

Estimation of Sedimentary Thickness of Parts of Upper Benue Trough, Nigeria, using Integrated High Resolution Aeromagnetic and GRACE data

Abangwu, J. U.¹  | Ekwueme, O. U.²  | Okwesili, N. A.¹  | Ugbor, D. O.¹  | Igwe, E. A.¹  |
Nwobodo, A. N.³  | Ugwuanyi, M. C.,⁴ 

1. Department of Physics and Astronomy, University of Nigeria, Nsukka, Nigeria.
2. Federal University of Technology Akure, Ondo State, Nigeria.
3. Department of Industrial Physics Enugu State University of Science and Technology, Enugu State, Nigeria.
4. Federal University of Allied Health Sciences, Enugu State, Nigeria.

Corresponding Author E-mail: johnson.abangwu@unn.edu.ng

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Abstract

High-resolution aeromagnetic and gravity data from the Gravity Recovery and Climate Experiment (GRACE) were analyzed to evaluate the sedimentary thickness and hydrocarbon potential of parts of the Upper Benue Trough in Nigeria. The study area is bounded by latitudes 9.0° to 10.0° North and longitudes 10.0° to 12.5° East, and covers approximately 30,250 km². Total Magnetic Intensity (TMI) and Bouguer gravity anomaly grids were generated using Oasis Montaj 8.4 software and subjected to polynomial fitting for regional-residual separation and qualitative interpretation. The magnetic and gravity fields exhibit similar regional trends, indicating that both deep and shallow sources are influenced by a common tectonic framework. Quantitative analysis using Source Parameter Imaging (SPI) and Euler deconvolution was performed to estimate the sedimentary thickness of the area. The magnetic and gravity SPI depth results ranged from -207.4 to -3523.0 m and -115.7 to -3767.3 m, respectively. The magnetic Euler depth values varied between 413.3 m and -3597.5 m, while gravity Euler depths ranged from 600.6 to -3606.4 m. The unconventional appearance of the gravity SPI and Euler depth maps is attributed to the coarse resolution and long-wavelength nature of satellite gravity data compared to the high resolution, near-surface sensitivity of aeromagnetic data. The maximum sedimentary thickness of -3767.3 m indicates adequate sediment accumulation for hydrocarbon generation. Areas such as Bashar, Yuli, Futuk, Dong, and Guyok are characterized by low gravity and magnetic anomalies with relatively deep basement depths, signifying zones of enhanced sedimentary deposition that are favorable for hydrocarbon entrapment.

Keywords: Gravity and magnetic data, Source parameter imaging, Euler deconvolution, Hydrocarbon accumulation.

1. Introduction

Located in northeastern Nigeria, the Upper Benue Trough represents one of the major sedimentary basins in West Africa and forms an integral part of the larger Benue Trough system. Extending from the northern segment of the Benue River to the Cameroon border, the Upper Benue Trough plays a key role in understanding the region's tectonic evolution, sedimentation history, and hydrocarbon potential (Obaje, 2009). The basin's geological framework reflects complex interactions among tectonic, volcanic, and sedimentary processes that have resulted in a structurally diverse subsurface environment (Carter et al., 1963;

Obaje, 2009). Accurate estimation of sedimentary thickness in this area is therefore critical for evaluating hydrocarbon potential, groundwater resources, and other subsurface applications.

Previous studies have employed direct exploration methods such as borehole drilling and seismic surveys to estimate sedimentary thickness in the Benue Trough (Abubakar et al., 2008; Epuh and Joshua, 2020; Abdulkadir et al., 2021). While these approaches provide reliable local information, they are limited in spatial coverage and often expensive to implement across large or inaccessible terrains.

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E-mail: (1) ngozi.okwesili@unn.edu.ng | desmond.ugbor@unn.edu.ng | emmanuel.igwe@unn.edu.ng (2) ouekwueme@futa.edu.ng (3) anthonia.nwaobodo@esut.edu.ng (4) chukwumakhoomelle@gmail.com



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Consequently, geophysical techniques, particularly magnetic and gravity methods, have become valuable tools for cost-effective regional subsurface investigations (Yakubu et al., 2020; Ajala et al., 2021; Eke et al., 2022). Although numerous studies have utilized either magnetic or gravity data to investigate the Benue Trough, few have attempted a comprehensive integration of both datasets, especially combining high-resolution aeromagnetic data with satellite GRACE gravity data. This integration offers improved reliability in depth estimation by correlating density and magnetic susceptibility contrasts within the subsurface. The GRACE mission provides global gravity measurements sensitive to large-scale mass distribution, while aeromagnetic surveys reveal finer details of basement configuration and fault structures. Their combined use allows for a more balanced interpretation of regional and local features.

This study therefore focuses on the integrated interpretation of aeromagnetic and GRACE gravity data to estimate sedimentary thickness and delineate subsurface structural patterns within parts of the Upper Benue Trough. Unlike earlier studies that relied on a

single data source, this work applies both Source Parameter Imaging (SPI) and Euler deconvolution methods to each dataset, thereby improving the accuracy of basement depth estimation. The findings are intended to refine existing geological models, highlight areas with significant sediment accumulation, and provide new insights into the basin's hydrocarbon potential.

2. Location and Geology of the study area

The study area spans 30,250 km² and is located between latitude 9.0⁰ to 10.0⁰ North and longitude 10.0⁰ to 12.5⁰ East. The Upper Benue Trough is a Cretaceous basin that extends in a northeast-southwest direction (Obaje, 2009). Its strata include the Precambrian Basement, which consists of igneous and metamorphic rocks. The Bima Sandstone is the earliest sedimentary layer, and it is overlain by the Yolde Formation, which consists of sandstone, shale, and siltstone, and marks the transition from continental to marine sedimentation (Carter et al., 1963; Obaje, 2009). The geological map of the research region is shown in Figure 1.

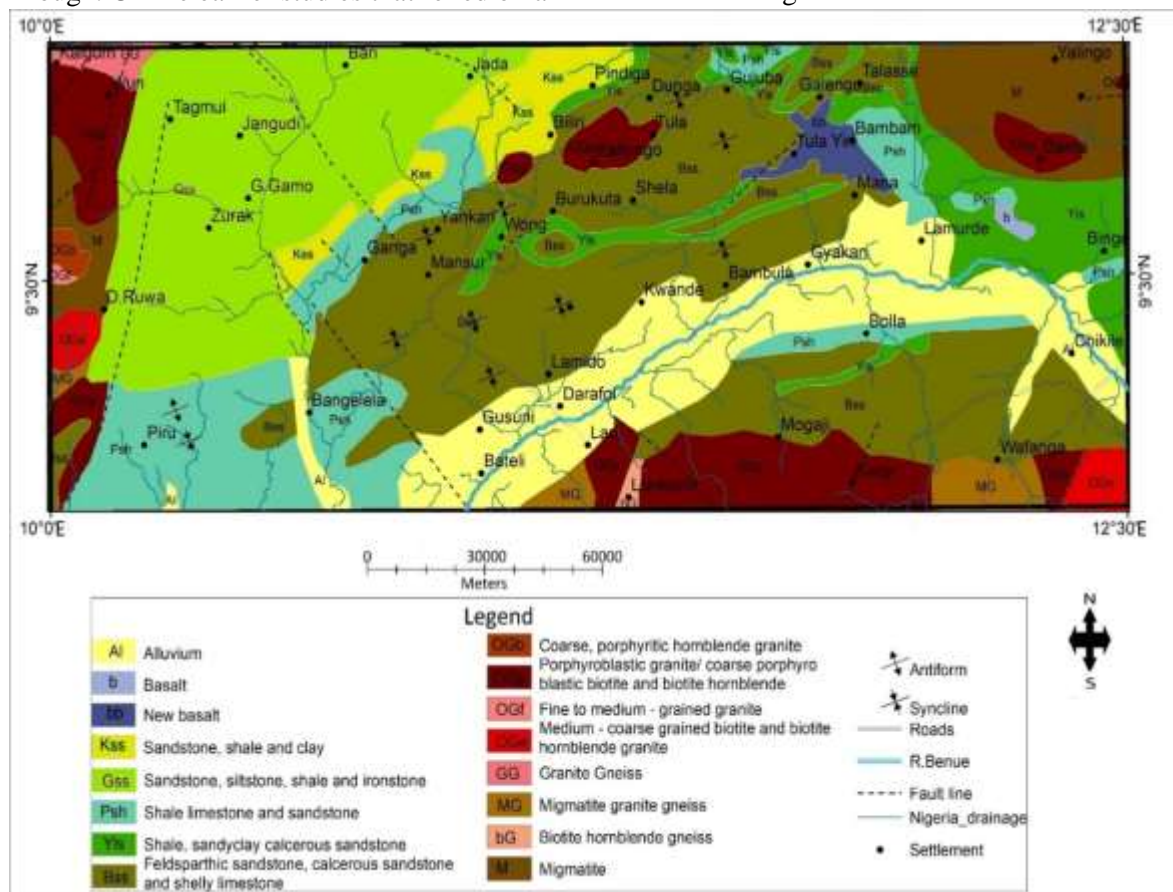


Figure 1. The geological map.

3. Materials and methods

3-1. Data

This research utilized ten high-resolution aeromagnetic datasets, corresponding to sheet numbers 171, 172, 173, 174, 175, 192, 193, 194, 195, and 196, which represent the locations of Yuli, Futuk, Kaltungo, Guyok, Shellen, Bashar, Muri, Lau, Dong, and Numan, respectively. These datasets were obtained from the Nigerian Geological Survey Agency (NGSA). Additionally, Gravity Recovery and Climate Experiment (GRACE) data for the same ten locations were acquired from the GFZ German Research Centre for Geosciences.

4. Methodology

The following procedures were employed as a step-by-step approach to analyze and interpret the data.

4-1. Data Merging and Gridding

The initial steps in the data analysis involved merging and gridding the datasets. The ten aeromagnetic data sheets were combined to define the study area, and the same process was applied to the GRACE data sheets. Following this, the data were gridded, which involved interpolating the data into evenly spaced cells. The aeromagnetic and GRACE data were then respectively gridded to produce the Total Magnetic Intensity (TMI) anomaly and Bouguer anomaly maps of the study area, using Oasis Montaj software. For quantitative interpretation, the Source Parameter Imaging (SPI) and Euler Deconvolution methods were applied.

4-2. Polynomial fitting

The first stage of the quantitative interpretation involved applying mathematical filters to the Total Magnetic Intensity (TMI) and Bouguer gravity anomaly data to enhance significant anomaly patterns. To obtain the residual anomalies representing local geological features, a polynomial surface was fitted and subtracted from the observed data to remove the long-wavelength regional field. This method, known as polynomial fitting, was carried out using the Oasis Montaj 8.4 software package. In this study, a first-order polynomial was selected to isolate regional trends. The choice of a first-order function was based on both the geological setting and the nature of the

anomaly distribution across the study area. The Upper Benue Trough exhibits a relatively gentle regional gradient caused by large-scale lithospheric warping and crustal thinning, which can be adequately approximated by a simple linear surface. Using a higher-order polynomial (e.g., second or third order) could introduce spurious curvature or artificial anomaly trends that do not correspond to real geological variations, thereby distorting the residual field.

4-3. Source parameter imaging

Source Parameter Imaging (SPI) is a quantitative geophysical technique used to estimate the depth to the top of potential-field sources, such as magnetic or density anomalies (Thurston and Smith, 1997). The method is based on the relationship between the depth (Z) of a source and the maximum local wavenumber (K_{max}) derived from the spatial gradients of the observed field. It requires both horizontal and vertical derivatives of the potential field data and provides rapid, objective depth estimates without assuming a specific source geometry. The general relationship is expressed as:

$$Z = \frac{1}{K_{max}} \quad (1)$$

where K_{max} represents the maximum local wavenumber, defined as:

$$K_{max} = \sqrt{\left(\frac{\partial Tilt}{\partial z}\right)^2 + \left(\frac{\partial Tilt}{\partial y}\right)^2} \quad (2)$$

Tilt is defined as the arctangent of the ratio between the vertical derivative and the horizontal gradient of the potential field. It indicates how steeply the potential field changes with depth relative to its horizontal variation. The tilt angle serves to reveal subsurface structure edges and stabilizes depth estimation in SPI by limiting the influence of amplitude changes in the data. This relationship is expressed in Equation (3) as:

$$Tilt = \arctan \left[\frac{\left(\frac{\partial P}{\partial z}\right)}{\sqrt{\left(\frac{\partial P}{\partial x}\right)^2 + \left(\frac{\partial P}{\partial y}\right)^2}} \right] \quad (3)$$

where P is the potential anomaly field, $\frac{\partial P}{\partial z}$ represents the vertical derivative while $\frac{\partial P}{\partial x}$ and $\frac{\partial P}{\partial y}$, are the horizontal derivatives. The SPI technique calculates depth at each grid point

by determining the local wavenumber from the field gradients. The higher the wavenumber is, the shallower the source will be, and vice versa. This makes SPI ideal for mapping basement relief and sedimentary thickness variations in complex geological terrains such as the Upper Benue Trough. It produces accurate and repeatable depth estimates across massive datasets and is less subjective and more computationally efficient than manual profile interpretation techniques.

4-4. Euler deconvolution

The Euler deconvolution method estimates the locations and corresponding depths of potential field anomaly sources (Thompson, 1982). The standard 3D form of Euler's equation (Reid et al., 1990) can be defined as:

$$x \frac{\partial P}{\partial x} + y \frac{\partial P}{\partial y} + z \frac{\partial P}{\partial z} + \eta P = x_0 \frac{\partial P}{\partial x} + y_0 \frac{\partial P}{\partial y} + z_0 \frac{\partial P}{\partial z} + \eta b \quad (4)$$

where x , y , and z are the coordinates of a measuring point; x_0 , y_0 and z_0 are the coordinates of the source location whose total field is detected at x , y , and z ; b is a base level; η is the structural index and P is the potential field anomaly. This method involves applying different structural indices of potential field models to the residual potential field using the standard Euler deconvolution tool of Oasis Montaj software. The structural indices for gravity and magnetic fields, as outlined by Whitehead and Musselman (2008), are as follows: for gravity, the indices are 0 for sill/dyke, 1 for pipe, 2 for sphere; for magnetic fields, the indices are 0 for contact, 1 for sill/dyke, 2 for pipe, and 3 for sphere.

5. Results

5-1. Total magnetic intensity (TMI) and Bouguer Anomaly results

The TMI ranges from -46.2 to 140.4 nT (Figure 2). According to the TMI map, the region is magnetically diverse with a visibility of wide range of anomalies. Areas

with significant positive anomalies probably signify igneous intrusions characterized by higher concentrations of magnetic susceptibilities. Similar to broad magnetic lows, these regions are probably low in magnetic concentration and so less susceptible. High magnetic anomalies (depicted in red to pink on the TMI map) correspond to igneous intrusions and basement uplift zones identified on the geological map (Figure 1). These areas typically expose Precambrian basement rocks or Bima Sandstone underlain by crystalline rocks, both of which have high magnetic susceptibilities. They are concentrated around areas like Lau, Muri, and Futuk, where dense, magnetically strong rocks are mapped. Low magnetic anomalies zones (shown in blue to green) coincide with sedimentary basins illustrated in Figure 1. These zones represent non-magnetic sediments, including shale, siltstone, and sandstone of the Yolde and Bima Formations.

Figure 3 shows the Bouguer anomaly map of the study area, which varies from -39.9 to -26.2 mGal. The high Bouguer anomalies (depicted in red to pink) zones indicate areas of high subsurface density, corresponding to igneous intrusions and basement uplifts shown on the geological map (Figure 1). These regions are associated with Precambrian crystalline basement rocks and Bima Sandstone units, which are denser than the surrounding sedimentary formations. The gravity highs are mostly found around Lau and Muri, where the basement is relatively shallow.

The Low Bouguer anomaly zones (indicated in blue) correspond to regions of low subsurface density, which are consistent with thick sedimentary accumulations, as shown in Figure 1. Areas such as Bashar, Yuli, Kaltungo, and Guyok display these gravity lows, implying the presence of deep sedimentary basins. These zones are favorable for hydrocarbon accumulation, as thicker sedimentary successions can serve as both source and reservoir rocks.

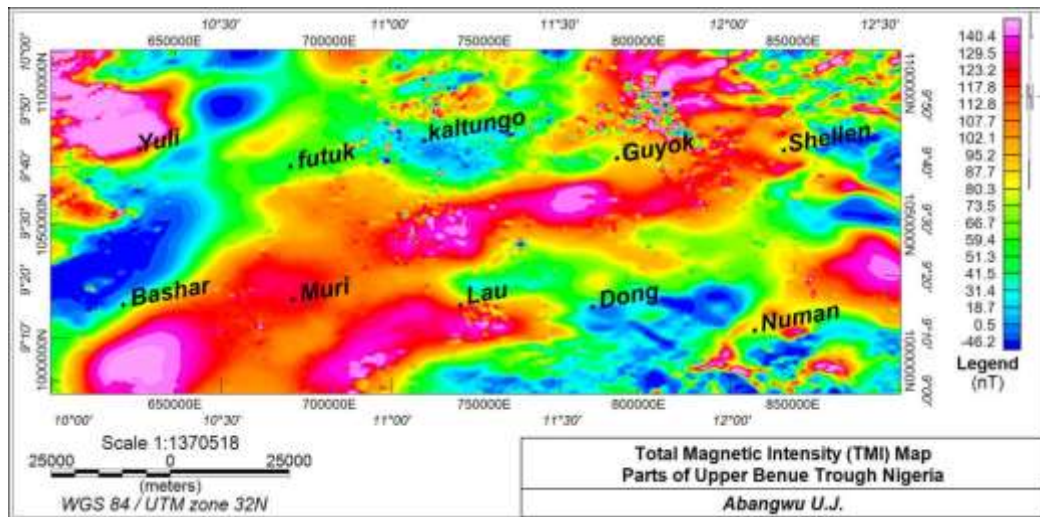


Figure 2. Total magnetic intensity (TMI) anomaly map.

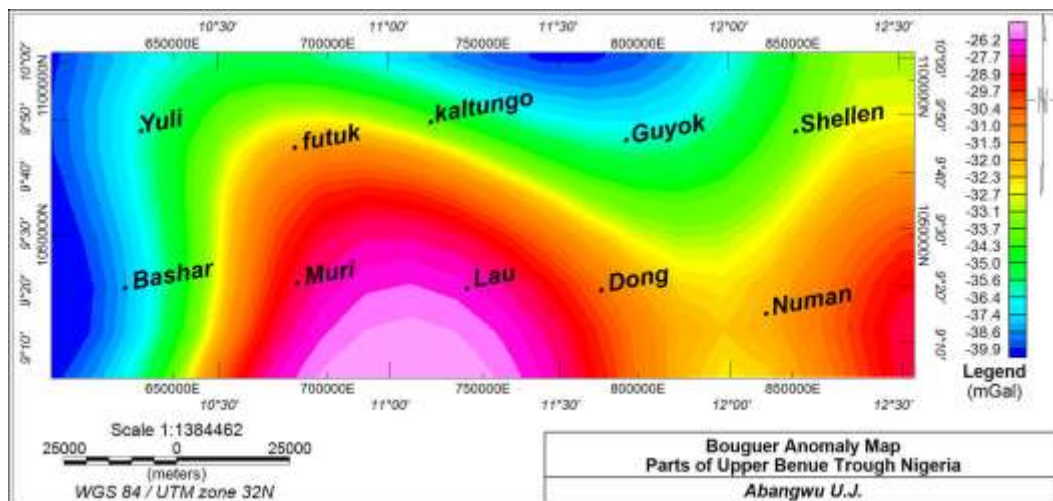


Figure 3. Bouguer anomaly map.

5-2. Magnetic and Gravity Residual Anomaly Results

The magnetic residual map (Figure 4) displays positive and negative residual anomalies ranging from -121.8 to 64.9 nT that may be caused by the combined action of zones of fundamental intrusive bodies that are present in the sedimentary basin or basement complex. Areas with significant positive anomalies (pink color) are most likely related to a larger concentration of magnetically susceptible materials, such as igneous intrusions. Similarly, magnetic lows (blue color) indicate low magnetic concentration and, as a result, less susceptibility.

The Bouguer residual map (Figure 5) of the study area ranges from -8.4 to 4.5 mGal. Areas such as Muri and Lau with gravity high (red and pink), correspond to regions with high-density contrast beneath the

surface and may be associated with igneous intrusions. Intermediate values (green and yellow) are distributed around the area, while Bashar, Yuli, Kaltungo, and Guyok area with gravity lows (blue color), likely resulting from sediment deposits in the area. After applying polynomial fitting to the total magnetic and Bouguer gravity field data, it was observed that the general trends of the residual maps remain almost identical to those of the original total field maps. This similarity indicates that the study area is largely influenced by broad regional geological features, such as basement undulations and deep-seated tectonic structures, and that both deep and shallow structures share similar orientations and sources. This reflects a geologically consistent crustal framework, in which the same basement faults and intrusions affect the potential field signals at all depths.

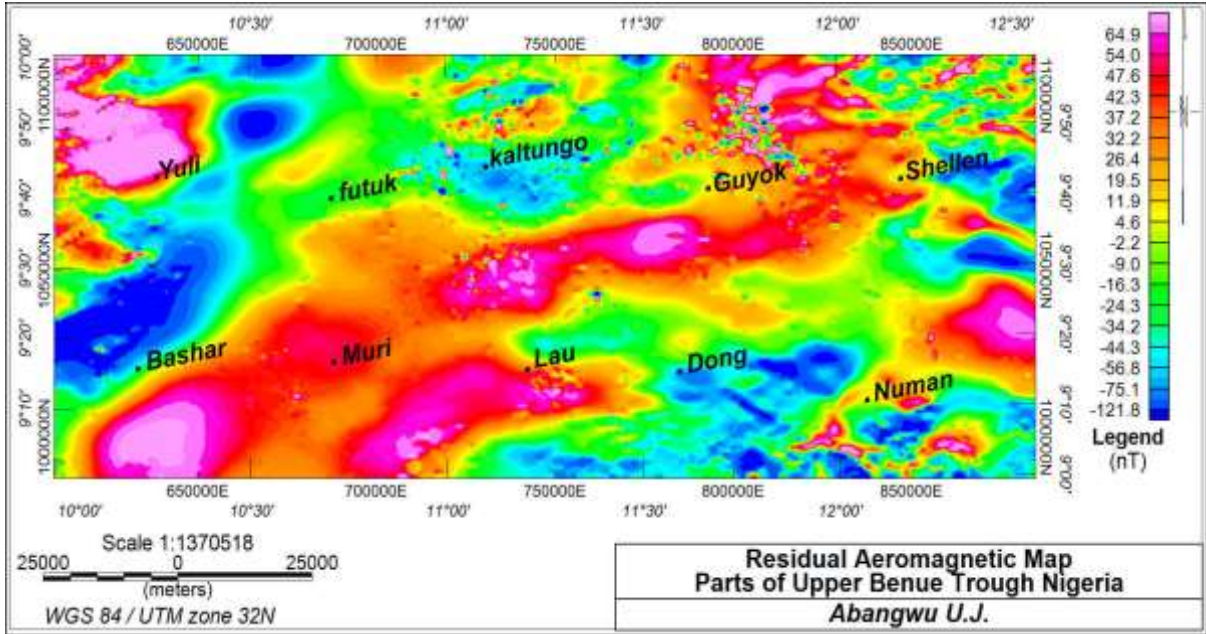


Figure 4. Residual magnetic anomaly map.

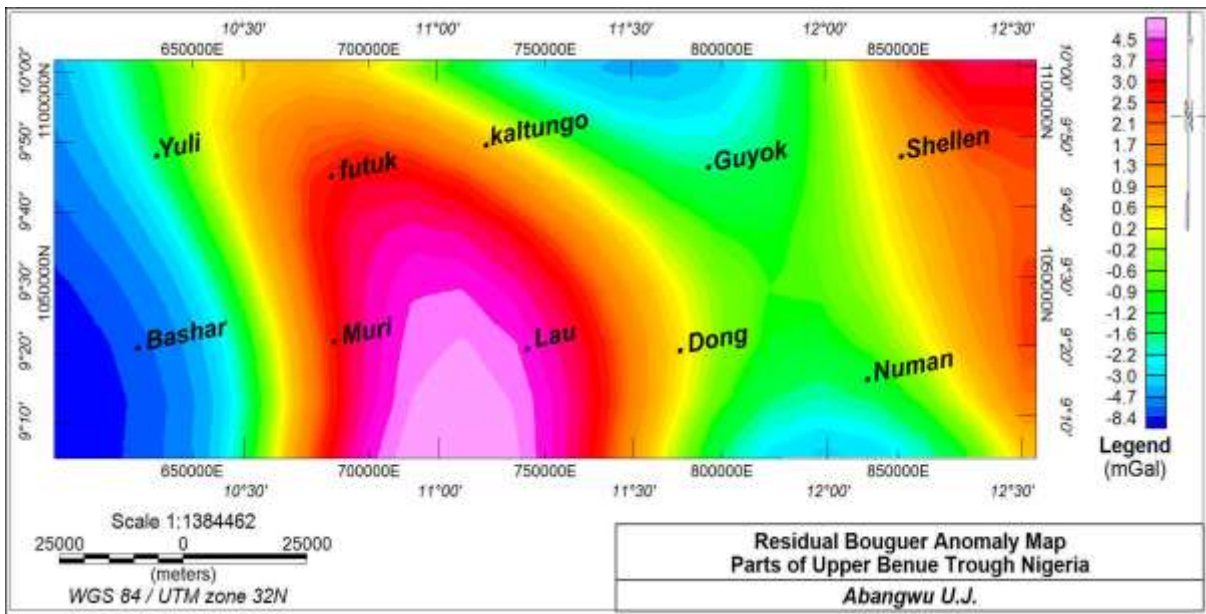


Figure 5. Residual Bouguer anomaly map.

5-3. Source Parameter Imaging (SPI) Result

Figure 6 presents the magnetic SPI map of the study area, with depth values ranging from -207.4 to -3523.0 m. The negative depth values on the SPI legend correspond to the depths of magnetic bodies beneath the surface. Areas with shallower depths are indicated in pink, while deeper regions are

represented in blue.

Figure 7 shows the gravity SPI depth map, with depth values ranging from -115.7 to -3767.3 m. Similar to the magnetic map, the negative values on the SPI legend denote the depths of subsurface gravity anomalies. Shallow areas are depicted in pink, while deeper regions are indicated in blue.

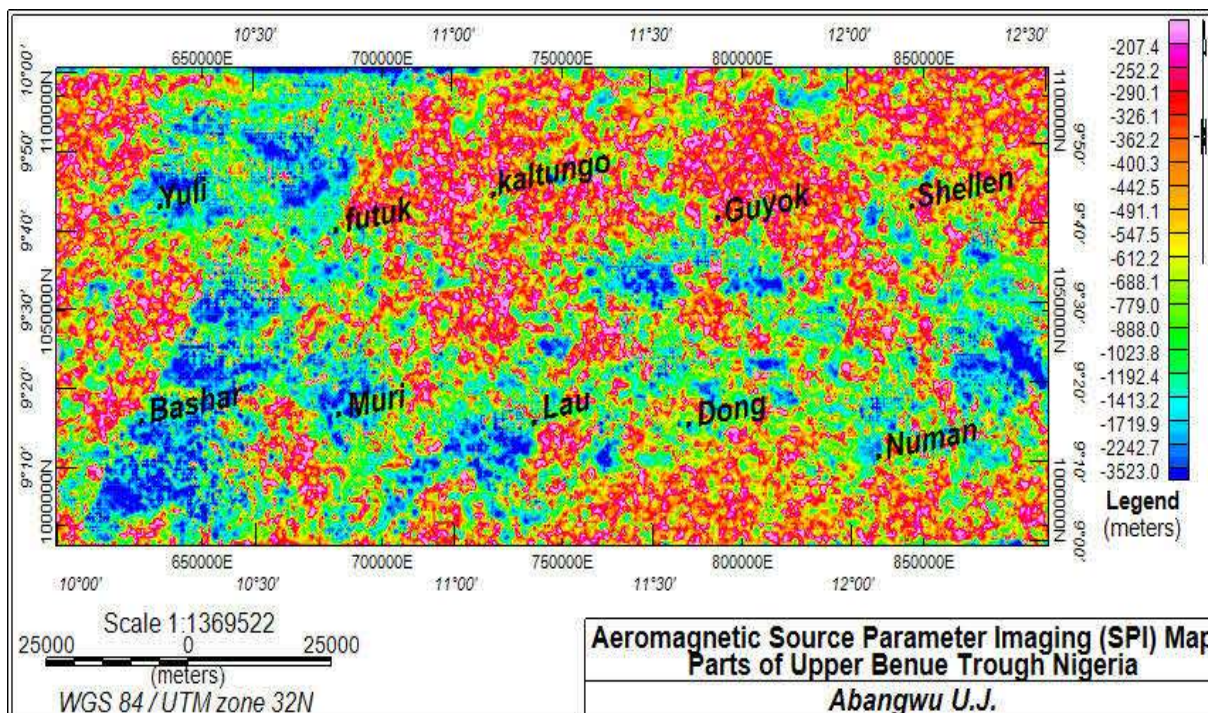


Figure 6. Magnetic source parameter image (SPI) map.

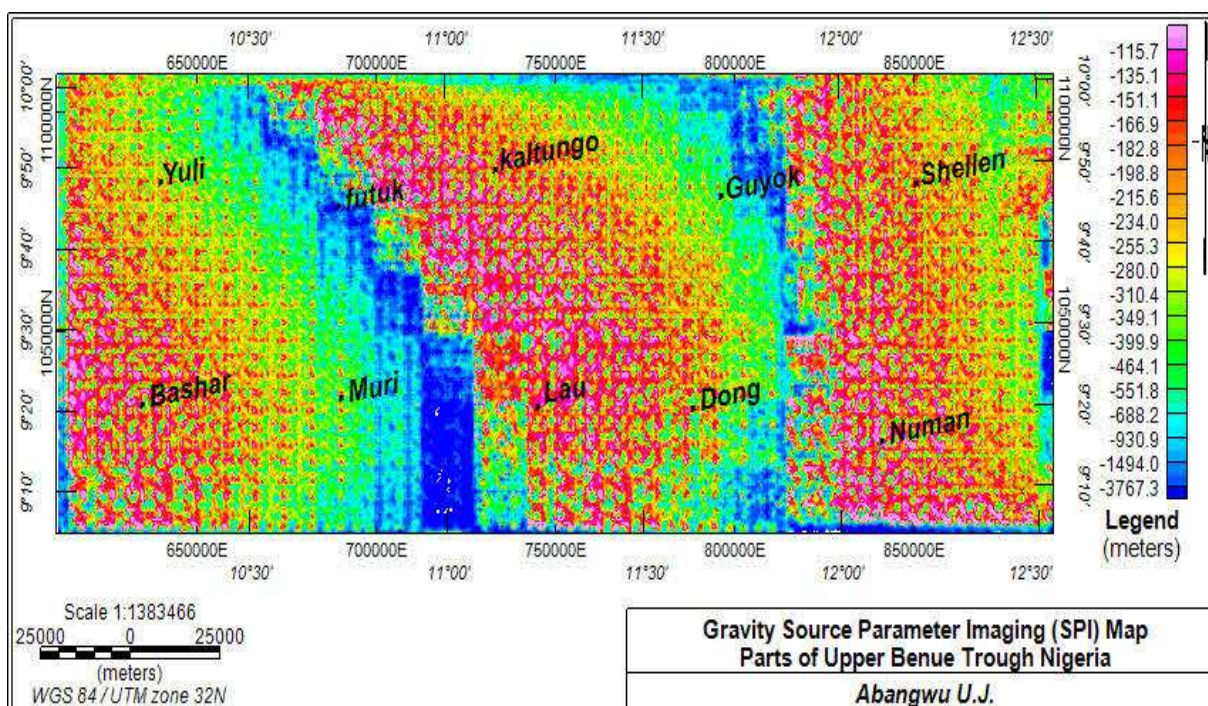


Figure 7. Gravity source parameter imaging (SPI) map.

A comparison of Source Parameter Imaging (SPI) depth maps obtained from residual magnetic and residual gravity data reveals a broadly comparable depth pattern, with both approaches indicating deep basins and shallower basement highs. Where the two maps agree (deep magnetic SPI coincides with deep gravity SPI), the anomaly is

most likely caused by a thick, non-magnetic sedimentary cover. Where gravity indicates deep values but magnetic depths are shallow, the source is most likely a sedimentary layer with poor susceptibility. In contrast, shallow magnetic SPI associated with gravity highs frequently marks dense, magnetically sensitive igneous intrusions or basement uplifts.

5-4. Euler Deconvolution Result

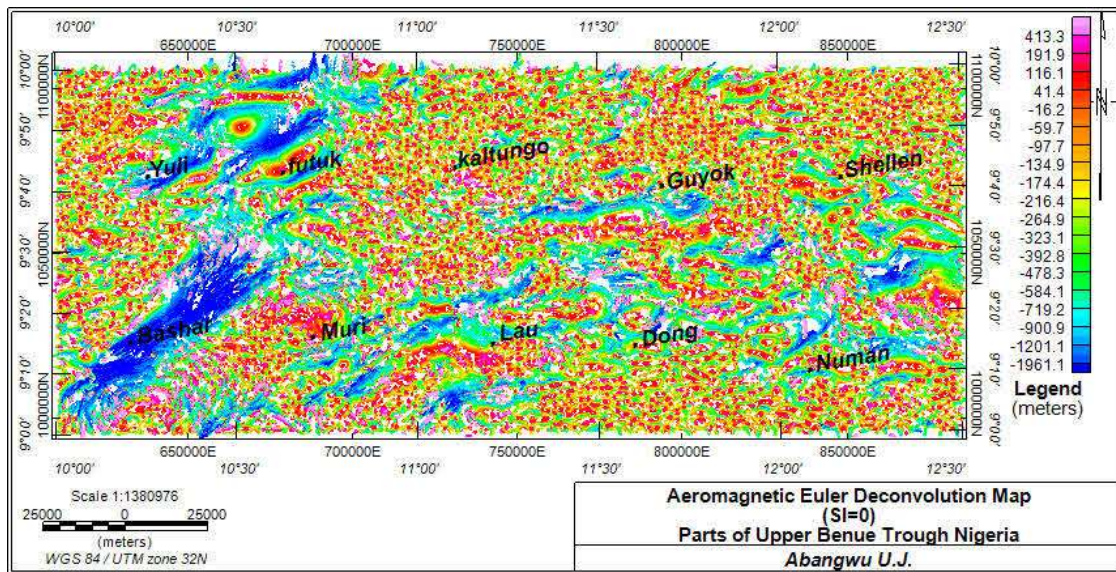
The magnetic Euler deconvolution maps are shown in Figure 8(a-d). The magnetic Euler depth for structural index 0 ranges from 413.3 to -1961.1 m, index 1 ranges from 174.7 to -2524.1 m, index 2 ranges from -193.1 to -3302.7 m, index 3 ranges from -400.9 to -3597.5 m. The gravity Euler deconvolution maps were generated as shown in Figure 9(a - c). The gravity Euler depth for structural index 0 ranges from 600.6 to -1908.1 m, index 1 ranges from 461.5 to -2969.3 m, index 2 ranges from 399.6 to -3606.4 m. These indices were selected based on the expected tectonic and structural configurations of the rift-related Upper Benue Trough. Therefore, using a range of structural indices from 0 to 3 ensures that different geological sources contributing to the magnetic and gravity anomalies are appropriately captured and interpreted. The positive depths value depicts thin sediment layers due to basement outcrops, whereas negative values indicate thicker sedimentary layers. Generally, the magnetic and gravity Euler solutions exhibit a close spatial correspondence, suggesting that both datasets respond to the same tectonic framework.

6. Discussion

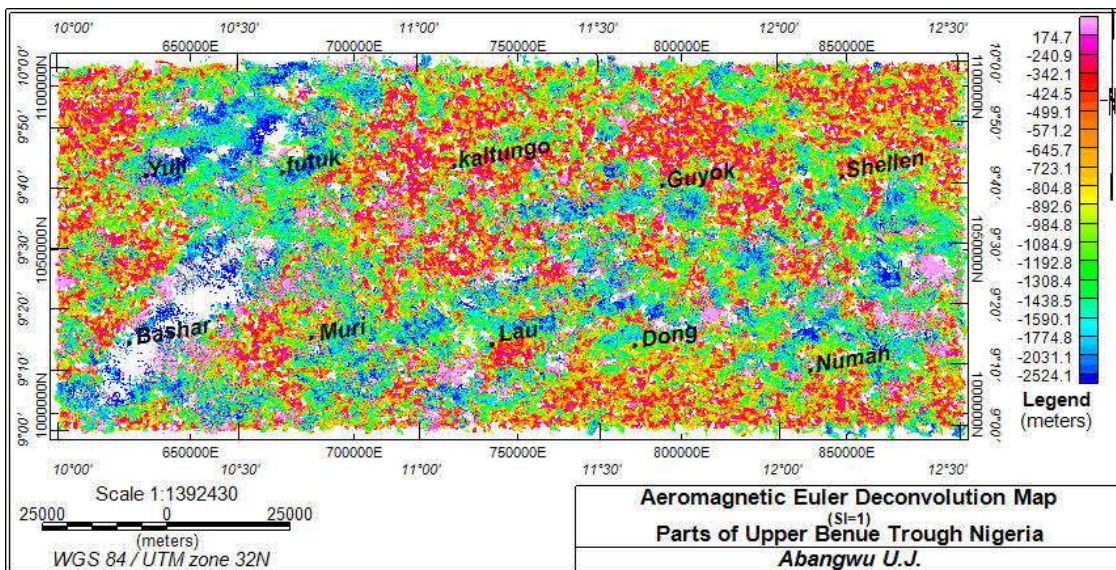
The depth estimates from the SPI and Euler Deconvolution are consistent with known stratigraphic units, such as the Bima Sandstone and Yolde Formation, confirming that the Upper Benue Trough contains substantial sedimentary thicknesses (Carter et al., 1963; Obaje, 2009). The unconventional appearance of the gravity SPI and Euler depth maps is mainly due to the coarse resolution and long-wavelength nature of satellite gravity data compared to the high-resolution, near-surface sensitivity of aeromagnetic data. Since these two datasets measure different physical properties (density versus magnetism) and respond to different depth ranges, their depth maps should not be expected to be identical.

To validate the reliability of the present results, the depth estimates obtained from the SPI and Euler deconvolution analyses were compared with those reported by previous researchers in the Upper Benue Trough. The maximum sedimentary thickness of -3767.3 m obtained in this study closely agrees with the 3.35 km maximum depth reported by Salako and Udensi (2013), who employed spectral analysis techniques on aeromagnetic data. The slight difference in values may be attributed to the integration of satellite gravity (GRACE) and aeromagnetic datasets in the present study, which provides greater sensitivity to deeper subsurface structures. Additionally, the maximum sedimentary thickness of approximately 4 km obtained in this study is comparable to the maximum thickness of above 4 km reported by Ajala et al. (2021) in the north-eastern part of the Adamawa Trough, which they identified as sufficient for hydrocarbon maturation and accumulation. This close agreement further supports the inference that the Upper Benue Trough possesses adequate sedimentary thickness capable of sustaining hydrocarbon generation.

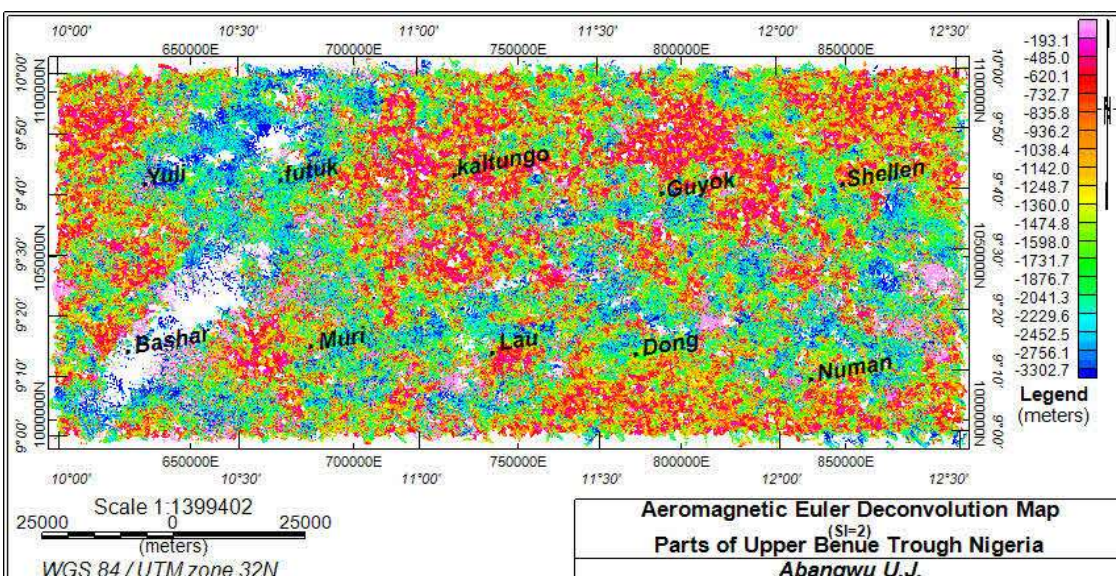
The limitations and uncertainties of the SPI and Euler methods arise from their assumptions of homogeneous source geometries and constant physical property contrasts, which may not accurately represent the heterogeneous nature of real subsurface conditions. Although explicit error margins were not computed due to the preprocessed nature of the available datasets, standard filtering and data processing procedures were applied using Oasis Montaj software to minimize potential uncertainties. Additionally, the depth estimation techniques (SPI and Euler Deconvolution) were cross-validated to ensure internal consistency. The close agreement between the SPI and Euler depth results, as well as their correlation with previous studies (Salako and Udensi, 2013; Ajala et al., 2021), provides confidence in the reliability of the interpretations.



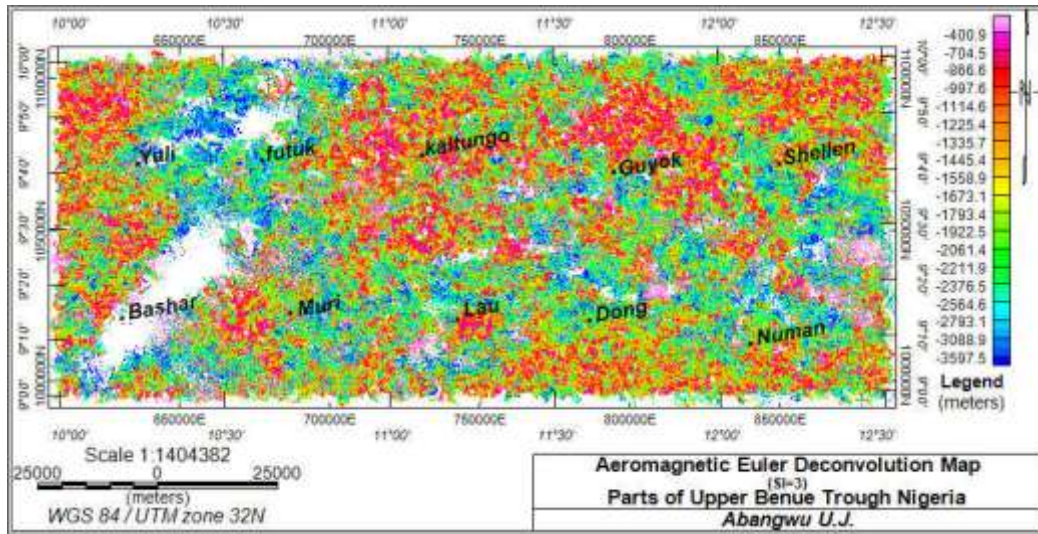
(a)



(b)

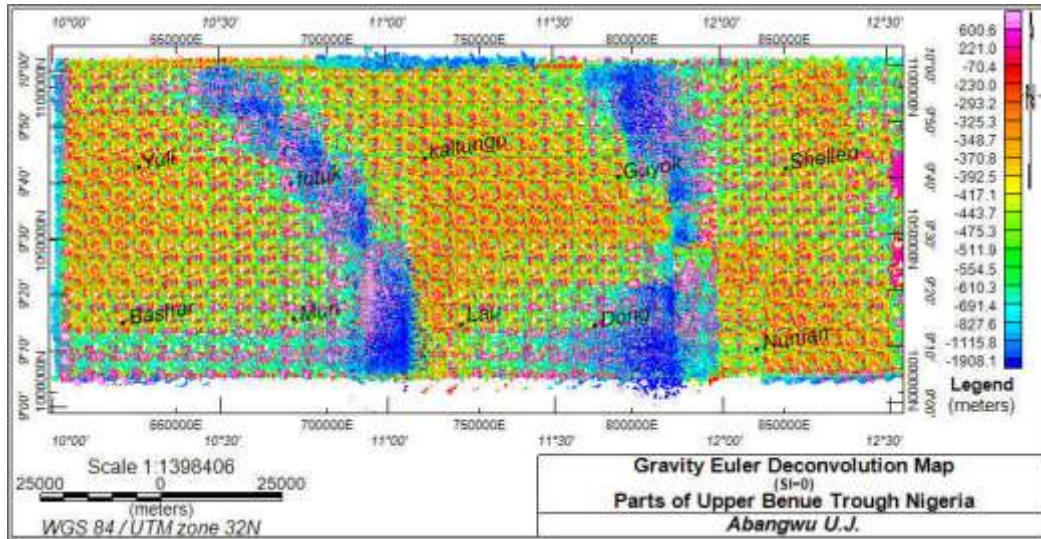


(c)

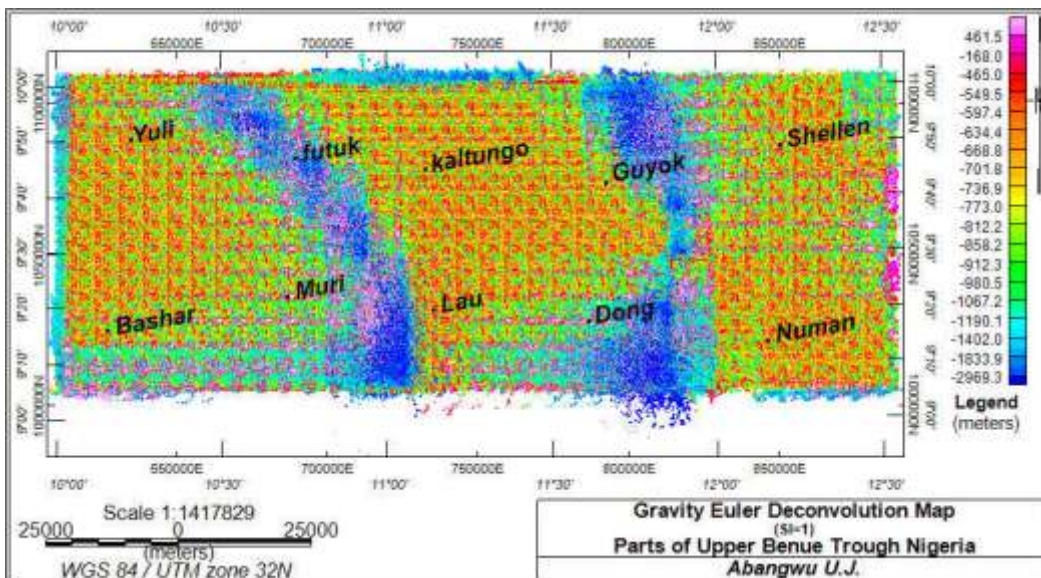


(d)

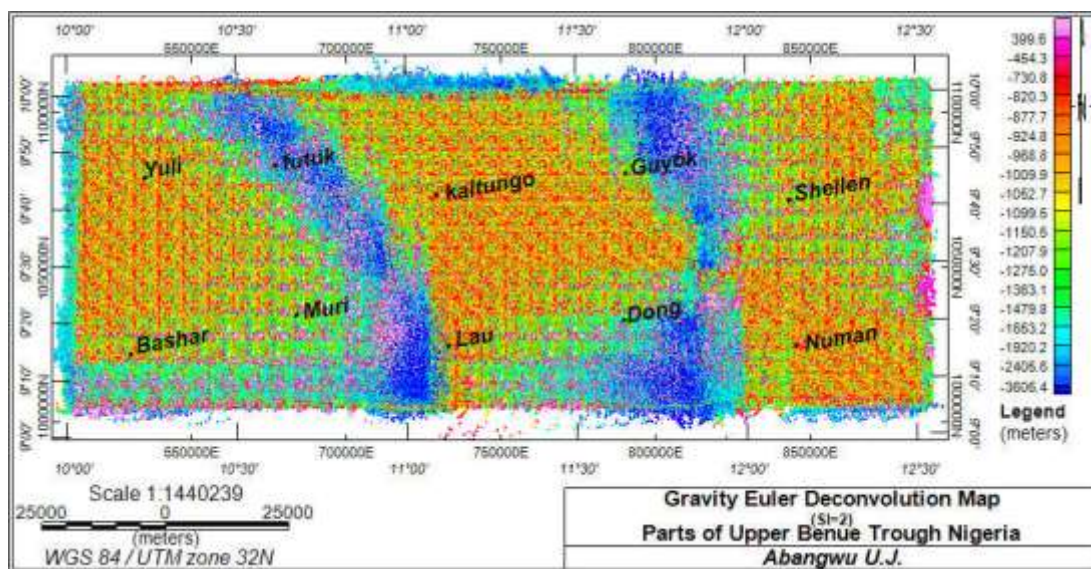
Figure 8. a) Magnetic Euler map, SI=0, b) Magnetic Euler map, SI=1, c) Magnetic Euler map, SI=2, d) Magnetic Euler map, SI=3.



(a)



(b)



(c)

Figure 9. a) Euler deconvolution map, SI=0, b) . Euler deconvolution map, SI=1, c) Euler deconvolution map, SI=2.

7. Conclusion

The high-resolution aeromagnetic as well as Gravity Recovery and Climate Experiment (GRACE) data for parts of the Upper Benue Trough were analyzed and quantitatively interpreted using two depth-estimation techniques: Source Parameter Imaging (SPI) and Euler Deconvolution. These methods were employed to estimate sedimentary thickness and evaluate the hydrocarbon potential of the study area. The SPI and Euler Deconvolution results indicate maximum sedimentary thicknesses of -3767.3 m and -3606.4 m, respectively.

The estimated sedimentary thicknesses suggest favorable conditions for hydrocarbon generation within the basin. However, sedimentary thickness alone is insufficient to confirm hydrocarbon potential, as successful accumulation also depends on several other geological factors, including the presence of mature source rocks, efficient migration pathways, appropriate reservoir formations, effective seals, and suitable trap mechanisms. Therefore, while the observed sedimentary thickness indicates a promising geological setting, further studies integrating seismic data, geochemical analysis, and well-log information are recommended to evaluate source rock maturity and structural closure conditions before making any definitive conclusions regarding hydrocarbon accumulation.

The results further show that areas such as Bashar, Yuli, Futuk, Dong, and Guyok are

characterized by low gravity and magnetic residuals with deep SPI and Euler-derived depths, suggesting significant sedimentary accumulation above a depressed basement. Consequently, these zones are interpreted as potential hydrocarbon-prone areas, where sufficient sedimentary thickness and favorable structural conditions may support hydrocarbon generation and entrapment.

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