x*0, *y*0, *z*0 can be expressed as

$$(x - x_0)dF/dx + (y - y_0)dF/dy + (z - z_0)dF/dz = N(B - F) \quad (3)$$

as proposed by Milligan et al. [32], *N* is Euler's structural index, and B is the whole field's regional value. It's an exponential factor that represents the pace at which a source's field diminishes with distance for a certain geometry. *N* is the source geometry's prior information input. For geologic contact, *N* = 0.0, 1.0 for dike, 2.0 for horizontal or vertical cylinder, and 3.0 for magnetic sphere. The Euler deconvolution algorithm was used in this study to determine the location and depth of causative anomalous bodies from gridded aeromagnetic data using Oasis Montaj TM. The resulting map depicts the locations of geologic sources as well as their estimated depths.

In addition, profiles were used to determine the depth of the magnetic basement using Extended Euler deconvolution. This is consistent with Reid et al.'s findings [33]. The Windowing Technique was used to refine the resulting answers and decrease uncertainty to the bare minimum. This was achieved by constraining the obtained Euler deconvolution solutions to accept a maximum depth limit of 10000 m, maximum % depth of tolerance of 10%, thus depth uncertainty (*dz* in %) greater than 10% were rejected. Similarly, horizontal uncertainty (*dx* in %) was set to 20%. This assigns masks to solutions with outcomes outside the chosen window [34]. To identify the depth of the magnetic source, processed aeromagnetic data was applied to Euler's deconvolution algorithm [33,35-37]. Deconvolution was done using both conventional and Located Euler techniques. The traditional technique looked at every grid position and kept only those with good solutions, whereas the localized method calculates the analytic signal, discovers peaks in the analytic signals, and then uses the determined locations for Euler deconvolution. The latter offers a benefit over the usual method in that solutions are only approximated over anomalies that have been identified, resulting in more accurate results [30]. Because the Euler plot depicts the spatial distribution of depth to magnetic sources across the entire area, regions with significant depths were isolated for further investigation. Furthermore, the depths of these isolated regions ranged from 3 km to 8 km, which aided in the selection process. This method is preferred over others because of its unique ability to produce credible results even when the geological model is incorrectly/inappropriately represented. It can also generate solutions in areas where there are no anomalies or at their edges.

2.3 Generation of 2-D and 3-D Models

The final step in properly visualizing the sub-basins shown by the Euler deconvolution graphic was the creation of the 3-D model. This was accomplished using the Surfer 13 program. The Euler deconvolution method generated over 120,000 solution sets, which were then exported into the Surfer worksheet. Each solution set's longitude (easting), latitude (northing), and depth to the top of the magnetic source (Z) were recorded in the three-column set utilized in the Surfer worksheet. The data was first gridded, and then the model was built. Smoothing and de-peaking techniques were used to improve the model further A contour map was created using Surfer 13 software and the above-mentioned gridded data collection. A 2-D profile was generated for each of the suspected sub-basins by drawing four profile lines across them. The geography of the magnetic basement was represented considerably more clearly in each 2-D model, which was exhibited as a cross-section (Figure 2).

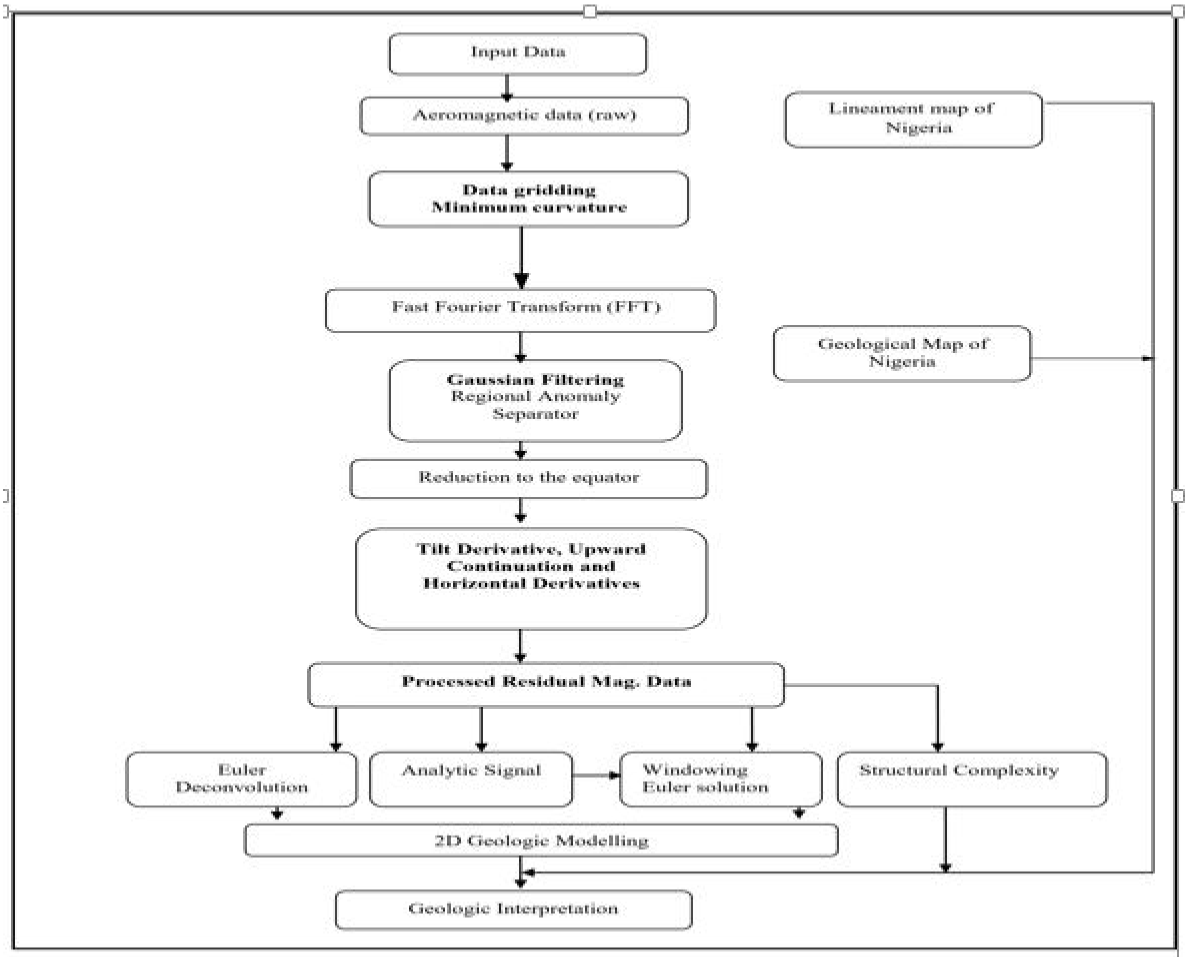

Figure 2. Simplified flow diagram of aeromagnetic data processing (Modified after Osinowo, 2013).

3. Results and Discussion

The residual map of the study area is shown in Figure 3. The study area's magnetic intensity distribution has values ranging from –68.597 to 132.362 nT. On the residual magnetic intensity map, prominent high amplitude magnetic intensities can be seen, which mostly trend in the NE-SW and NNE-SSW directions. The high amplitude magnetic strengths can be seen in the Benue State areas of Katsina-Ala and Zoki Bam, Taraba State's Donga, Ibi, and Banlaji, Nassarawa State's Obi, and Cross River State's Ogoja. The dominant trends that have been observed in these areas are NE-SW. Magnetic anomalies with a high positive amplitude correspond to locations with a high magnetic mineral composition, such as magnetite. Since the area under study is in a basin, volcanic intrusions could give a high response of magnetic intensity. High negative amplitude magnetic anomalies also characterized Tokum and Wukari areas of Taraba State, BojuEga, Bokem, and Alade areas of Benue State as well as some parts around the western part of the study area.

The RTE map of the study area is shown in Figure 4. The graphic depicts the elongation effects imposed on anomalies near the equator, as well as the correction in the distribution of the anomalies to locate them over their sources and lessen the elongation effects imposed on anomalies near the equator. The asymmetry in the anomalies has been removed, indicating that they have been appropriately aligned over their causal bodies, as seen by a comparison of the total magnetic intensity map and the RTE map. The low-frequency anomaly around the Ogoja area of Cross River state in Figure 4 became more pronounced after the data had been reduced to the equator in Figure 5. Also, there is a high demarcation of individual high amplitude anomalies around the northern part of the study area which initially looked like a massive linear feature before this process. Figure 5 shows that the regions around Oboko and Kado have magnetic intensities in the range of 125 to 190 nT. The values of these regions, when the data had not been reduced to the magnetic equators, were in the range of –38.3 to 7.4 nT. The anomaly has been aligned over the causal body thanks to the RTE filter.

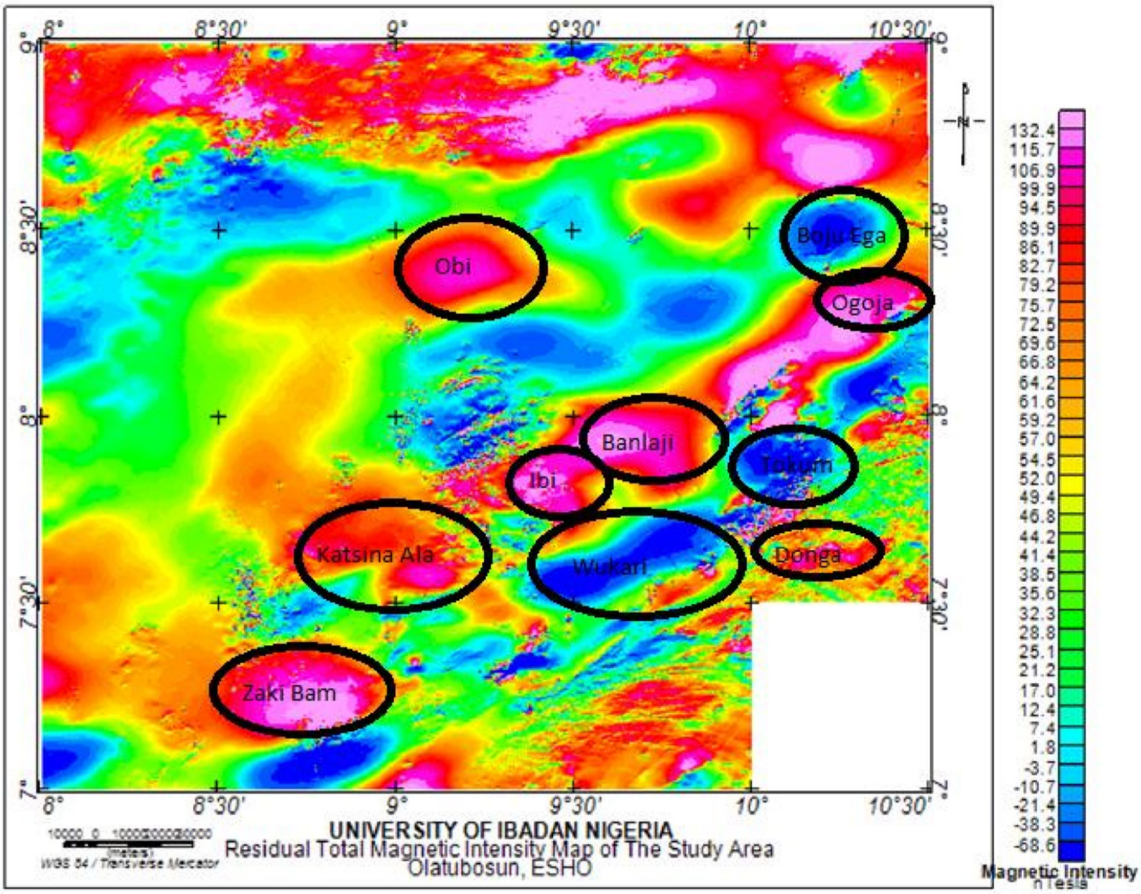

Figure 3. Residual aeromagnetic map of the study area.

Source: NGSA.

The magnetic intensity ranges of this region before and after the application of the RTE filter are –68.6 to 52.0 nT and 57.0 to 115.7 nT, respectively, at Mahanga, the central part of the study area. In the two aforementioned cases, the color changed from blue (low value of magnetic intensity) to pink (high value of magnetic intensity) as can be seen on the maps (Figures 3 and 4).

A structural analysis must be taken into account for a full understanding of the basement complex [38]. As a result, the study's enhanced Residual Magnetic Intensity map will need to be processed further.

The RTE map was extended upwards to 2 km (Figure 5) to emphasize the response of the basement rocks. The most essential consequence of this filter on the map is that it smoothes it out and makes it more regional, allowing regional basement abnormalities to be seen. Furthermore, shallow-seated abnormalities are muted, allowing the deep-seated ones to shine. The short-wavelength anomalies have begun to fade at the 2 km continuation (Figure 6), allowing longer wavelength anomalies to consolidate; anomaly units are increasing. Concrete linkages between anomaly types are obvious and distinct, enhancing signals from deeper sources and showing a rise in the amplitude and spread of the magnetic sources responsible for the high magnetic intensity signals that spread throughout key portions of the research area.

Figures 6 and 7 present the results of horizontal derivative maps of the study area in the x and y direction respectively. The magnetic values are very low and range from about –0.0710 to 0.0752 nT. Eight regions of positive anomalies were identified in Figure 7 (x-direction) with the highest value of 0.0454 nT while nine regions of such were detected in Figure 8 (y-direction), the highest value being 0.0752 nT. Although with an uneven distribution of anomalous bodies across the study area, there is a concentration of such around the northeastern part. The region with the highest positive anomaly in Figures 7 and 8 is around Ogoja, the central part of the study area. The maps further helped, as indicated with different colors, to delineate the edges of the deep-seated anomalies that have been enhanced by the horizontal derivative filter [16]. The regions of high anomalous behavior (pink and red color)

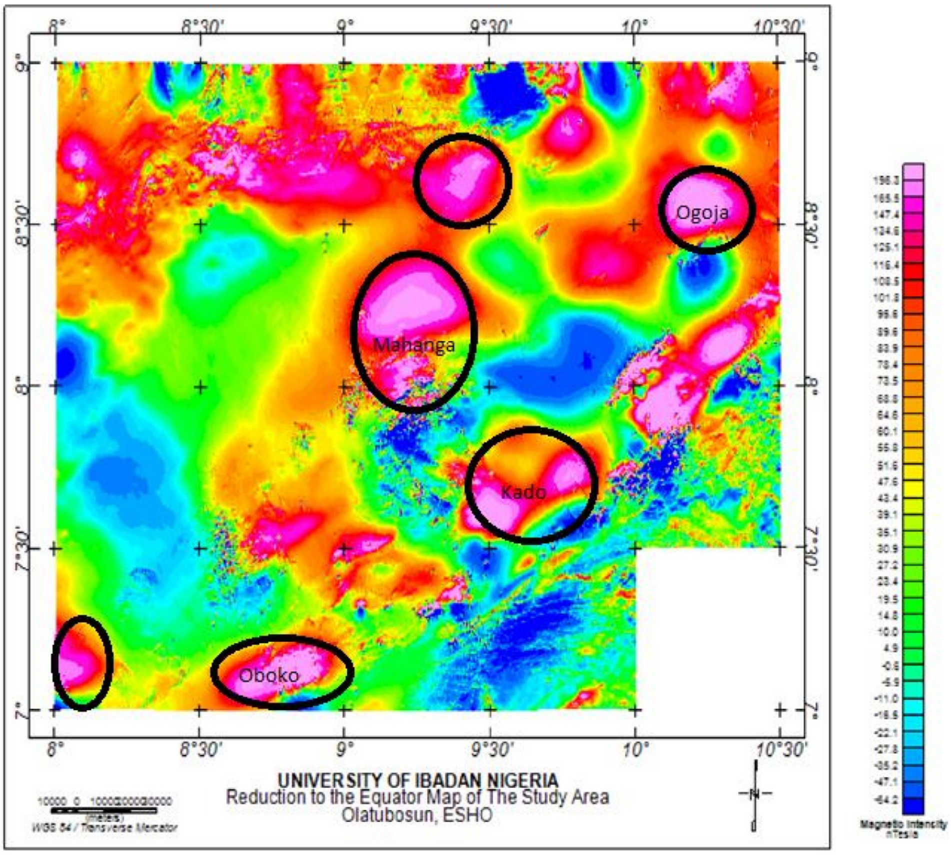

Figure 4. Reduced to the equator map of the study area.

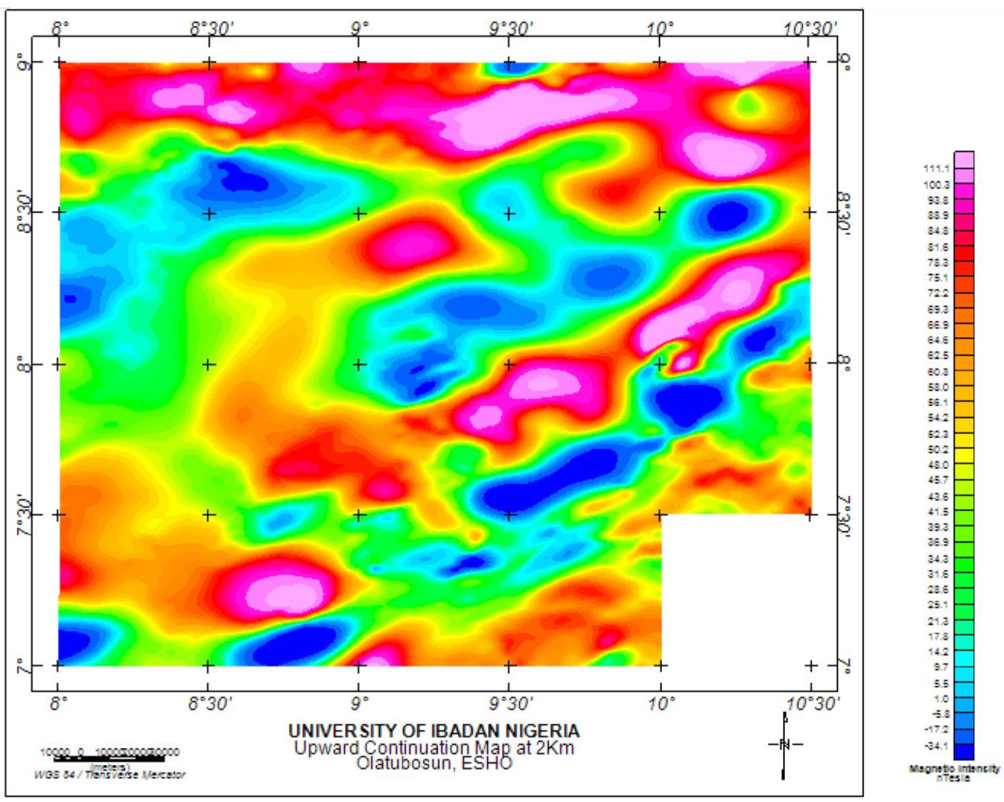

Figure 5. Upward continuation map at 2 km.

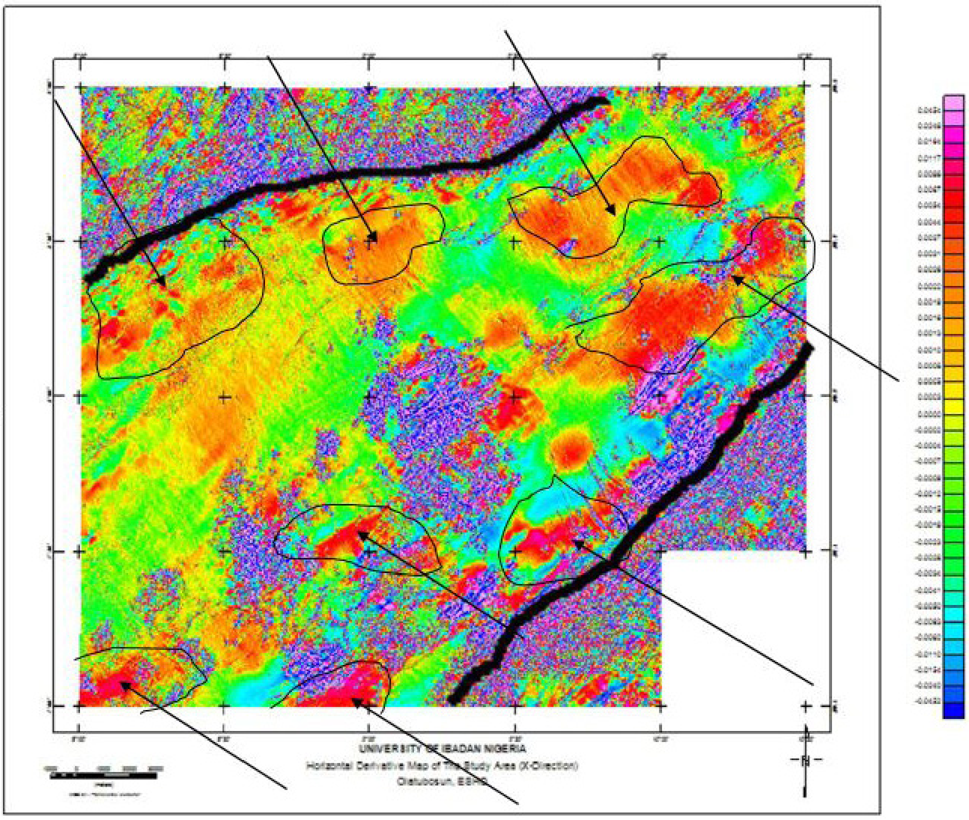

Figure 6. Horizontal derivative map (x-direction).

are identified as the sub-basins and this agrees with the work of Abubakar [1]. A close look at Figures 7 and 8 shows a NE-SW trend of the identified anomalous zones [16].

The delineated linear characteristics in the research area were visible on the tilt angle derivative map (Figure 9). A careful observation of the trends of the lineaments shows that most of the faults present in the study area align NE-SW direction but except for some trending in the NNW-SSE, NNE-SSW, and NW- SE directions [39]. The tilt derivative map's dominant fault trend corresponds to the whole Benue trough, Benkhelil's axial NE-SW trending (1988, 1989). Figure 9 shows the research area's lineament map, which was derived from a Nigerian lineament map. A large degree of similarity was obtained when comparing the faults/trends obtained from the tilt derivative map and that of the lineament map of Nigeria. From these maps, it could be seen that a major fault runs from around Oturkpo in Benue state across Bantaji in Taraba state. Another conspicuous major fault could be seen running from the same Oturkpo to Dep in Nassarawa state. A good number of minor faults dominate the study area giving the impression that the area is structurally controlled. Some of the faults intercepted the suspected sub-basins while some aligned with the edge of some of the sub-basins.

In the graph, the estimated average power spectrum is shown on a semi-log graph of amplitude against spatial wave number (Figure 10). It distinguishes between two separate sources, one with a low amplitude but a higher wavenumber and the other with a low amplitude but a higher wavenumber. The negative slope of a straight line fitted to the two radial power amplitudes was calculated to be twice the depth to the centre of mass of the bodies creating the magnetic anomalies [26]. Figure 10 further shows that the deepest area is 5.2 kilometers deep, whereas the shallower parts are 0.5 kilometers deep on average. According to the plot of average radial power, deep structures have a longer wavelength than shallow sources. The spectral solution also offers information about the average anomaly size (wavelength and amplitude), predicted depths (maximum and minimum), and window size, all of which are required to constrain Euler deconvolution [33]. The analytic signal derivative map (Figure 11) was created

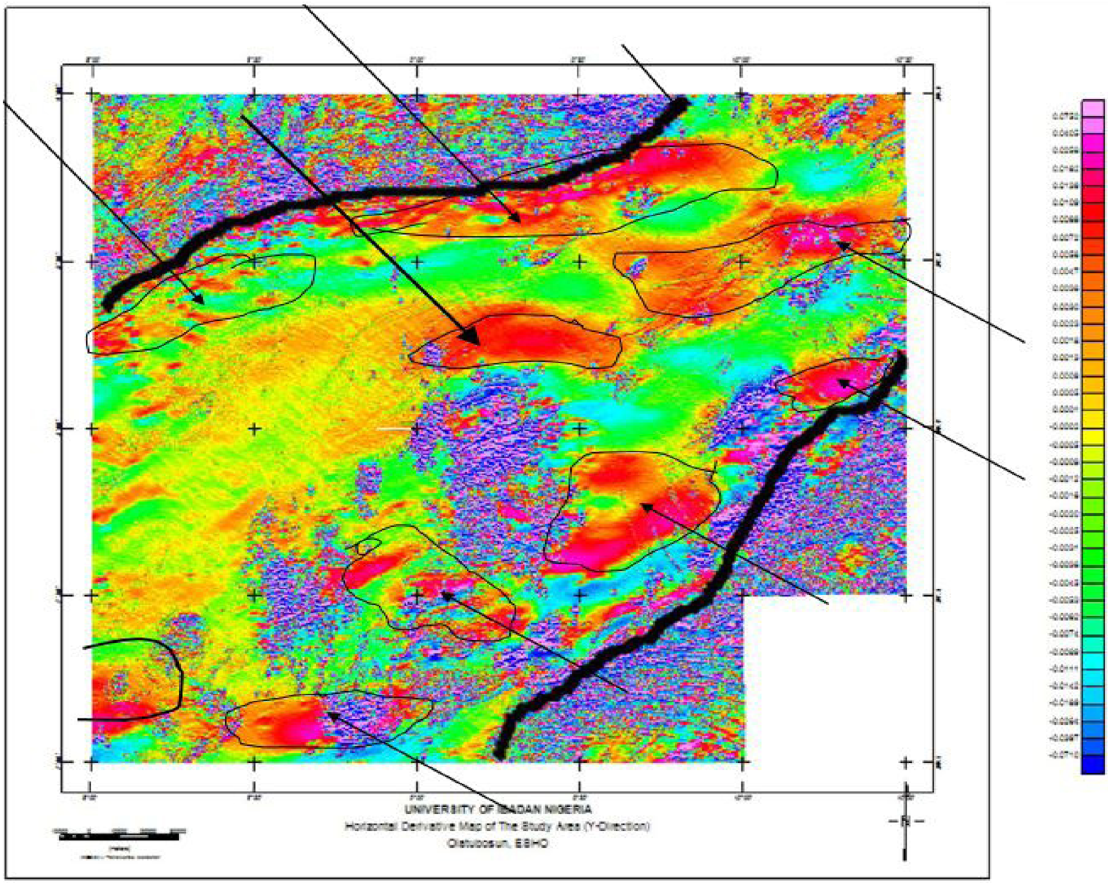

Figure 7. Horizontal derivative map (Y- direction).

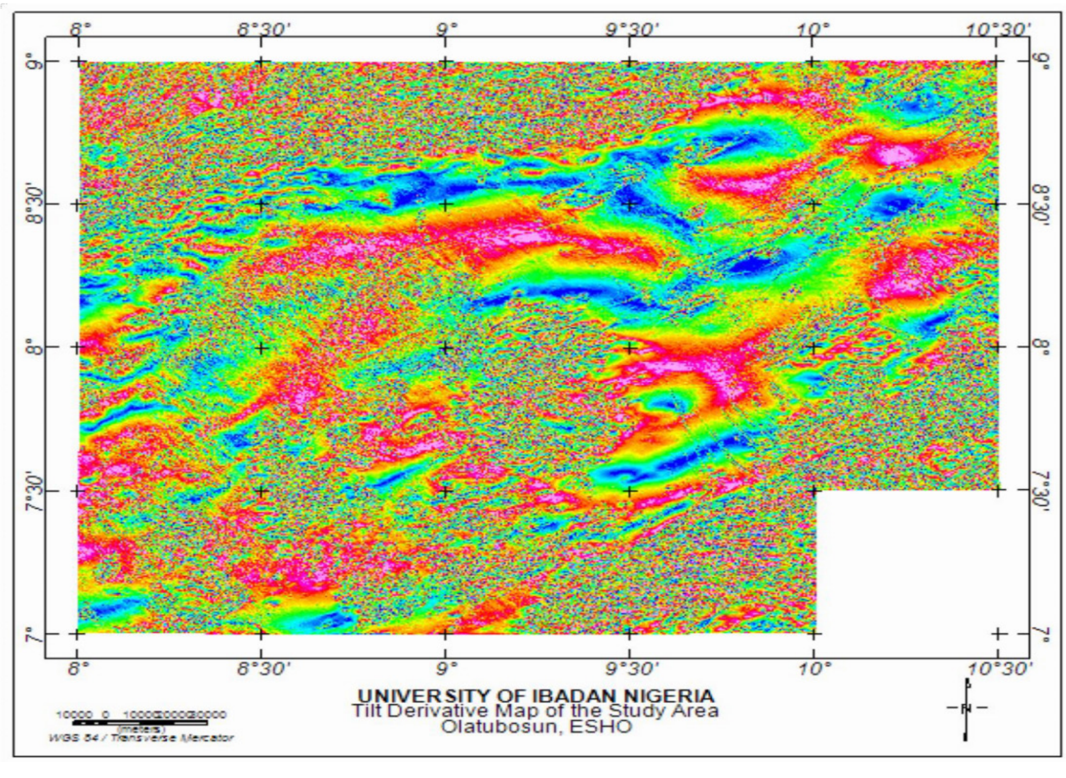

Figure 8. Tilt angle derivative map of the study area.

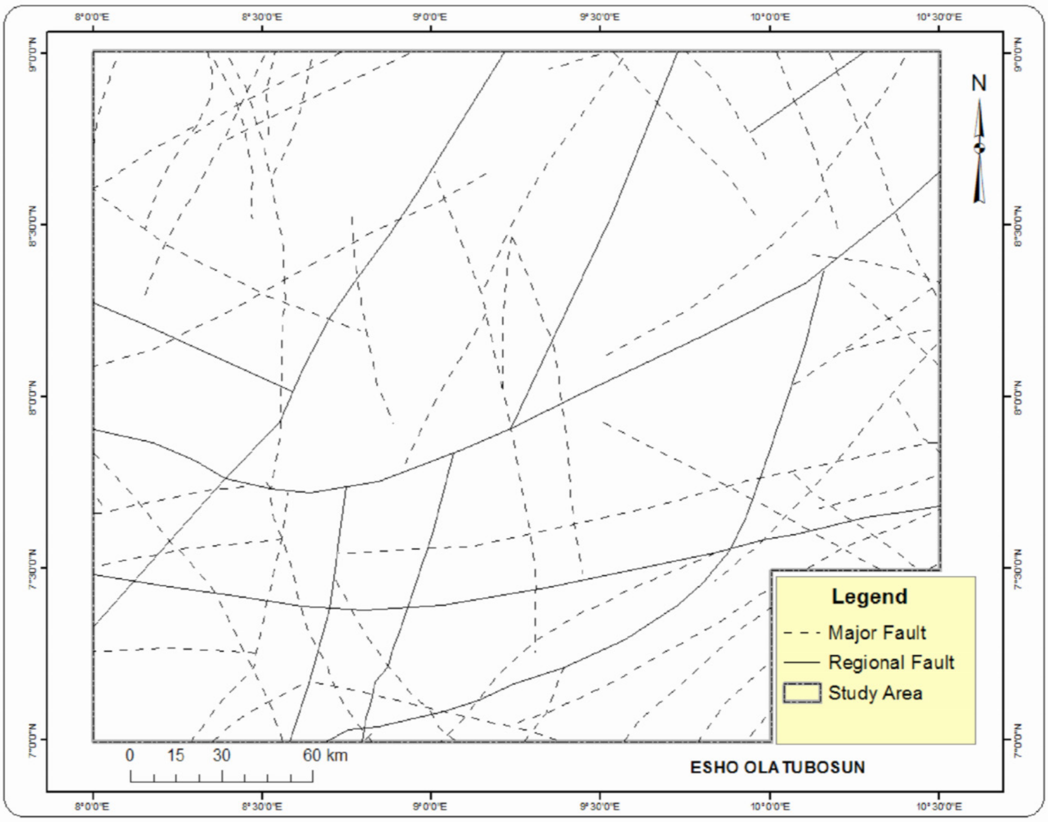

Figure 9. lineament map of the study area (Extracted from Lineament map of Nigeria).

Source: NGSA.

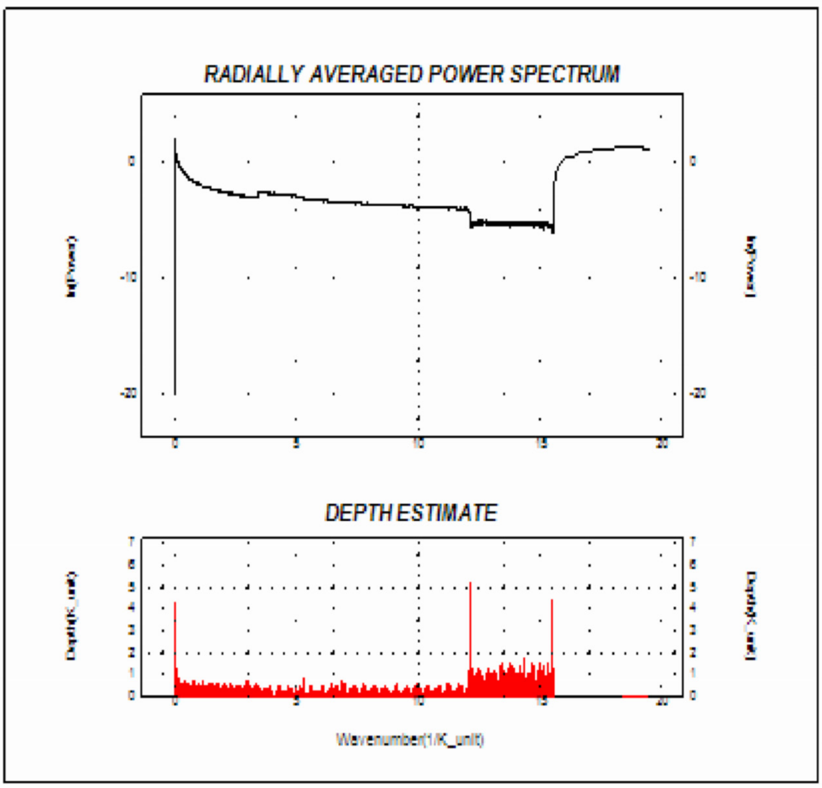

Figure 10. Radially averaged power spectrum with depth estimate.

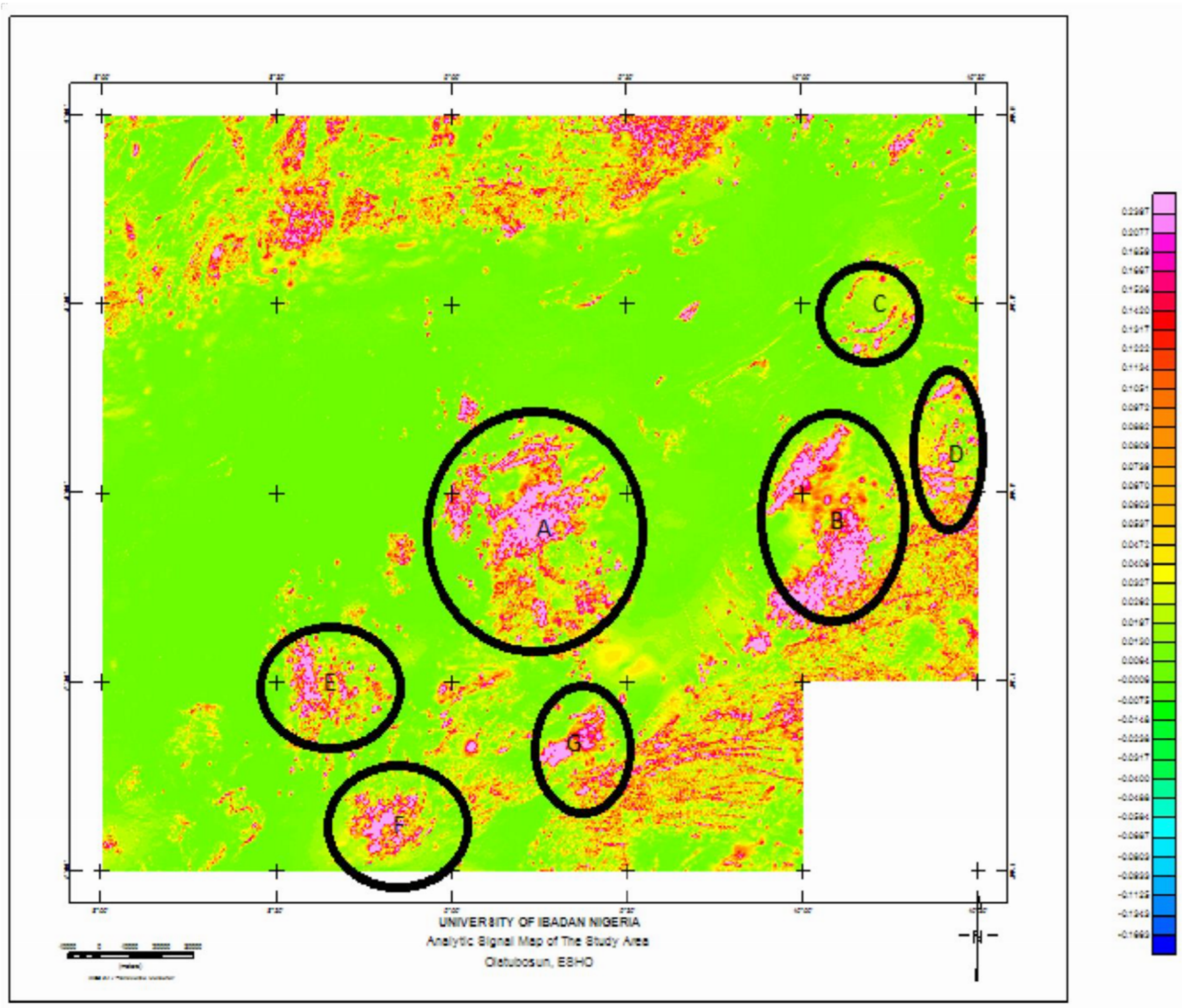

Figure 11. Analytic signal map of the study area.

using the analytic signal grid, which was created by taking the first-order derivatives of two horizontal gradients and one vertical gradient of the mapped area's magnetic strength [30]. The map emphasizes the magnetic source magnetization fluctuation in the research area, as well as discontinuities and anomaly texture. Magnetic zones with high intensities of 0.09-0.2 nT (pink) are inconspicuously isolated places in the research area, whereas regions with low magnetic intensities of 0.01 nT (green) occupy a larger percentage of the study area. A through G are the names of seven significant magnetic zones, or high magnetic anomaly zones. The number of magnetic minerals present in the magnetic sources is thought to be responsible for the high amplitude signal anomalies [40]. The contrast between the greatest and minimum signatures enhances these abnormalities, allowing the causal bodies' limits to be traced out. When compared to the rest, the signals in Regions A, B, F, and G have a higher amplitude.

In Figure 12, you can see the vectorized standard deviation map. On this map, the orientation and length of the lineaments are shown, resulting in the geographical distribution of lineaments that aids in understanding the structural control directions in the studied area. Linear features were discovered on the map that corresponded to those found on the tilt derivative map (Figure 9). Magnetic contour lineation typically follows regional geology, according to Dobrin and Savit [41]. The extracted lineaments reveal NE-SW, NNE-SSW, and NW-SE trends, as well as minor ENE-WSW and E-W directions. The majority of these trends were consistent with recent work by Ajakaiye [42], in the Benue Trough and areas of the surrounding Nigerian basement complex (1991). Figure 13 shows the structural complexity map. The densities of structural connections and diversities in the strike were measured, allowing for a better selection of potential regions. The map's beginning data was reduced to a pole grid, and the map was designed to correctly depict ridges or margins of geologic features.

From the structural complexity map below, the thick black lines correspond to the points where the junction high density is greatest. This marks the side flanks of the trough indicating the existence of a higher mass of the body as compared with the surroundings. The circled areas in the figure correspond to the areas with high density which are capable of hosting deposits of interest. The result obtained from this map agrees with that obtained from the vectorized standard deviation map of the study area (Figure 12). For example, KadiBlam and Kado areas of Benue state fall within these circles whereas the place was also depicted as having high analytic signals (Figure 11).

The study area's Euler solution map is presented in Figure 14. A gridding interval of 14 line spacing was utilized to improve the detection of shallow seated anomalies due to their tiny amplitudes. The gridding interval allows for the detection of any anomaly with a wavelength of up to 75 m, resulting in a large number of solution points; a total of 3565078 solution points were collected. In comparison to the results from the analytic signal map, the output of the Euler deconvolution solution plot shows a high level of similarities. On the Euler Deconvolution solution plot, most of the locations identified as having high amplitude by the analytic signal map were also significant. The depth estimates within the area of investigation range from –176 m (highest portion) to –6951 m (lowest part) according to the Euler Deconvolution solution plot (deepest part). The Minna Datum in Nigeria was used to plot depth solutions, and the fact that all depths are less than zero confirms that the research area is below sea level (sedimentary basin). As a result of this fact, nine points were isolated from the study area as sub-basins within the main basin. They have depths ranging from –3376 m to –6951 m. The suspected sub-basins have their locations around Ibi, Takum and Bantaji areas of Taraba state, Ogoja and Obudu areas of Cross River state, and Gboko and Zakiblam areas of Benue state.

Figure 15 presents the map showing the topographic

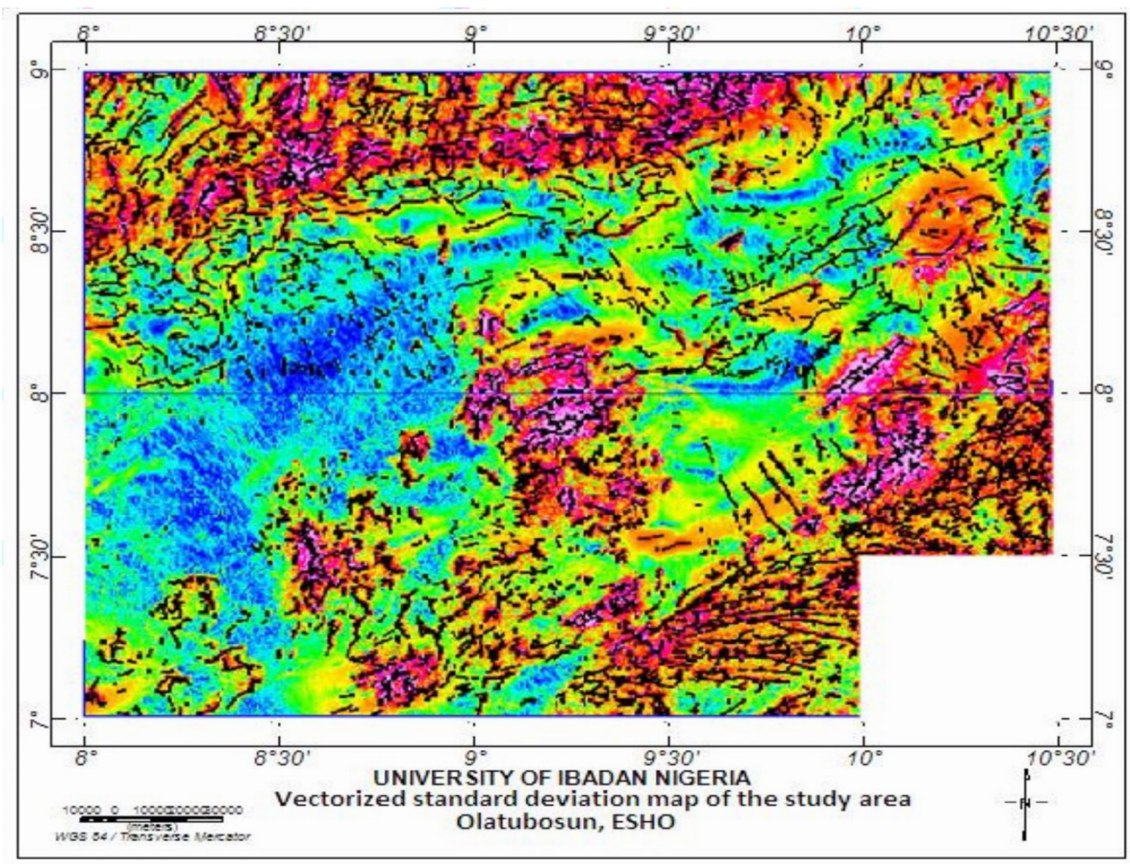

Figure 12. Vectorized standard deviation map of the study area.

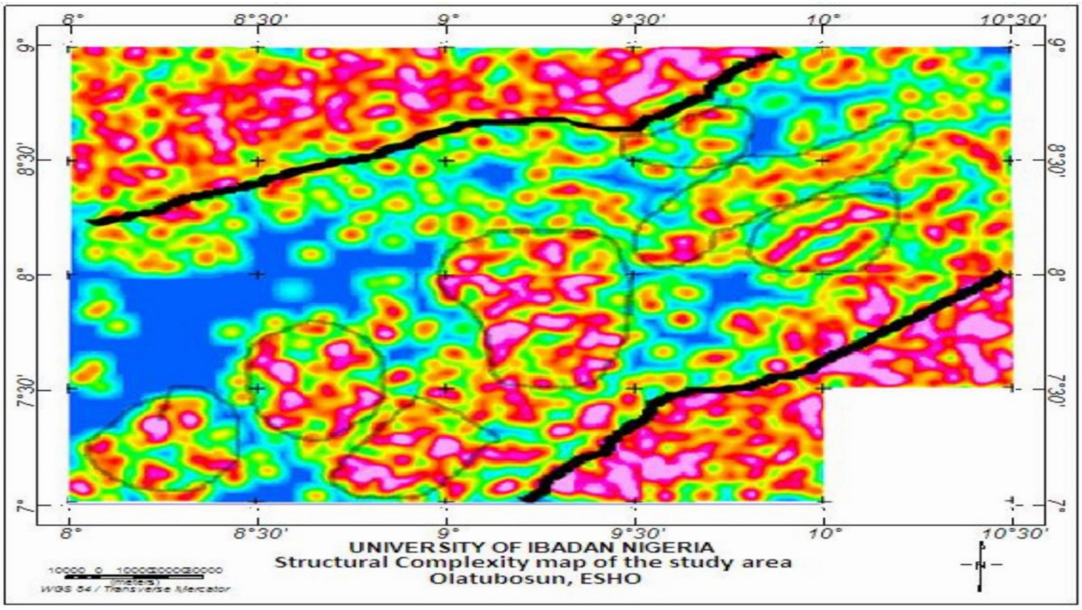

Figure 13. Structural complexity map of the study area.

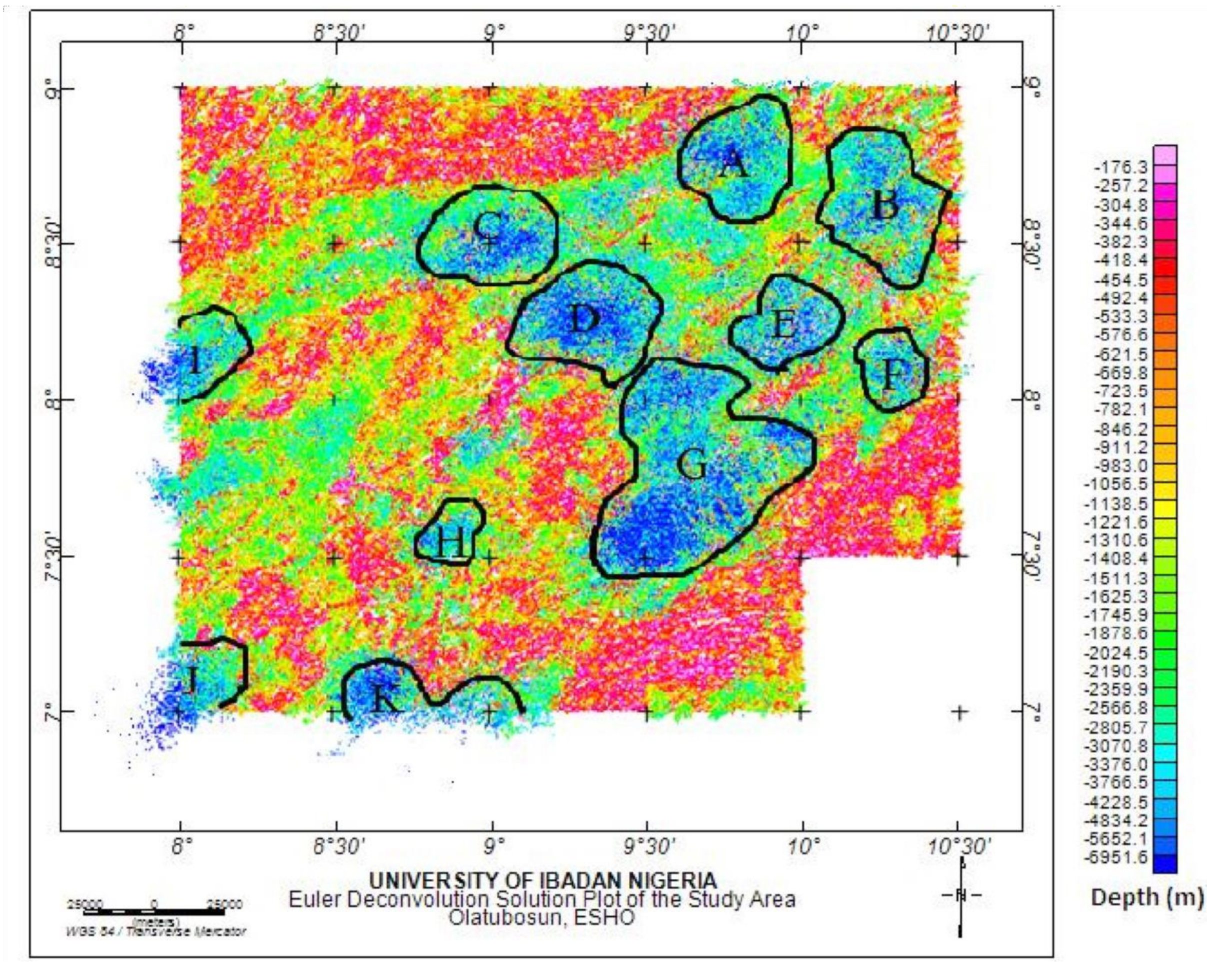

Figure 14. Euler deconvolution solution plot of the study area (S.I = 3.0).

nature of the area of study. A corresponding contour map was also generated and this is presented in Figure 16. From the two maps, it could be shown that the topography of the magnetic basement is undulating and irregular, confirming the results of earlier workers [43,39]. The topography of the basement surface also exhibits a general trend from shallow in the northeast and southwest regions to deep in the northwest section of the area, according to the surface plot. The magnetic basement map depicts a succession of ridges and troughs throughout the area, with a few depressions thrown in for good measure. In the northeastern section of the research area, population density is higher in these micro-basins. The magnetic basement surface beneath the basin appears to be shallow and low relief, based on the basement depth measurements. The magnetic basement can be found at depths ranging from 300 m to 8 km, which corresponds to the sub-basin depth range.

The general trend in sedimentation as seen from the plot implies that the basin is thickest at the southwestern and central parts of the study area. The configuration of the basement is very irregular; a series of depressions that could have been a result of tectonic activities. If all other hydrocarbon-producing factors are constant, some of the micro-basin will be adequate to serve as reservoirs because of the thickness of their sediment cover (greater than 3 km) [44]. The identified sub-basins appeared clearly on this map. Figure 16 shows the basement topography map represented on a contour map.

Four cross-sections (Figure 17 a-d) were generated from the profile lines A-B, C-D, E-F, and GH drawn on the contour map (Figure 16). From these sections, it could be seen that the topography of the magnetic basement of the area of study is very irregular, which conforms with the result obtained from the basement topographic map (Figure 16). In cross-section A-B, three (3) sub-basins exist and range in depth between 2500 m and 3400 m. The second cross-section (C-D) presents five sub-basins with depths ranging from 2000 m to 3900 m. The third cross-section (E-F) shows two sub-basins that are relatively deeper than those found in the cross-section discussed earlier. These sub-basins have a depth range of 3000 m to 6000 m. Due to the result presented in cross-section G-H with one of the sub-basin having the highest depth of 8000 m, it is believed that tectonic activities must be highest on the south-eastern part of the study area; Kado and Zoki Bam areas of Benue state to be precise.

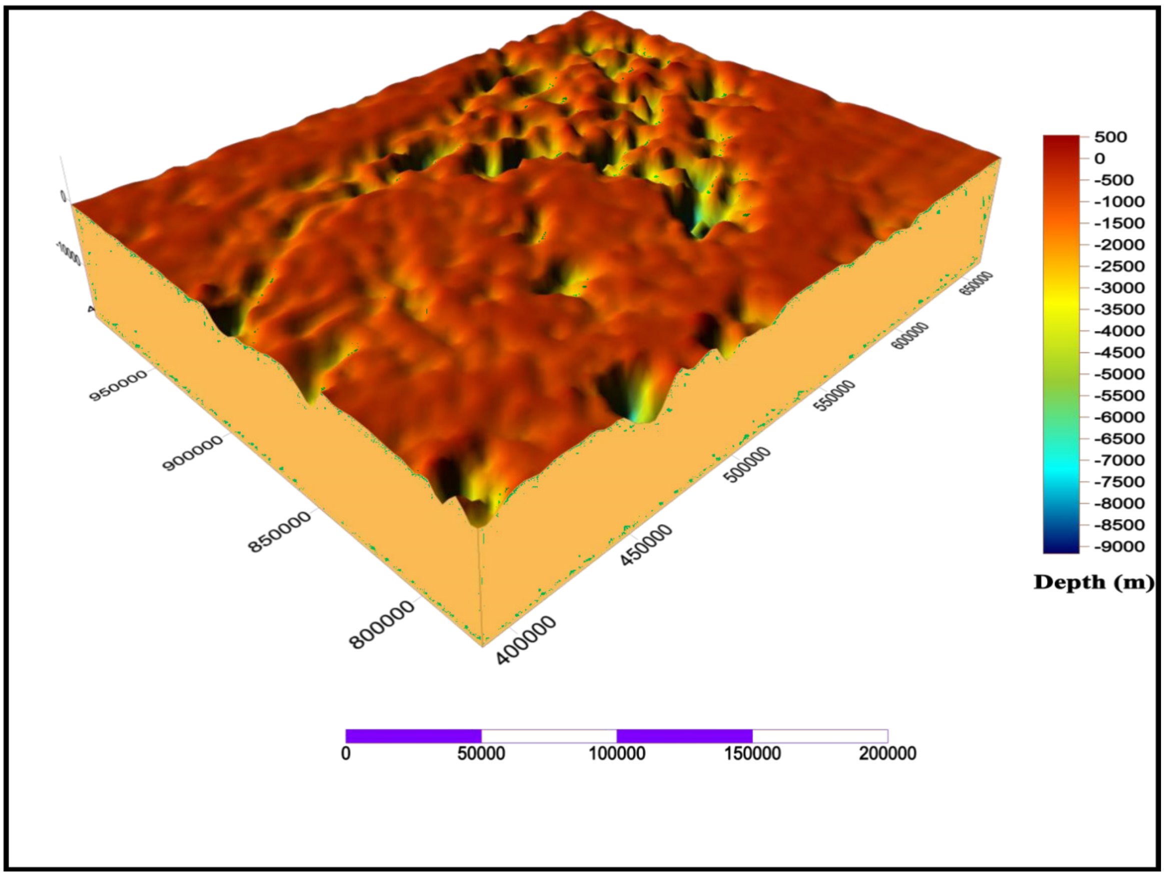

Figure 15. Magnetic basement topographic map of the study area.

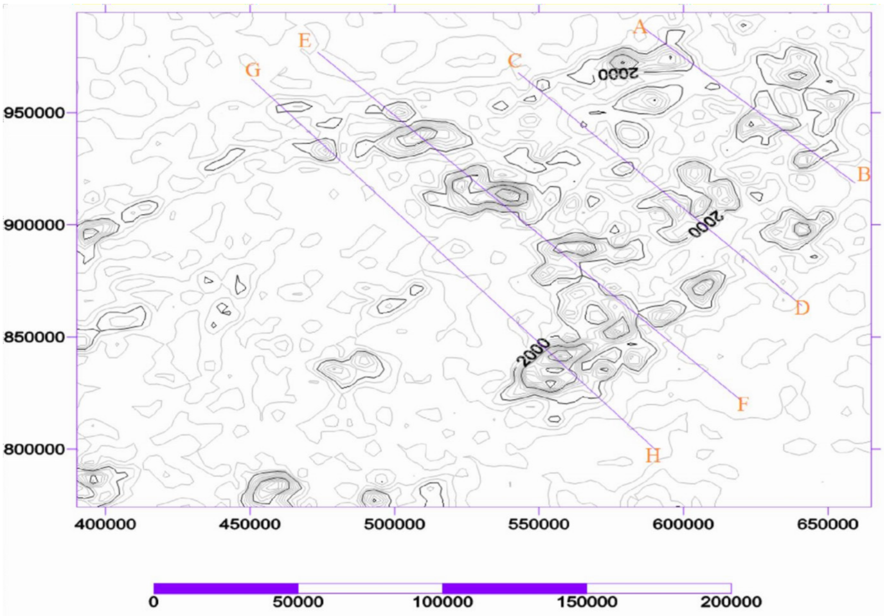

Figure 16. Contour map showing the sub-basins and profiles.

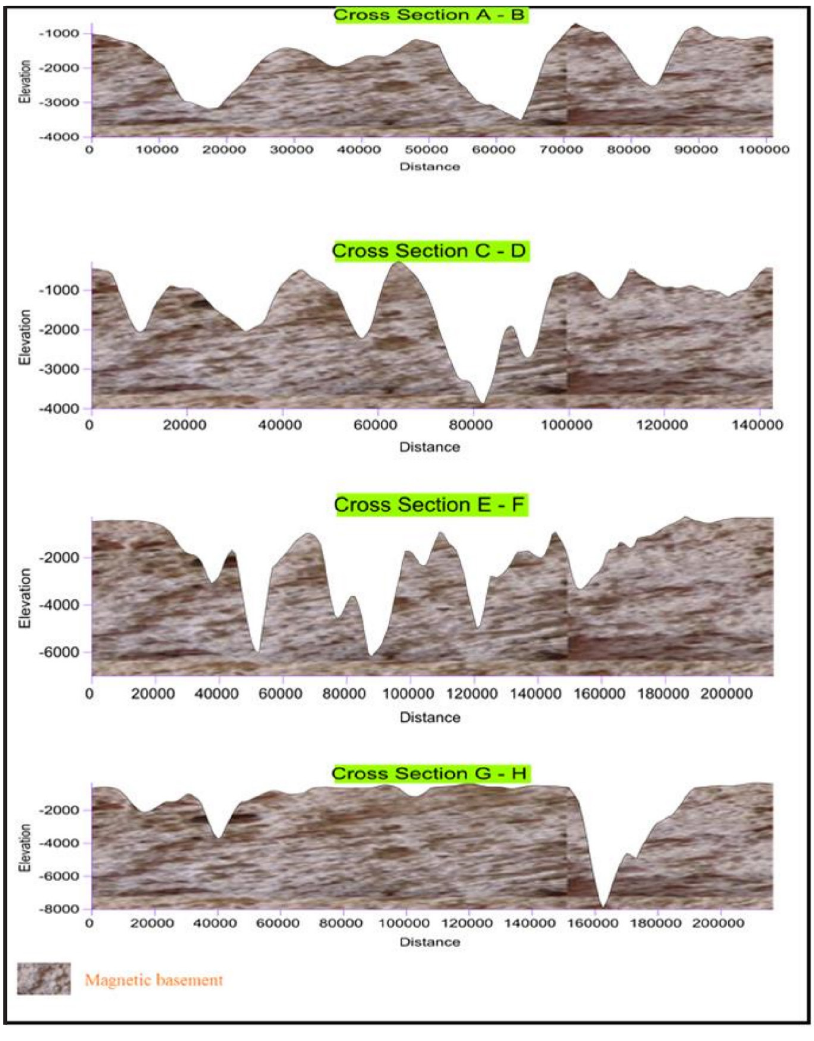

Figure 17. Cross-sections along with profiles A-B, C-D, E-F, and G-H.

4. Conclusions

The study evolved a detailed analysis of aeromagnetic data acquired to delineate basement topography and relief as well as depths to the top of magnetic sources of middle Benue Trough. Using the Oasis Montaj software, the results of this study have revealed that the basement surfaces comprise a successive pattern of crests and troughs which detailed the fact that the magnetic basement is very irregular and likely due to a series of tectonic activities that occurred in the study area. Lineaments mainly trending in the NE-SW directions were identified. The basin is also found to consist of eleven sub-basins. A display of the magnetic basement topographic map revealed the widespread of the identified sub-basins with a large number of them dominating the north-eastern part of the study area. They identified eleven distinct sub-basins (A-K) with sediment cover ranging from 2 km to 8 km and further probed for hydrocarbon potentials. Regions A, B, C, D, E, and G have sediment thicknesses of more than 3 km and might therefore be suitable to act as hydrocarbon reservoirs provided all other factors are in place. Aeromagnetic interpretation of basement structures and geometry in parts of the middle Benue Trough has proven efficient in providing useful information about the nature of the basement as well as determining the basement topography and structures which can provide necessary guides to explorations.

Conflict of Interest

Every corresponding author certifies that there are no conflicts of interest on behalf of all authors. There are no actual or potential conflicts involving the work.

Funding

No funding was received to assist with the preparation of this manuscript.

Acknowledgement

Our special gratitude goes to the Nigerian Geological Survey Agency (NGSA) for providing the aeromagnetic data utilized in this research study.

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