Communication in Physical Sciences, 2024, 12(3): 1109-1122

Magnetic Response Analyses in Parts of the Southern Benue Trough: Implications for Mineral Prospecting

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Received: 12 November 2024/Accepted: 01 March 2025/Published: 14 March 2025
https://dx.doi.org/10.4314/cps.v12i3.31

Abstract: *This study presents an analysis of high-resolution aeromagnetic data from parts of the Lower Benue Trough, specifically covering regions in Abia, Imo, Enugu, Anambra, Ebonyi, Cross River, and Benue States, situated between latitudes 05° 00′ N and 07° 00′ N and longitudes 07° 30′ E and 09° 00′ E. The data was obtained from nine aeromagnetic sheets (numbers 287, 288, 289, 301, 302, 303, 312, 313, and 314), which cover Nsukka, Igunmale, Ejekwe, Udi, Nkalagu, Abakaliki, Okigwe, Afikpo, and Ugep. The Total Magnetic Intensity (TMI) map of the study area revealed magnetic intensity values ranging from -47.3 nT to 151 nT, with the highest intensity observed in the northern part of the study area near Bende, where a prominent NE-SW trend was noted. The reduction to equator (RTE) showed a range of -34.84 nT to 135.26 nT, with significantly high-intensity anomalies observed around Okigwe, Isiukwuato, and Afikpo. The regional anomaly map revealed deeply seated rocks around Isuikwuato and Okigwe, marked by a prominent NE trend. Upward continuation of the data at heights of 50 m, 500 m, 5 km, and 10 km demonstrated a decrease in near-surface magnetic responses, confirming that as the upward continuation height increased, the regional magnetic anomaly became more pronounced. These findings indicate the presence of magnetic intrusions in the North-Eastern and South-Western parts of the study area, making it a viable region for mineral exploration. The results are consistent with previous studies in the region, further supporting the potential for mineral prospecting.*

Keywords: *Total Magnetic Intensity, Intrusive, Magnetic Response, Upward Continuation and Analytical Signal*

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1.0 Introduction

Magnetic methods play a vital role in geophysical investigations aimed at understanding the Earth's subsurface structures, particularly in the context of mineral exploration and geological mapping. These methods are based on the principle that subsurface materials exhibit varying responses when exposed to the Earth's magnetic field. Such variations, referred to as magnetic anomalies, are localized deviations in the

Earth's magnetic intensity caused by differences in magnetic susceptibility, mineral composition, or the presence of ferromagnetic minerals. Some subsurface materials become magnetized in the presence of an external magnetic field, while others possess remnant magnetization, resulting in anomalies that offer insight into geological structures and compositions (Telford et al., 2001; Reeves, 2005).

Magnetic surveys are particularly effective in providing diagnostic information regarding the geometry, depth, strike, and extent of causative bodies, as well as their lithology, magnetic susceptibility, and intrinsic magnetization. The Earth's magnetic field, measured in nanoTesla (nT), increases in intensity with latitude, and anomalies are interpreted by analyzing variations relative to the regional magnetic field (Musset and Khan, 2000). These techniques have gained traction in structural mapping, basement depth estimation, lithological boundary delineation, and identifying potential zones for mineral accumulation (Murphy, 2007; Nwokeabia et al., 2021).

In Nigeria, magnetic surveys have been widely applied to explore the mineral and structural settings of the Benue Trough, a geologically significant rift structure formed during the separation of South America and Africa in the Early Cretaceous. The Benue Trough is subdivided into northern, central, and southern segments, each exhibiting distinct tectonic and stratigraphic characteristics. Numerous researchers have investigated different portions of the trough using aeromagnetic datasets. For instance, Udegbe et al. (2017) and Anyadiegwu et al. (2019) examined the structural frameworks of the Middle Benue Trough and southeastern Nigeria, respectively, revealing fault zones, intrusive bodies, and magnetic lineaments with implications for mineralization. Similarly, Chukwu et al. (2013) and Cyril (2019) analyzed magnetic anomaly maps to infer basement topography and potential mineral-bearing structures. Ugwu and Ezema (2017) and Ike et al. (2017) used upward continuation and analytical signal techniques to isolate deep-seated sources and characterize the magnetic features of the region. Obi et al. (2010) and Azunna et al. (2020) contributed to the understanding of regional tectonics and lithological differentiation through magnetic methods.

Despite the wealth of literature, much of the existing research has focused on the central and northern segments of the Benue Trough, leaving the southern part relatively underexplored in terms of detailed magnetic characterization. This gap is significant given the complex geological setting and the known occurrence of igneous intrusions, hydrothermal systems, and sedimentary sequences in the southern trough, which may host economically viable mineral deposits. A more comprehensive geophysical investigation is therefore warranted to delineate the spatial distribution, depth, and structural alignment of magnetic anomalies in this area, particularly in light of the region's increasing appeal for mineral prospecting and investment.

The present study addresses this gap by analyzing high-resolution aeromagnetic data from selected parts of the southern Benue Trough. The study area spans latitudes 05°00′N to 07°00′N and longitudes 07°30′E to 09°00′E, covering parts of Abia, Imo, Enugu, Anambra, Ebonyi, Cross River, and Benue States. The analysis involves combining nine aeromagnetic sheets and applying various filters including reduction to equator, upward continuation, and analytical signal techniques to extract relevant subsurface features. The goal is to delineate intrusive bodies, structural lineaments, and zones of high magnetic intensity that are indicative of potential mineralization. By building upon and extending the findings of previous researchers, this work aims to contribute a detailed and updated geophysical model for the southern Benue Trough that can serve both academic and industrial applications in mineral resource exploration.

1.1 The Study Area

The study area is geographically situated between latitudes 05°00′N and 07°00′N and longitudes 07°30′E and 09°00′E, encompassing a significant portion of the Southern Benue Trough. This trough represents the southernmost segment of the larger Benue Trough, one of the most prominent sedimentary basins in Africa. The Benue Trough itself extends for over 1,000 kilometers in length and varies in width from approximately 150 to 250 kilometers. It constitutes a major component of the Cretaceous West African Rift System (WARS), which spans nearly 4,000 kilometers, beginning in southern Nigeria, extending through the Republic of Niger, and terminating in Libya (Binks and Fairhead, 1992).

Structurally and geographically, the Benue Trough is subdivided into three principal segments aligned in a northeast-southwest orientation: the Lower Benue Trough, the Middle Benue Trough, and the Upper Benue Trough, as illustrated in Fig. 1, which is adapted from Obaje et al. (1999). The focus of this study lies within the Southern Benue Trough, which encompasses parts of Abia, Imo, Enugu, Anambra, Ebonyi, Cross River, and Benue States. Notable towns within this region include Nsukka, Igumale, Ejekwe, Udi, Nkalagu, Abakaliki, Okigwe, Afikpo, and Ugep.

The geological framework of the study area is diverse and is depicted in Fig. 2. It includes several stratigraphic formations such as the Ogwashi/Asaba, Ameki/Nanka, Imo, Nsukka, Mamu, and Odukpani Formations. In addition, the region comprises lithostratigraphic groups including the Asu River Group, Eze-Aku Group, Awgu Group, and Nkporo Group. Basement complex rocks and the Ajali Sandstone also occur within the area, reflecting a complex and multi-phase depositional history. The stratigraphy of the Southern Benue Trough spans from the Cretaceous to the Tertiary periods and is characterized by three distinct sedimentary phases: the Abakaliki-Benue Phase (Aptian to Santonian), the Anambra-Benin Phase (Campanian to Middle Eocene), and the Niger-Delta Phase (Late Eocene to Pliocene) (Azunna et al., 2021). These phases reflect significant tectono-sedimentary episodes that have contributed to the structural and lithological evolution of the basin.

2.0 Materials and Methods

2.1 Data Acquisition

The airborne magnetic data used in this study were obtained from the Nigerian Geological Survey Agency (NGSA). These data were collected on a scale of 1:100,000 and encompass parts of the Southern Benue Trough. The covered locations include Nsukka, Igumale, Ejekwe, Udi, Nkalagu, Abakaliki, Okigwe, Afikpo, and Ugep. These correspond to the aeromagnetic map sheets numbered 287, 288, 289, 301, 302, 303, 312, 313, and 314 respectively.

2.2 Data Preparation and Compilation

To create a comprehensive magnetic representation of the study area, the individual map sheets were georeferenced and merged into a single composite dataset. This compilation was essential for generating a regional Total Magnetic Intensity (TMI) map. The NGSA had previously removed a constant base value of 33,000 nanoTesla (nT) from the original total magnetic field data to normalize the values before release.

2.3 Data Processing

The merged composite data were subjected to a series of processing and enhancement techniques, carried out in both the wavenumber and Fourier domains. These processes aimed to improve the interpretability of magnetic anomalies and to isolate geological features of interest. Key geophysical transformations applied include Reduction to the Equator (RTE) and Reduction to the Pole (RTP), which corrected for the effects of magnetic latitude and ensured that the anomalies were centered over their causative sources.

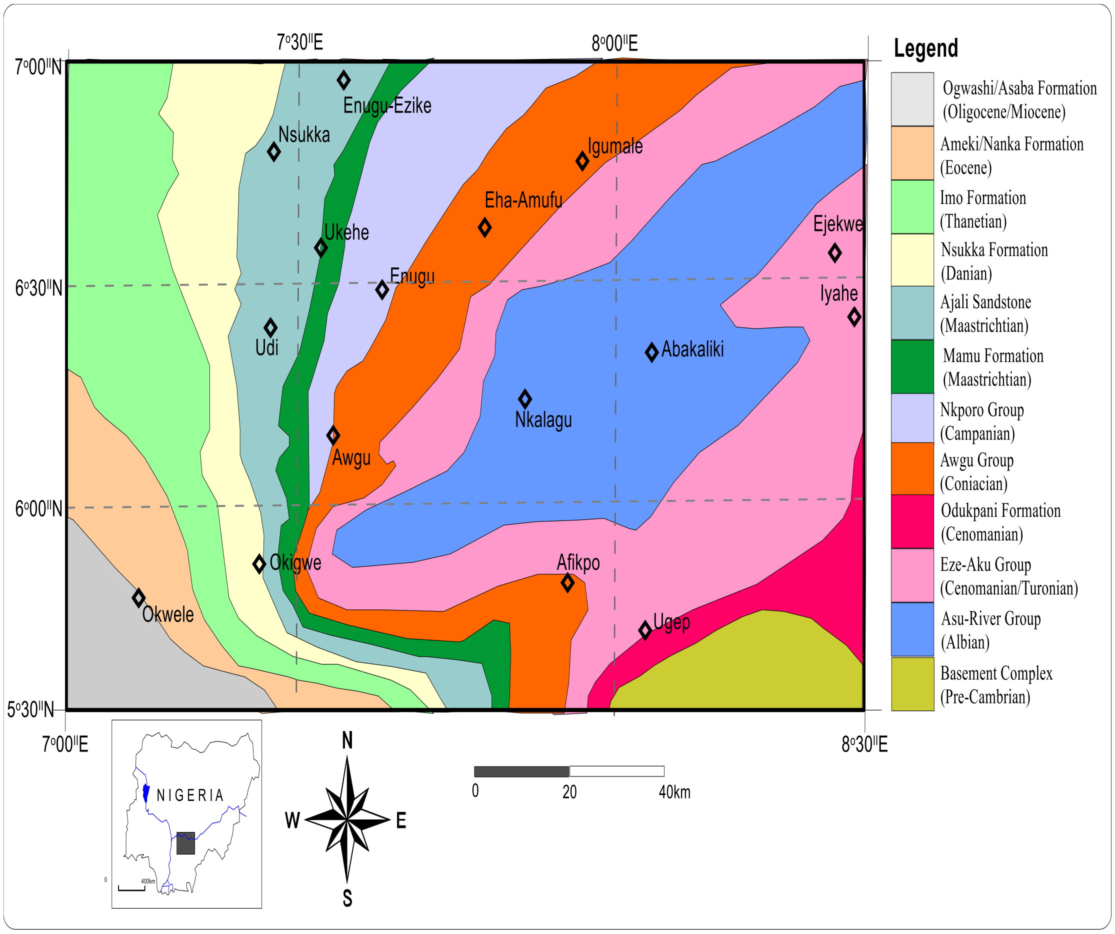

Fig. 2: Geology map of the study area

In addition, upward continuation at varying heights was applied to suppress near-surface noise and highlight deeper-seated magnetic sources. Vertical derivatives were also computed to enhance shallow subsurface structures by amplifying high-frequency components associated with lithological contacts and faults.

2.4 Analytical Techniques

Further analytical techniques, such as regional-residual separation, were performed to distinguish deep-seated (regional) magnetic signals from shallow (residual) sources. The analytical signal method, which utilizes the combined horizontal and vertical gradients of the magnetic field, was employed to define the edges of magnetic bodies and to estimate the locations and dimensions of causative geological features.

3.1 Total Magnetic Intensity (TMI)

The Total Magnetic Intensity (TMI) map of the study area, after IGRF correction, exhibits variations in magnetic intensity across both long and short wavelengths. The magnetic intensity values range from -47.3 nT to 151 nT. High magnetic intensity values, depicted in pink, are primarily located in the northern part of the area, near Bende. This region exhibits a prominent northeast-southwest (NE-SW) trending long-wavelength anomaly, which is likely regional in origin. Conversely, localized magnetic signals, which are residual in nature, are observed around Igumale in the northeastern part of the study area.

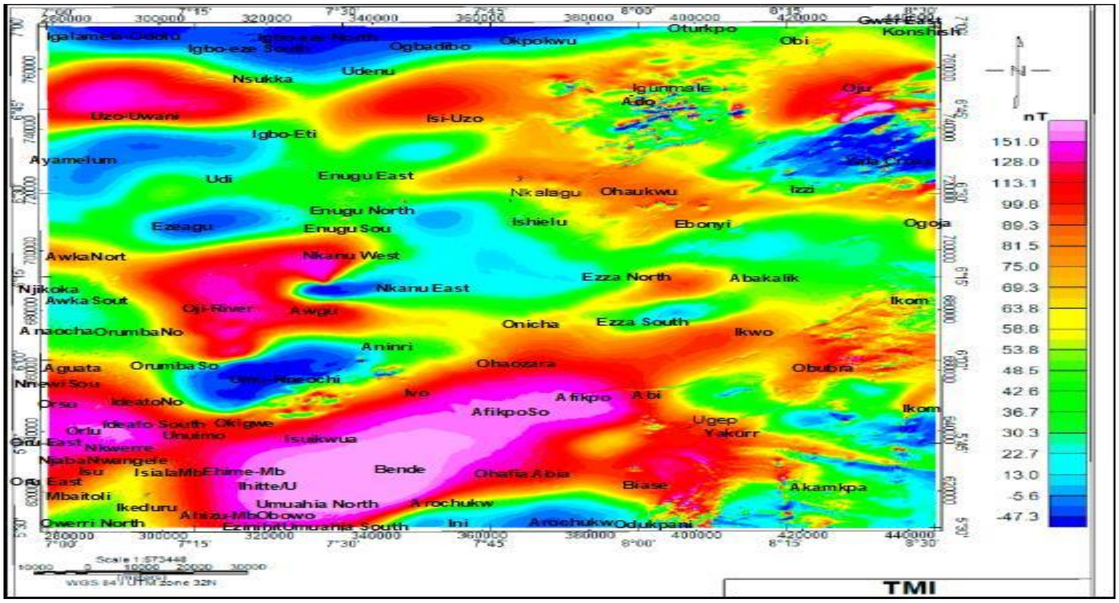

Fig. 3 : The Total magnetic intensity map of the area of study

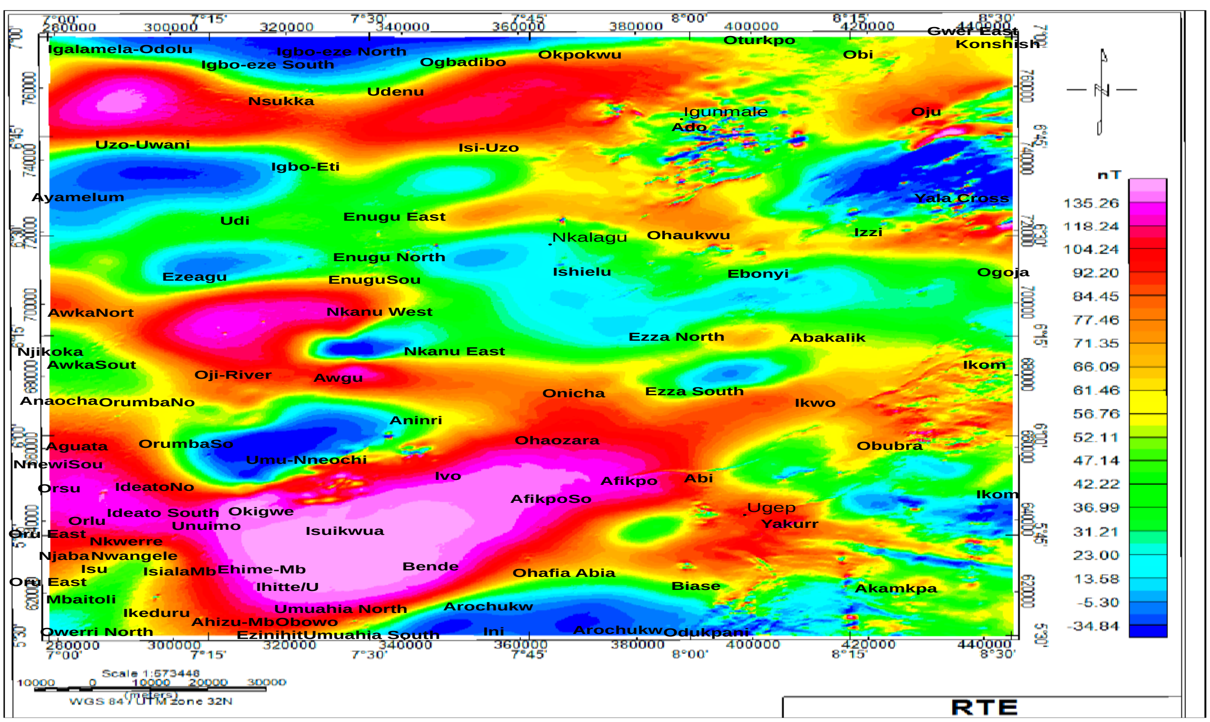

Fig.. 4: The total magnetic intensity map reduced to magnetic equator (RTE)

3.2 Reduction to Magnetic Equator (RTE)

The Total Magnetic Intensity map was reduced to the magnetic equator due to the study area's proximity to the equatorial zone. This approach was preferred over reduction to the pole (RTP), as it helps to preserve the original shape of magnetic anomalies. The magnetic anomaly shape depends on the causative body, and reducing to the equator minimizes distortions caused by magnetic latitude effects. The RTE map (Fig. 4) exhibits values ranging from -34.84 nT to 135.26 nT. High magnetic intensity areas (shown in pink) are found around Okigwe, Isuikwuato, and Afikpo in the southwestern part of the composite map, while low magnetic intensities (shown in blue) are observed near Udi, the eastern part of Igunmale, and the northern part of Nsukka. The RTE map combines both regional and residual anomalies.

3.3 Regional Anomaly Map

The regional anomaly map highlights long-wavelength anomalies, which are typically associated with deeply seated rocks, regardless of their magnetic susceptibility. Long-wavelength (low frequency, low amplitude) anomalies primarily originate from deep-seated sources. The regional filter applied to the RTE map accentuates these long-wavelength signals. The regional anomaly map (Fig. 5) shows magnetic intensity values ranging from 28.3 nT to 77.7 nT. The study area is predominantly sedimentary, and the basement rocks are located at considerable depths, with some near-surface intrusions. High-intensity anomalies along the NE-SW trend, such as those observed around Isuikwuato and Okigwe, indicate low magnetic susceptibility and suggest deeply seated rocks. The regional anomaly map also reveals regional trends in NE-SW and east-west directions.

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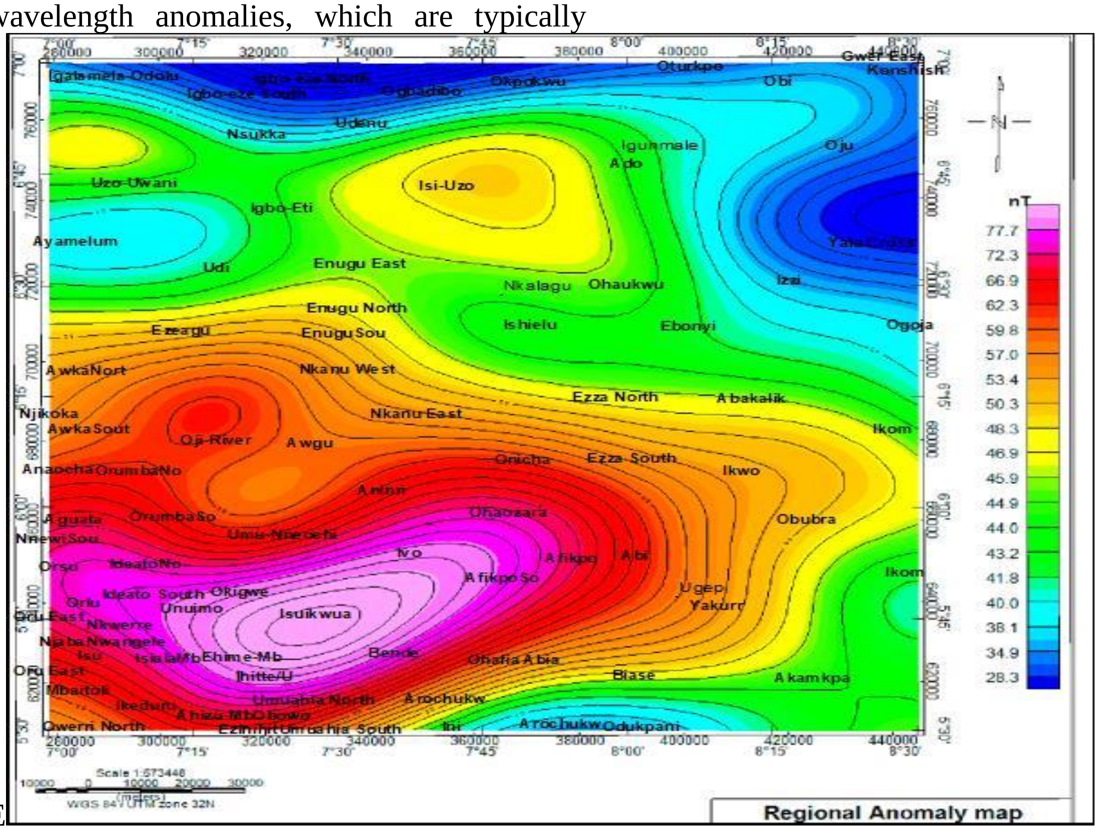

Fig. 5: The Regional magnetic Anomaly map of the area

3.4 Residual Anomaly Map

The residual anomaly map was generated using a high-pass filter applied to the RTE map. This map emphasizes anomalies originating from near-surface magnetic rocks, particularly those resulting from recent intrusions within the sedimentary environment. The residual anomaly map (Fig. 6) shows a narrow intensity range from -13.866 nT to 7.550 nT, with high-amplitude, short-wavelength anomalies identified in areas like Igunmale, Okigwe, Enugu North, Nsukka, Oju, Ugep, Obubra, Akamkpa, and Ikom. These short-wavelength anomalies are indicative of remanent magnetization resulting from near-surface basement intrusions. The depth of occurrence is defined by the wavelength of these clustered signals. The high-intensity areas (pink) indicate low magnetic susceptibility, while the low-intensity areas (blue) suggest high susceptibility rocks. These areas are potential sites for hydrothermal-related deposits associated with basement intrusions.

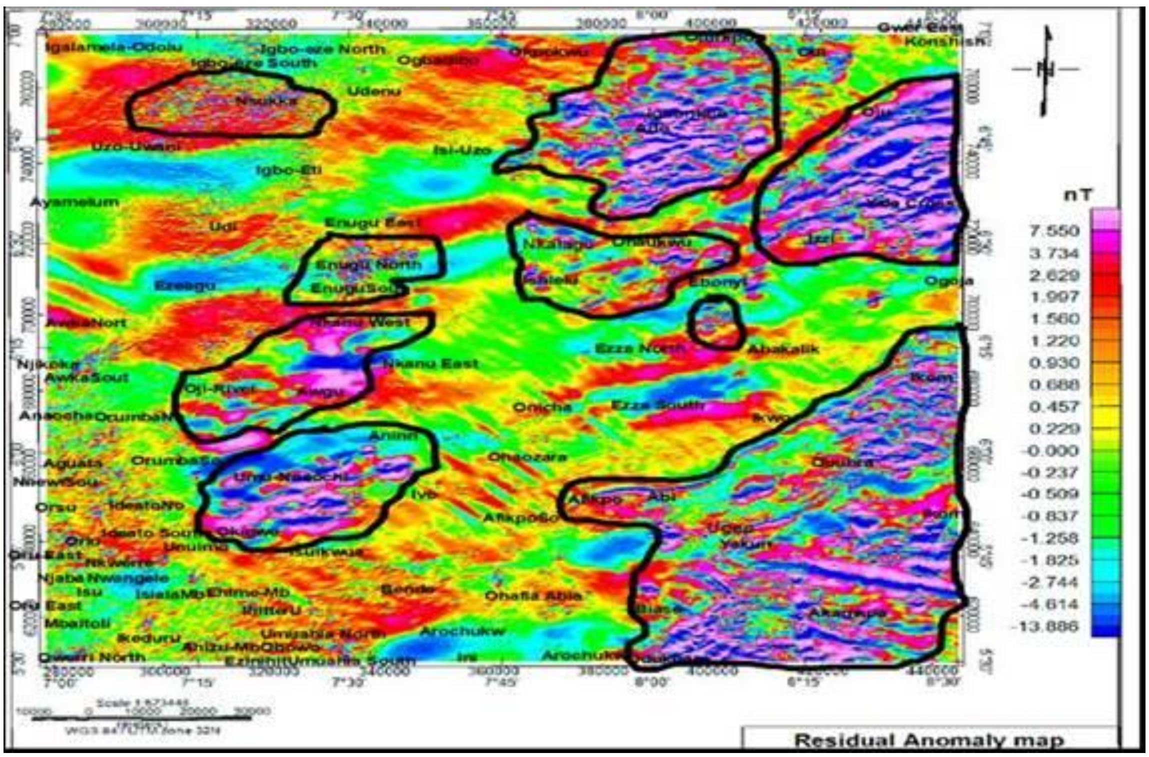

Fig. 6: The residual Magnetic anomaly map of the area (the areas with short wavelength remanent magnetism resulting from near surface magmatic emplacement in Black Polygon)

3.5 Vertical Derivatives

The first vertical derivative map was computed to enhance the local magnetic response and highlight near-surface geological features. This derivative filter decreases broad regional anomalies, enabling the identification of localized structures associated with near-surface basement intrusions. The first vertical derivative map (Fig. 7) reveals three primary structural trends: ENE-WSW, NE-SW, and NW-SE. These prominent structures, particularly in areas with near-surface basement intrusions, may serve as conduits for mineral deposits.

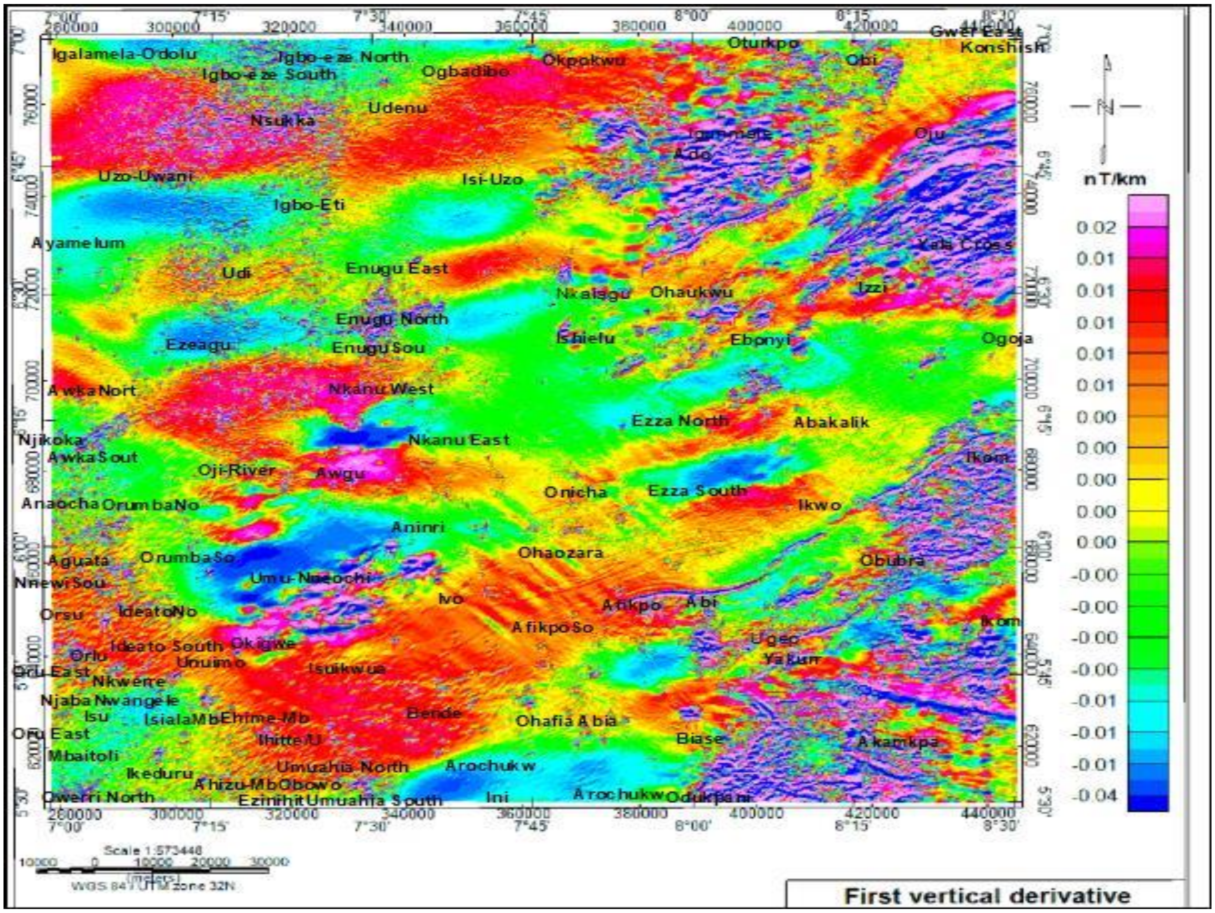

Fig. 7: The first vertical derivative map of the area

3.6 Analytical Signal

The analytical signal, an edge-detection technique, was used to identify areas with significant magnetic gradients. The amplitude of the analytical signal is independent of the direction of magnetization and reflects both horizontal and vertical derivatives. The analytical signal map (Fig. 8) identifies areas with positive gradients, especially in the southeastern part of the study area (Ugep, Obubra, Akamkpa) and the northeastern region (Oju, Igunmale). These areas correlate with those identified in the residual anomaly and first vertical derivative maps as locations with remanent magnetism due to intrusive activities. The strength of the signal corresponds to the intensity of intrusive activity, with higher signals indicating shallower bodies.

3.7 Upward Continuation

The RTE map was subjected to upward continuation at various heights (50 m, 500 m, 5,000 m, and 10,000 m) to observe the effect of filtering on the magnetic data. As the upward continuation height increases, near-surface magnetic responses are attenuated, leaving only the broad, regional anomalies. This process smooths the curves of the original signal, indicating the reduction of high-amplitude, short-wavelength signals while preserving long-wavelength, regional magnetic anomalies. The upward continuation maps (Fig.s 9-12) provide insight into the crustal geology of the area by enhancing the deep-seated basement rocks responsible for regional magnetic trends.

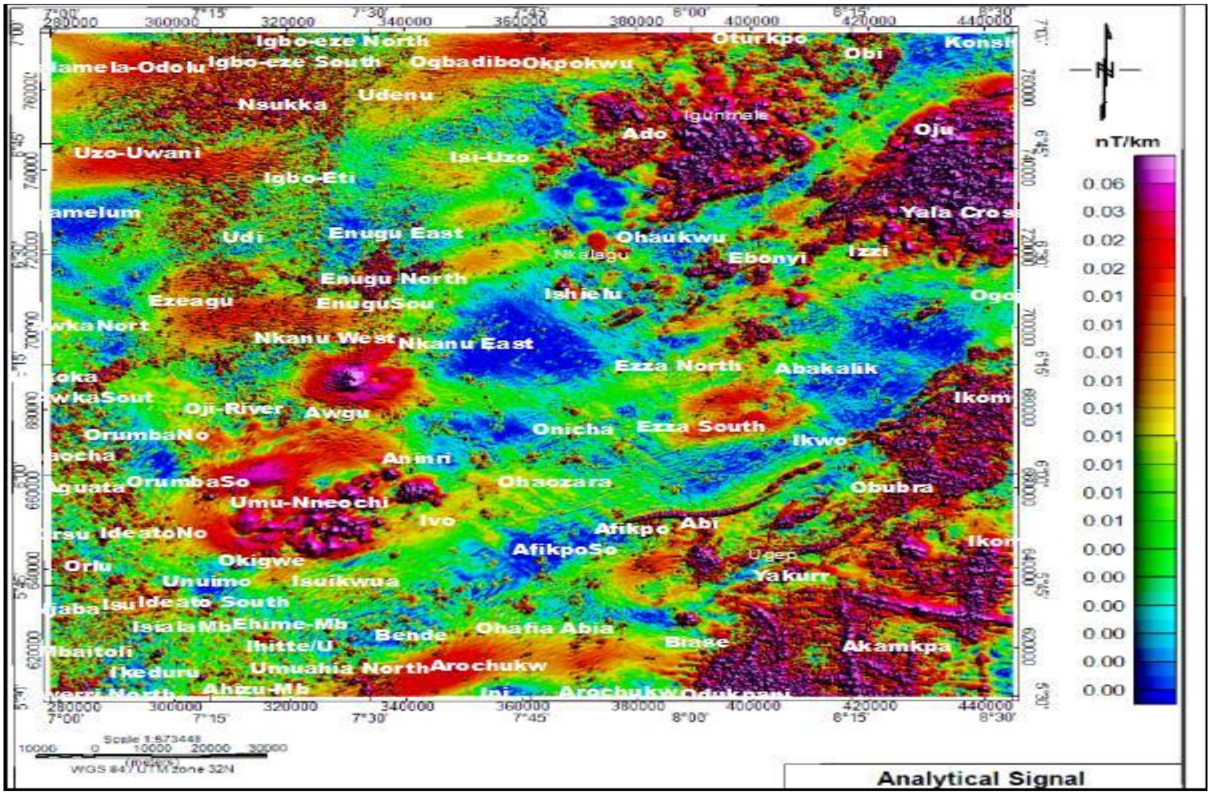

Fig. 8: The Analytical signal map of the area (Colour shaded image)

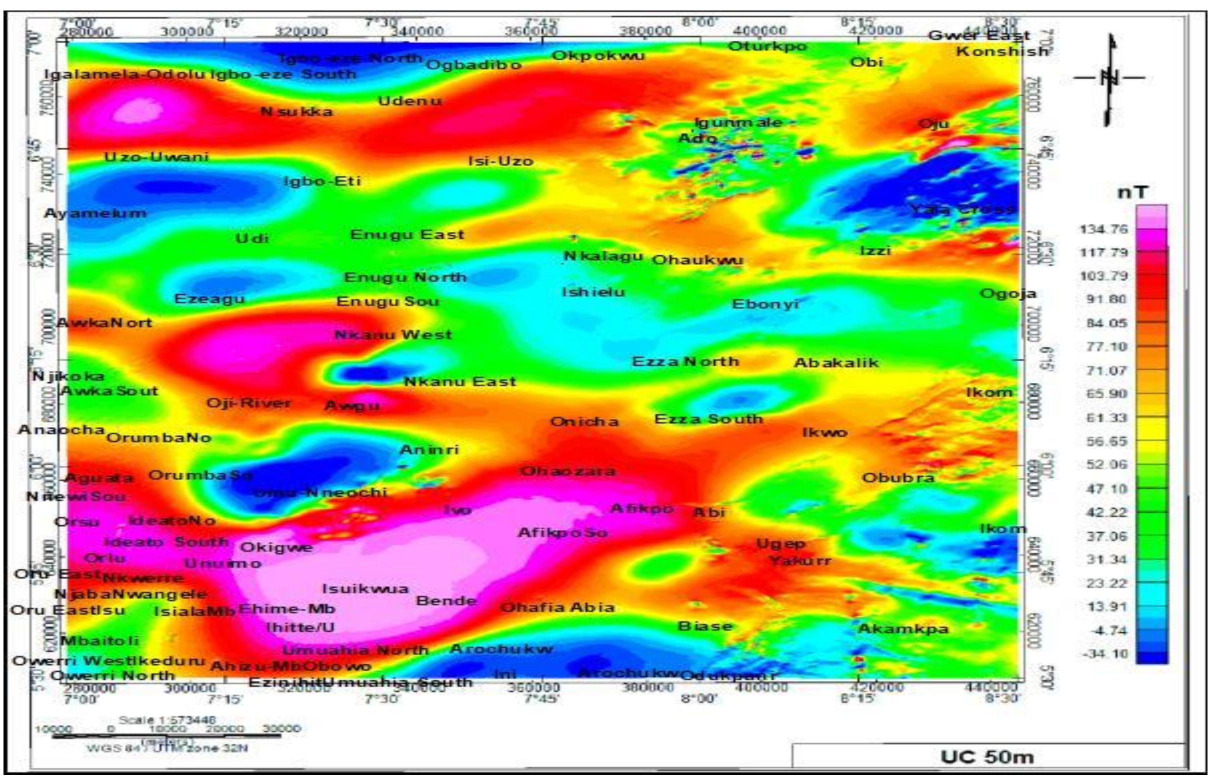

Fig. 9: The upward continuation map UC distance of 50 m

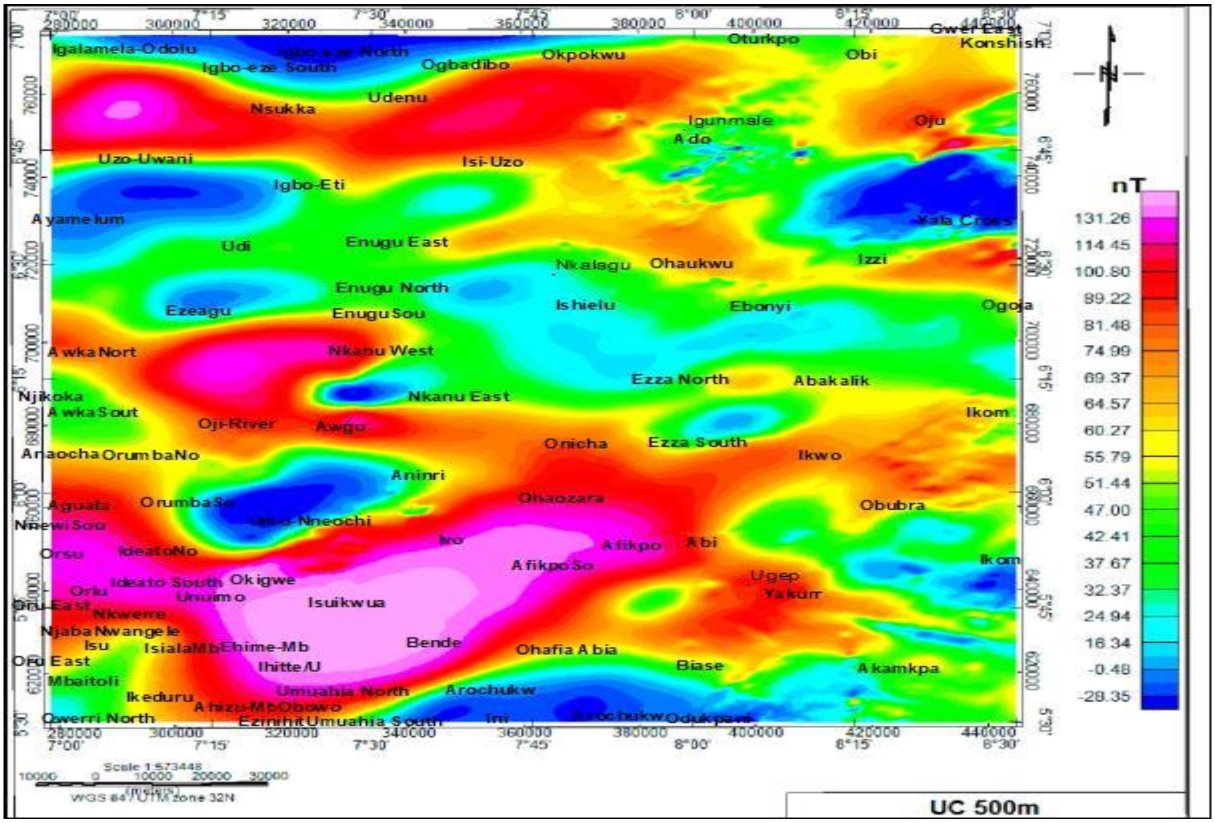

Fig. 10: The upward continuation map UC distance of 500 m

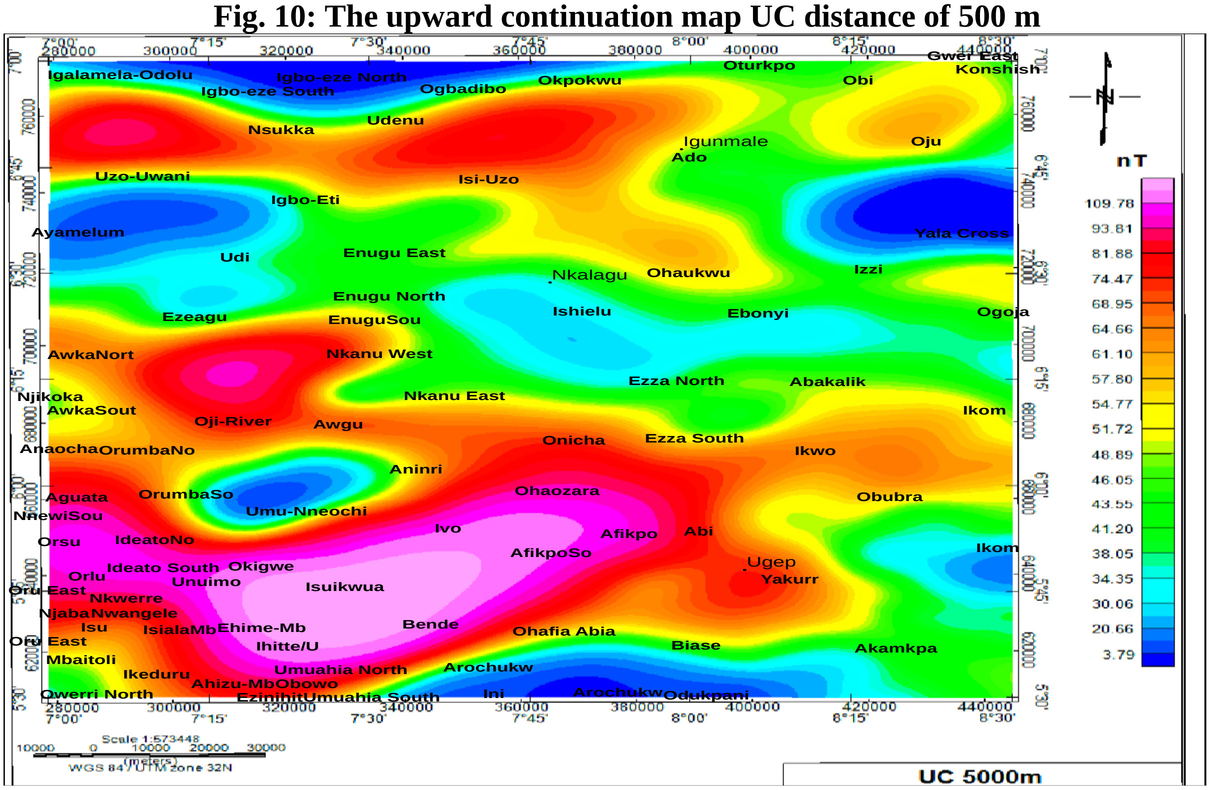

Fig. 11: The upward continuation map UC distance of 5,000 m

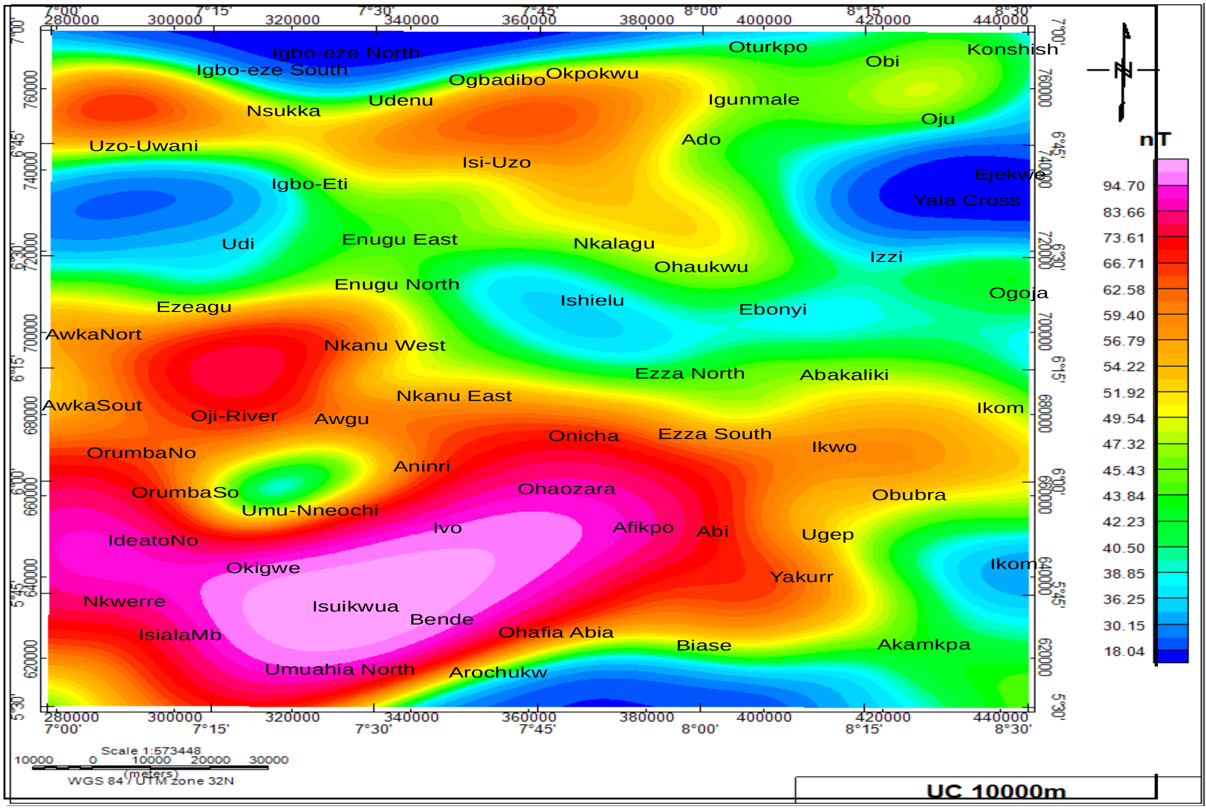

Fig. 12: The upward continuation map UC distance of 10,000 m

4.0 Conclusion

The findings from the magnetic survey of the study area revealed several key geological features related to the magnetic anomaly characteristics. The total magnetic intensity (TMI) map showed significant variations in magnetic intensity, ranging from -47.3 nT to 151 nT, with high-intensity areas observed in the northern part of the study area near Bende, indicating a regional anomaly. The reduction to the magnetic equator (RTE) map helped preserve the original shape of the magnetic anomaly, with intensity values ranging from -34.84 to 135.26 nT, highlighting prominent regions like Okigwe, Isuikwuato, and Afikpo, where high magnetic intensity was observed. The regional anomaly map showed low-frequency, low-amplitude anomalies indicative of deeply seated rocks, with variations in susceptibility across the area. The residual anomaly map, created through a high-pass filter, highlighted near-surface magnetic sources, with significant anomalies observed in areas such as Igunmale, Okigwe, Enugu North, Nsukka, and the southeastern part of the map. These residual anomalies, indicative of remanent magnetization, suggest the presence of near-surface basement intrusions. The first vertical derivative map enhanced localized magnetic features associated with geological structures, identifying trends in the ENE-WSW, NE-SW, and NW-SE directions. The analytical signal map confirmed the presence of remanent magnetism, with high-amplitude responses observed in areas with intrusive activities. Upward continuation analysis at varying heights (50 m, 500 m, 5,000 m, and 10,000 m) revealed a decrease in the influence of near-surface anomalies with increasing continuation distance, with regional magnetic trends becoming more pronounced at greater heights.

The study indicates that the area is dominated by both regional and residual magnetic anomalies, with evidence of near-surface basement intrusions and deeply seated rocks. The magnetic data provide valuable insights into the crustal geology of the region, with prominent features such as intrusive bodies and basement structures being identified. The results suggest that the area has potential for mineral exploration, especially in regions with localized magnetic responses associated with basement intrusions.

In conclusion, the magnetic survey has successfully identified key geological features, including near-surface basement intrusions and deep-seated rock structures. The findings provide a comprehensive understanding of the magnetic anomalies in the region, which are crucial for mineral exploration and geological mapping. It is recommended that further detailed geophysical surveys be conducted in the identified areas of interest, particularly around the prominent magnetic anomalies, to enhance the understanding of the subsurface geology and assess the potential for resource extraction. Additionally, integrating these findings with other geophysical and geological data could lead to a more comprehensive geological model of the area.

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Declaration

Consent for publication

Not applicable

Availability of data

Data shall be made available on demand.

Competing interests

The authors declared no conflict of interest

Ethical Consideration

Not applicable

Funding

There is no source of external funding.

Authors' contributions

All components of thr work were carried out by the authors