

Delineation of Mineralization Zones in parts of Yola Arm, Upper Benue Trough, Northeast Nigeria Using High Resolution Aeromagnetic Data

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ABSTRACT

This work focuses on the use of aeromagnetic data to delineate potential mineralization zones within the Yola Arm, Upper Benue Trough, northeast, Nigeria. The area exhibits a complex geological framework, where igneous and sedimentary formations interact along various fault structures. In this study, the Total Magnetic Intensity (TMI), Reduction to the Equator (RTE), Residual, First Vertical Derivative (FVD), Analytic Signal, Horizontal Gradient Magnitude (HGM), and Tilt Derivative maps were analyzed to delineate mineralization zones and analyze structural trends. The results reveal prominent high-intensity magnetic anomalies around northern and southeastern sections of the study region, indicative of magnetite-rich bodies and igneous intrusions. Structural trends extracted from lineament and rose diagram analyses highlight major NW-SE and N-S orientations with subsidiary NE-SW orientations, corresponding to regional fault systems and fracture zones. Superimposition of lineaments on the Analytic Signal map demonstrates strong correlations between tectonic features and zones of high magnetic susceptibility, confirming the structural control on mineralization.

Keywords:

Aeromagnetic Data,
Mineralization Zones,
Structural Trends,
Fault Systems,
Yola Arm.

INTRODUCTION

Nigeria has substantial deposits of solid minerals, yet many of these resources remain underexploited, limiting their potential as significant contributors to the nation's economy. This underutilization is largely due to the overwhelming focus on oil and gas, given that Nigeria is Africa's leading oil producer and a major exporter of crude oil (Augie & Sani, 2020; Ejepu et al., 2018). With the vast reserves of solid minerals present across the country, mining can play a crucial role in boosting Nigeria's economy if properly harnessed. The Upper Benue Trough is a significant Cretaceous rift basin known for its complex tectonic history, rich mineral potential and other valuable resources (Guiraud & Maurin, 1992). A key component of this geological system is the Yola Arm, which stands out for its intricate basement structures, fault systems, and variations in sedimentary thickness. These features can be effectively mapped using geophysical methods, particularly aeromagnetic survey (Emberga et al., 2016; Ogunmola et al., 2016). Formed during the Early Cretaceous as part of the South Atlantic rifting, Yola Arm exhibits a highly heterogeneous structure, characterized by significant

variations in sedimentary fill and complex tectonics (Obi et al., 2008)

Aeromagnetic data, due to its sensitivity to lithological contrasts and structural anomalies, has been widely used in the Benue Basin to delineate subsurface features, including lineaments, basement depth, and the configuration of magnetic sources (Akpaneno, 2024; Jimoh et al., 2021 Rahaman, 1988). In terms of mineral exploration, aeromagnetic surveys offer a non-invasive and effective method for detecting magnetic anomalies linked to variations in rock types, fault zones, intrusive bodies, and mineralized areas (Abdelrady et al., 2023; Ogunkoya et al., 2025). These geophysical surveys are instrumental in delineating subsurface geological structures that control mineralization processes and fluid migration (Alaba et al., 2025; Aminu et al., 2024). Numerous studies have been conducted on Nigeria's schist belts, especially in hydrothermally altered zones, which historically host a large portion of the country's solid mineral resources, particularly gold (Afolabi et al., 2024; Sanusi & Amigun, 2020). These studies have highlighted the importance of geophysical methods in

identifying mineralization areas (Aisabokhae et al., 2023; Akinlalu, 2023).

This study employs advanced aeromagnetic processing techniques such as Total Magnetic Intensity (TMI), Residual Magnetic Intensity (RMI), Reduction to the Equator (RTE), First Vertical Derivative (FVD), Total Horizontal Derivative (THDR), Tilt Derivative (TD), and Analytic Signal (AS) maps to delineate mineralization zones in the Yola Arm. By analyzing these maps, we aim to uncover structural trends and mineralized areas essential for future exploration. Aeromagnetic methods, particularly derivative techniques, are invaluable in mapping subsurface anomalies, such as faults and fractures, which play a key role in identifying areas of mineralization (Abdelrady et al., 2023; Mam et al., 2020; Narimi et al., 2025; Salako et al., 2024). These methods enhance detection of both shallow and deep magnetic anomalies, providing a clearer insight into the subsurface geology and structural controls that influence mineral distribution (Abdelrady et al., 2023; Alao et al., 2024; Salawu et al., 2019).

Despite the numerous studies conducted in the broader Benue Trough, there remains a gap in focused applications of integrated aeromagnetic interpretation specifically within the Yola Arm. This study seeks to address this gap by applying advanced aeromagnetic filtering and depth estimation techniques to aeromagnetic data to delineate mineralization zones and their structural controls within the Yola Arm.

Location and Geological Setting of the Study Area

The research area (Figure 1) is located in northeastern Nigeria's Upper Benue Trough, between latitudes 9°00'00" and 10°00'00" N and longitudes 11°30'00" to 13°00'00" E, covering an approximate area of 18,481.5

km², and is geologically characterized by a complex assemblage of Precambrian Basement Complex rocks and Cretaceous sedimentary sequences (Figure 2). The basement rocks are dominated by gneiss, migmatite, augen gneiss, granite gneiss, hornblende granite, and coarse to medium-grained granitic intrusions, which represent metamorphosed meta-sediments and older granites that have undergone intense deformation and magmatic reworking during Precambrian tectonothermal events, with the augen gneisses exhibiting distinctive eye-shaped feldspar porphyroclasts formed by deformation (Carter, 1963; Obaje, 2009; Rahaman, 1988; Wright et al., 1985). These crystalline basement rocks are unconformably overlain by Albian Cretaceous sedimentary units of the Benue Trough, including Bima Sandstone, Yolde Formation, and Dukul Formation, together with associated shale, limestone, and calcareous sandstone. Bima Sandstone, which forms the basal sedimentary unit of Benue Trough, rests directly on the basement complex, is largely derived from granitic source rocks, and is characterized by feldspathic lower beds that grade upward into less feldspathic sandstones (Carter, 1963; Kasidi, 2019; Zaborski et al., 1997). The lower parts of the sedimentary succession consist predominantly calcareous sandstone and shale, reflecting a transition from continental depositional environments to shallow marine conditions, with localized limestone beds near base marking Yolde Formation, while younger sedimentary units such as the Dukul Formation reflect continued marine influence (Obaje, 2009; Zaborski et al., 1997). Recent alluvial deposits occur along major drainage channels, consisting of unconsolidated sands, silts, and clays derived from the weathering of both basement and sedimentary rocks (Obaje, 2009; Nigerian Geological Survey Agency, 2006).

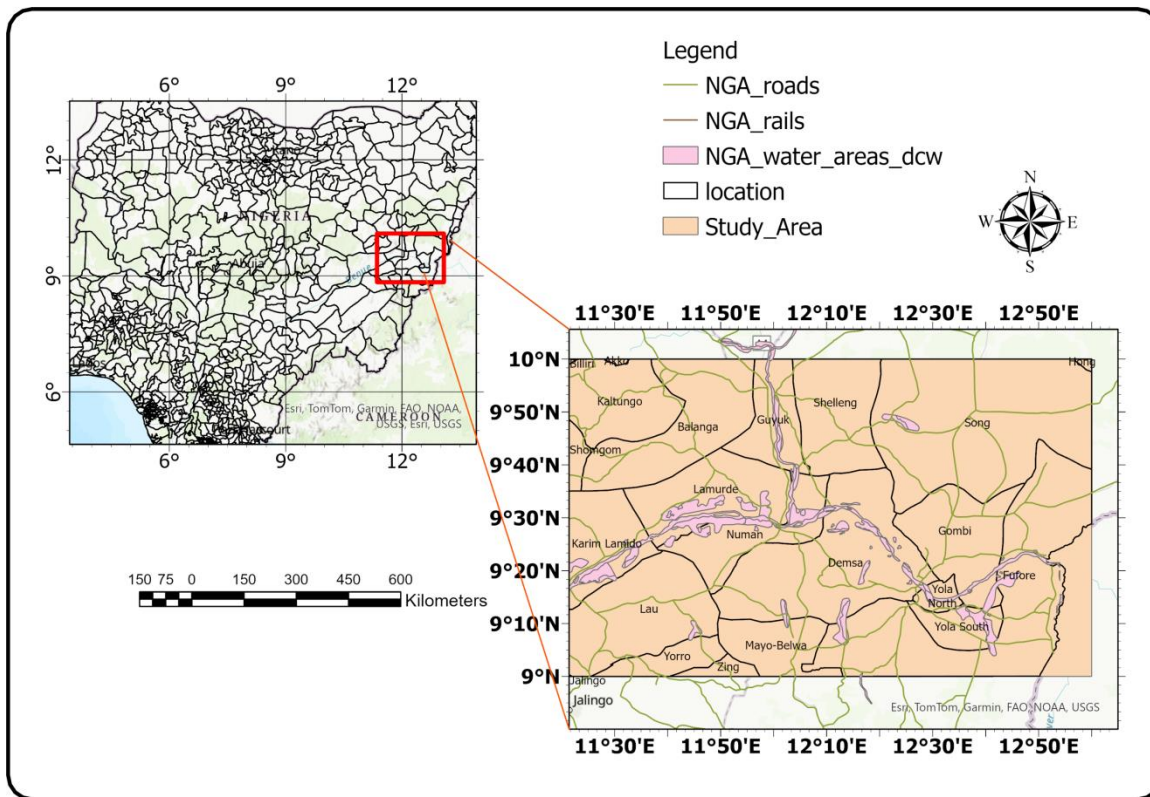


Figure 1: The Research Area's Map (Source: NGSA)

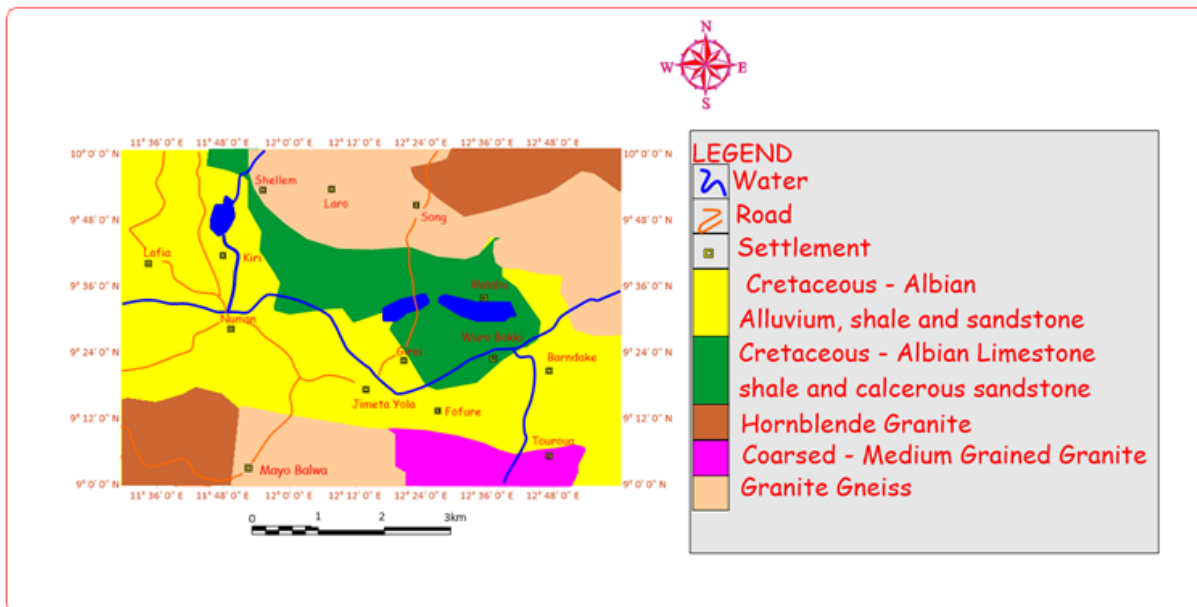


Figure 2: Geology Map of the Research Area (Source: NGSA)

MATERIALS AND METHODS

The dataset utilized in this study consists of aeromagnetic data grids covering sheets 174 (Guyuk), 175 (Shellen), 176 (Zummo), 195 (Dong), 196 (Numan), and 197 (Gerei). These data were acquired from the Nigerian Geological Survey Agency (NGSA) and processed using

Geosoft Oasis Montaj (version 8.4). The original data, collected between 2003 and 2009 by Fugro Airborne Surveys using high-resolution airborne magnetic surveying techniques. Standard corrections were applied during acquisition, including compensation for diurnal magnetic variations and removal of the main magnetic

field of the Earth using Definitive Geomagnetic Reference Field (DGRF-2005), ensuring that the dataset reflects only crustal magnetic anomalies (Reeves, 2005; Telford et al., 1990). Initial processing involved data quality control, levelling, and micro-levelling to remove line-to-line discrepancies and enhance continuity across flight lines. The corrected data were then gridded to an appropriate cell size, allowing for optimal representation of magnetic anomalies while minimizing interpolation errors (Oladunjoye et al., 2016; Patterson & Reeves, 1985; Reeves, 2005). To improve the positional accuracy of magnetic anomalies in the low-latitude study area, the Total Magnetic Intensity (TMI) data were first processed using the Reduction to the Equator (RTE) filter. This transformation corrects the influence of magnetic inclination and declination, ensuring that anomalies are symmetrically positioned over their causative sources (Blakely, 1996; Nabighian et al., 2005; Okpoli, 2019). The magnetic field was separated into regional and residual. The regional field reflects broad, deep-seated geological trends, whereas the residual field isolates localized anomalies associated with shallow structures and potential mineralization zones (Telford et al., 1990). Further enhancement techniques were applied to the residual field, including derivative-based filters and amplitude-based methods, to highlight structural features including faults, fractures, and lithological boundaries.

The Reduction to the Equator (RTE)

Since the study area is situated in a low magnetic latitude region, the Total Magnetic Intensity (TMI) data were processed using the Reduction to the Equator (RTE) filter to correct anomaly asymmetry and enhance the accuracy of source positioning. The transformation was performed in the frequency domain using a two-dimensional Fast Fourier Transform (2D-FFT). This procedure repositions magnetic anomalies directly over their causative sources by correcting for the influence of the Earth’s magnetic field at low latitudes (Blakely, 1995; Nabighian et al., 2005). The RTE operator applied is given as:

$$L(\theta) = \frac{[\sin(I) - i \cos(I) \cos(D - \theta)]^2 x (-\cos^2(D - \theta))}{[\sin^2(I_a) + \cos^2(I_a) \cos^2(D - \theta)] x [\sin^2(I) + \cos^2(I) \cos^2(D - \theta)]} \quad (1)$$

where I denotes the geomagnetic inclination, D represents the declination, θ is the wave number direction, and I_a corresponds to the adjusted inclination used for amplitude stabilization (Yohanna et al., 2023).

First vertical derivative (FVD)

The first vertical derivative (FVD) is a useful technique in geoscience for highlighting shallow geological features while reducing the influence of deeper sources.

It enhances short-wavelength components and improves resolution for closely spaced sources, making it less prone to noise than higher-order vertical derivatives (Blakely, 1996; Reeves, 2005). The first vertical derivative, as defined by Phillips (2000), is expressed:

$$FVD = -\frac{\delta F}{\delta z} \quad (2)$$

This filter works well for defining lineaments and near-surface contacts.

Horizontal Gradient Magnitude (HGM)

The Horizontal Gradient Magnitude (HGM) technique is commonly employed to delineate linear geological features such as faults, lithological contacts, and structural boundaries from magnetic data. It enhances lateral variations in the magnetic field, making it particularly effective for identifying edges of magnetized bodies (Cordell & Grauch, 1985). The HGM of a magnetic field M(x,y) is expressed as:

$$HGM(x, y) = \sqrt{\left(\frac{\delta M}{\delta x}\right)^2 + \left(\frac{\delta M}{\delta y}\right)^2} \quad (3)$$

where $(\delta M / \delta x)$ and $(\delta M / \delta y)$ represent the horizontal derivatives of the magnetic field in the x and y directions, respectively.

Tilt Derivative (TDR)

Tilt Derivative (TDR) is an effective filtering technique used in potential field analysis to enhance subtle and pronounced geological features, thereby improving the interpretation of subsurface structures. It is defined as the arctangent of the ratio between the vertical derivative and the total horizontal derivative of the magnetic field (Hosseini et al., 2023; Miller & Singh, 1994).

$$TD = \tan^{-1} \left(\frac{VDR}{THDR} \right) \quad (4)$$

where VDR represents the vertical derivative, and THDR is the total horizontal derivative.

Analytic signal

The Analytic Signal (AS) method is a robust tool for mapping geological structures, including faults, lithological contacts, intrusions, and sheet-like bodies, providing accurate horizontal positioning irrespective of magnetic latitude (Azizi et al., 2015). The AS amplitude is independent of the source’s magnetization direction, causing the signal to peak directly over causative bodies, with local maxima marking their edges or boundaries (Alagbe & Sunmonu, 2014; Macleod et al., 1993). The analytic signal is defined as:

$$AS(x, y, z) = \sqrt{\left(\frac{\delta M}{\delta x}\right)^2 + \left(\frac{\delta M}{\delta y}\right)^2 + \left(\frac{\delta M}{\delta z}\right)^2} \quad (5)$$

where M represents the observed magnetic field at coordinates x, y, and z (Olasunkanmi et al., 2023; Shuey et al., 1977).

RESULTS AND DISCUSSION

Total Magnetic Intensity (TMI) and Residual Magnetic Intensity (RMI)

The Total Magnetic Intensity (TMI) and Reduction to the Equator (RTE) maps are shown in Figure 3 and Figure 4 respectively. The TMI values ranged from 31178.39 nT to 31355.91 nT. The areas with higher magnetic values, indicated by red and pink colours, are mainly concentrated in the northern and southeastern sections of the research area, whereas the regions with lower magnetic values, displayed in blue, are predominantly located in the southern and northeastern areas. High magnetic anomalies are likely zones of elevated magnetic susceptibility, possibly associated with magnetite-bearing rocks or igneous intrusions (Blakely, 1996; Telford et al., 1990). In contrast, the low values are associated with non-magnetic or weakly magnetic rocks, such as sedimentary or altered rock types (Blakely, 1996; Karim et al., 2025; Kletetschka et al., 2000). The anomaly trends reveal a clear northeast-southwest (NE-

SW) direction of high magnetic intensities, possibly indicating a fault system or mineralized zone, as well as a regional northwest-southeast (NW-SE) pattern of both high and low magnetic intensities, indicating the influence of significant geological structures, including major faults or fold systems.

In Figure 4, the range of magnetic intensity values varied from 31229.15 nT to 31306.07 nT. Elevated values, represented by the red and pink regions on the map, are primarily located in the northern and southeastern sections, whereas lower values, depicted in blue, are predominantly observed in the southwestern and northeastern parts. High values in the RTE map are often associated with strong magnetic sources, including dense rock formations or mineralized zones. On the other hand, low values are likely associated with sedimentary rocks or deeper sections with weaker magnetic responses, possibly due to less magnetically susceptible rocks or deeper sources of magnetism.

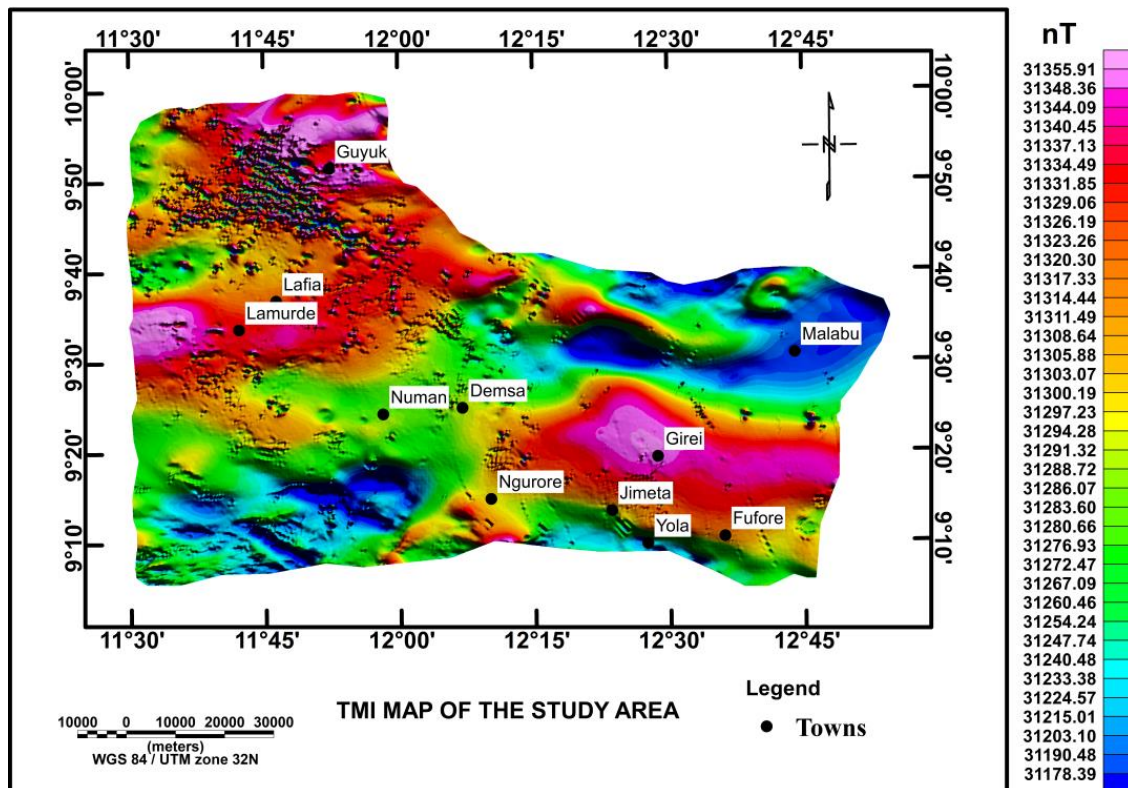


Figure 3: Total magnetic field intensity map

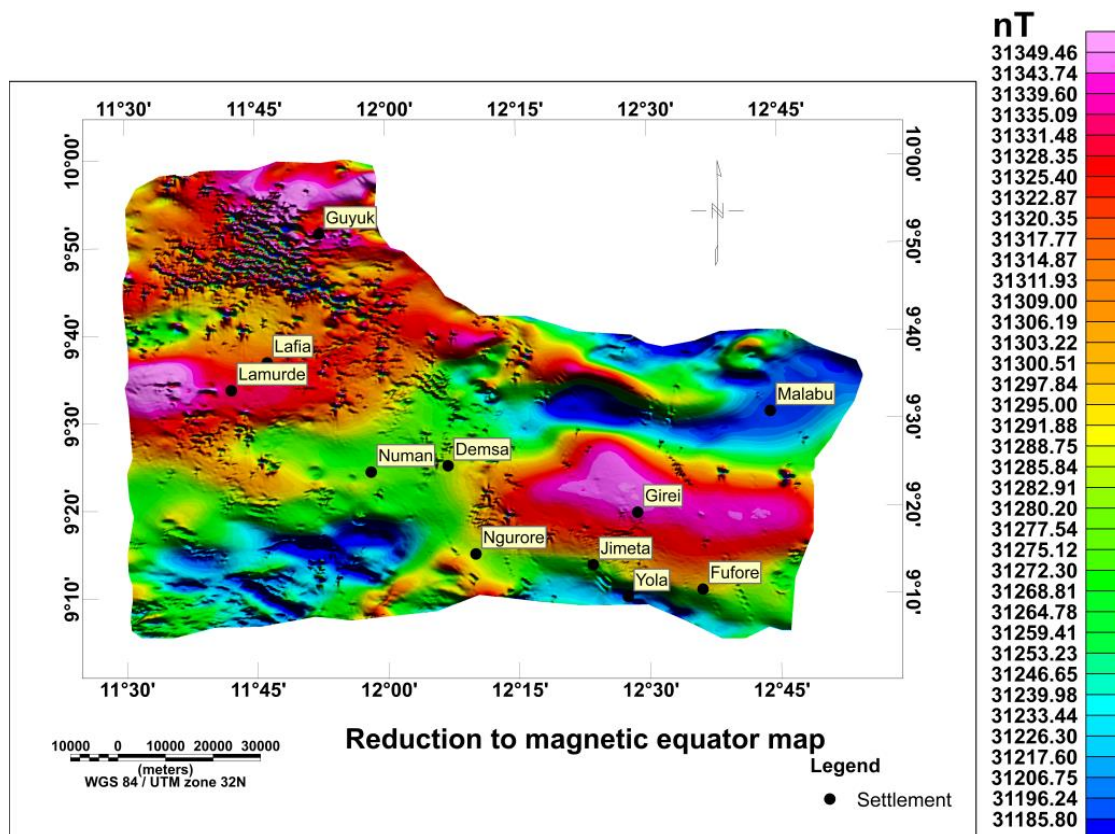


Figure 4: Reduction to the Magnetic Equator Map

Figure 5 displays the Residual Magnetic Intensity map, showing magnetic values that range from 31229.15 nT to 31306.07 nT. The higher values are mainly found in the southeastern region, while the lower values are primarily in the southwestern and northeastern parts. Elevated values on the RMI map are generally linked to areas with

localized magnetization, which may include magnetite-rich mineral deposits or the effects of specific geological features such as fault zones or intrusive rocks. In contrast, lower values are likely a result of deeper, non-magnetic geological formations (Caracciolo et al., 2014).

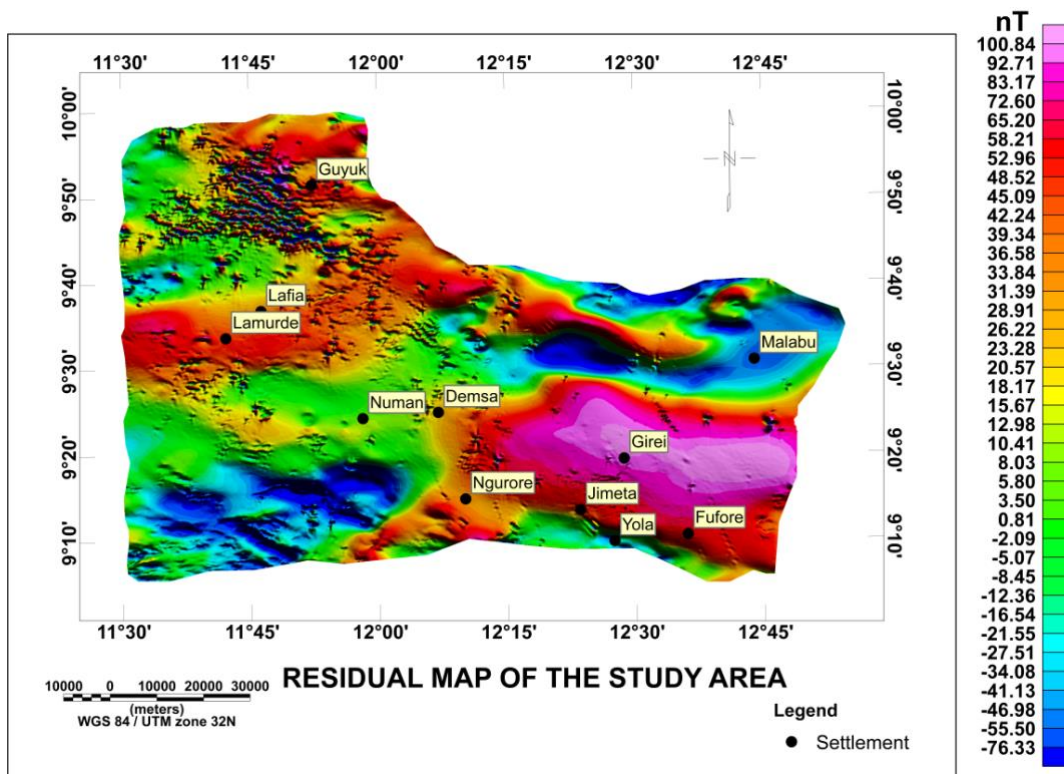


Figure 5: Residual magnetic intensity map

The First Vertical Derivative (FVD) map is shown in Figure 6, with values ranging from -0.0399 nT to 0.0423 nT. The map enhances magnetic gradients, highlighting areas with abrupt changes in magnetic intensity that are indicative of shallow geological structures, faults, or potential mineralization zones. High-gradient (HG) areas, shown in red and purple, correspond to steep magnetic variations, likely associated with mineralized zones or structures like faults, fractures, or lithological

contacts (Hinze et al., 2013; Reeves, 2005). These high-gradient (HG) regions are of particular interest for mineral exploration. In contrast, low-gradient areas, indicated by blue colours, exhibit relatively smooth magnetic variations, suggesting the absence of significant changes in the underlying geology and are less likely to be directly related to mineralization (Kearey et al., 2002).

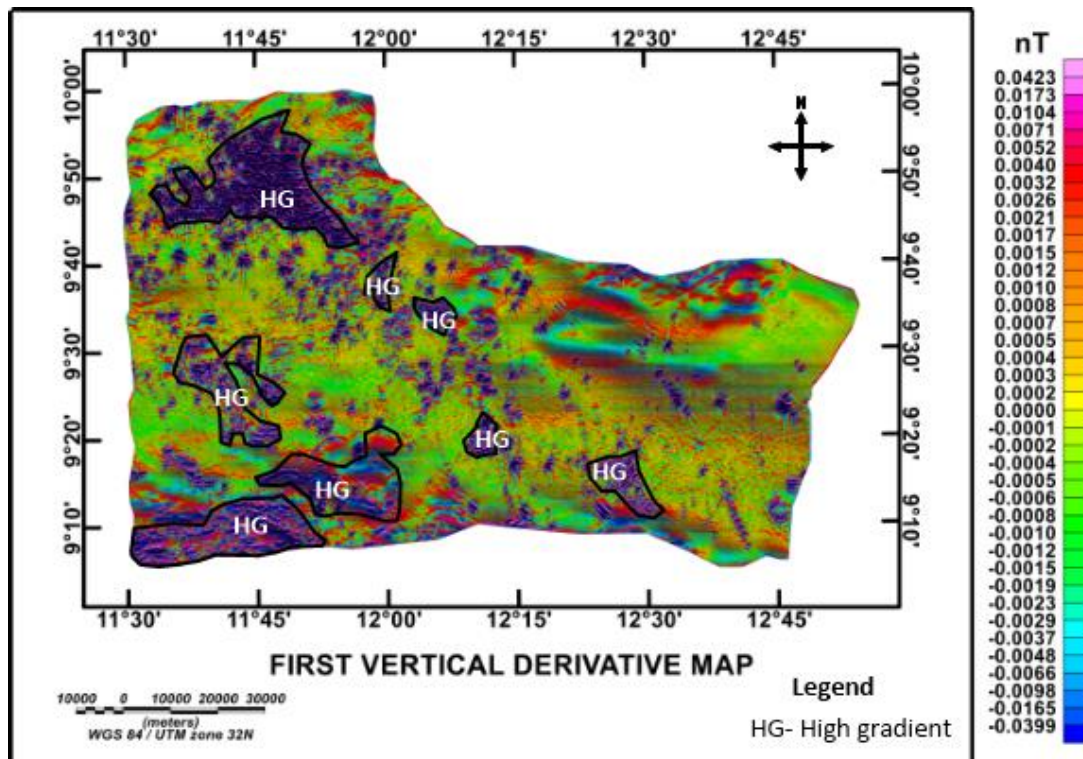


Figure 6: First Vertical Derivative (FVD) map

The map also reveals prominent magnetic trends along NW-SE, N-S, and E-W directions, which are indicative of structural controls such as fault systems or tectonic stress that influence mineralization.

Horizontal Gradient Magnitude (HGM)

The HGM map (Figure 7) shows gradient values ranging from approximately 0.0009 nT/m to 0.1473 nT/m and reveals distinct high and low-intensity zones. High-Intensity Zones (HIZ), shown by red and purple colours, are characterized by sharp magnetic gradients and are interpreted as areas of significant structural discontinuities, including basement faults, fracture corridors, and igneous intrusions (Hinze et al., 2013; Nabighian et al., 2005). These zones indicate strong contrasts in magnetic susceptibility, suggesting tectonically disturbed regions or areas of intense deformation within the shallow basement. Similar interpretations of magnetic gradient anomalies as

structurally controlled features have been reported in recent studies (Lawal et al., 2022; Moujane et al., 2024). These structurally complex zones are therefore considered important targets for mineral exploration, as they may act as conduits for hydrothermal fluid migration (Gunn & Dentith, 1997). Conversely, Low-Intensity Zones (LIZ), represented by blue and green colours, exhibit subdued magnetic gradients and are interpreted as relatively homogeneous basement blocks or sediment-covered regions with limited structural complexity. The smooth magnetic response in these areas suggests minimal faulting and a more stable basement configuration (Kearey et al., 2002). Prominent linear and curvilinear high-gradient anomalies define major structural lineaments across the area. The dominant NW-SE trend represents the principal basement fault and fracture orientation and reflects regional tectonic control of the Upper Benue Trough (Benkhelil, 1989).

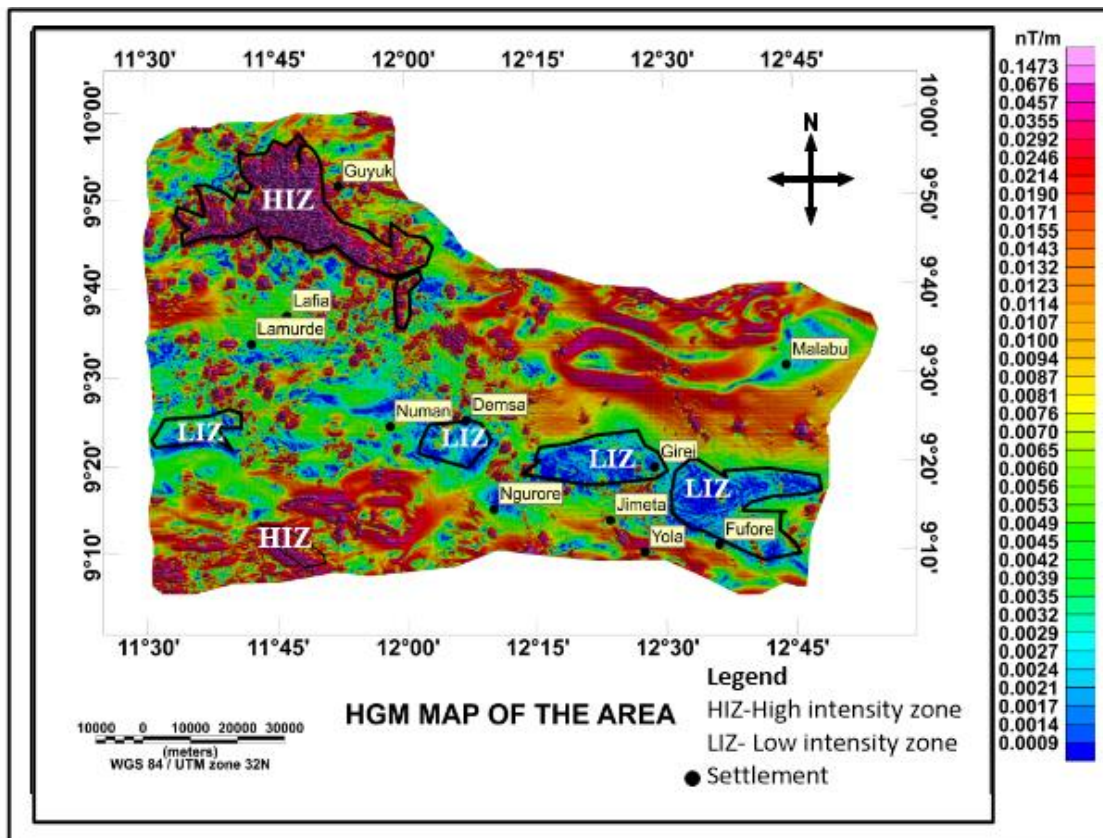


Figure 7: Horizontal Gradient Magnitude (HGM) map

A secondary NE-SW trend is also evident, locally cross-cutting the dominant fabric and indicating zones of structural interaction. Minor E-W and N-S trends occur as short, discontinuous features, interpreted as shallow fractures or subsidiary faults superimposed on the main basement structures (Reeves, 2005). Sharp boundaries between high and low intensity zones mark geological contacts between rocks with contrasting magnetic properties, such as crystalline basement and sedimentary units or intrusive bodies. These structural boundaries are significant as they may control fluid migration, mineralization pathways, and geothermal heat transfer within the subsurface (Blakely, 1996; Hinze et al., 2013).

The Tilt Derivative (TD) map (Figure 8) shows values ranging from approximately -1.3467 nT to 1.4228 nT, with high positive values (in pink/red) indicating high magnetic intensity areas (HIA) associated with magnetically dense bodies such as intrusive rocks or mineralized zones. These high-amplitude anomalies often correspond to faults, fractures, or shear zones, which can control the migration of mineralizing fluids and contribute to the formation of mineral deposits (Verduzco et al., 2004). Such structures are significant as they may serve as pathways for hydrothermal fluids, thereby playing a critical role in the localization of mineral deposits (Groves et al., 2003; Lawal et al., 2022).

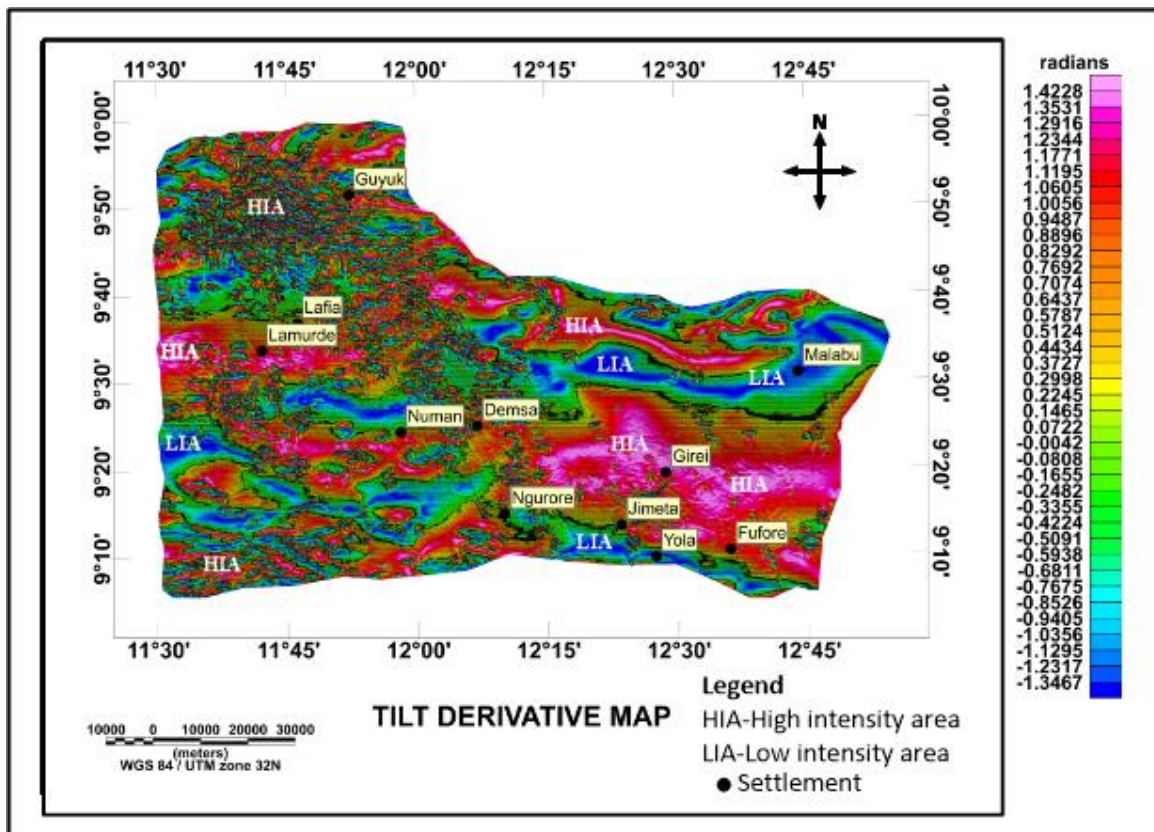


Figure 8: Tilt Derivative map

On the other hand, areas with low negative values (in blue/green) correspond to Low magnetic intensity areas (LIA), which may represent sedimentary formations, altered zones, or areas with low magnetic susceptibility, typically less likely to host significant mineralization (Hinze et al., 2013; Kearey et al., 2002). The map also highlights several structural trends oriented in NW-SE, N-S, and E-W directions, which align with regional tectonic features, such as fault systems and shear zones (Benkhelil, 1989; Moujane et al., 2024). These structural trends suggest areas where mineralizing fluids may have been concentrated, making these regions prime targets for exploration. The sharp transitions between magnetic highs and magnetic lows further indicate the presence of faults, which often serve as pathways for mineralization (Obaje, 2009).

The Analytic Signal (AS) map (Figure 9) reveals values ranging from 0.0024 nT/m to 0.0251 nT/m, with high values (red/pink) indicating magnetic highs, which are often associated with dense, magnetically susceptible

materials like magnetite-rich intrusions or mineralized zones, suggesting areas of potential mineralization (Li, 2006; Roest et al., 1992). In contrast, low values (blue/green) correspond to magnetic lows, typically reflecting sedimentary formations, altered zones, or areas with low magnetization, which are less likely to host significant mineralization but remain important for understanding the overall subsurface structure (Hinze et al., 2013; Kearey et al., 2002). The sharp transitions between high and low values highlight the presence of structural boundaries, such as fault zones, shear zones, or fold axes, which often act as pathways for mineralizing fluids. These structural features, marked by the map's magnetic contrasts, are crucial in controlling the location of mineralization (Nabighian et al., 2005). The map also reveals structural trends oriented in NW-SE, E-W and N-S directions, corresponding to regional fault systems, shear zones, or folds (Abdulsalam et al., 2024; Benkhelil, 1989), which are critical for understanding the movement and concentration of mineralizing fluids.

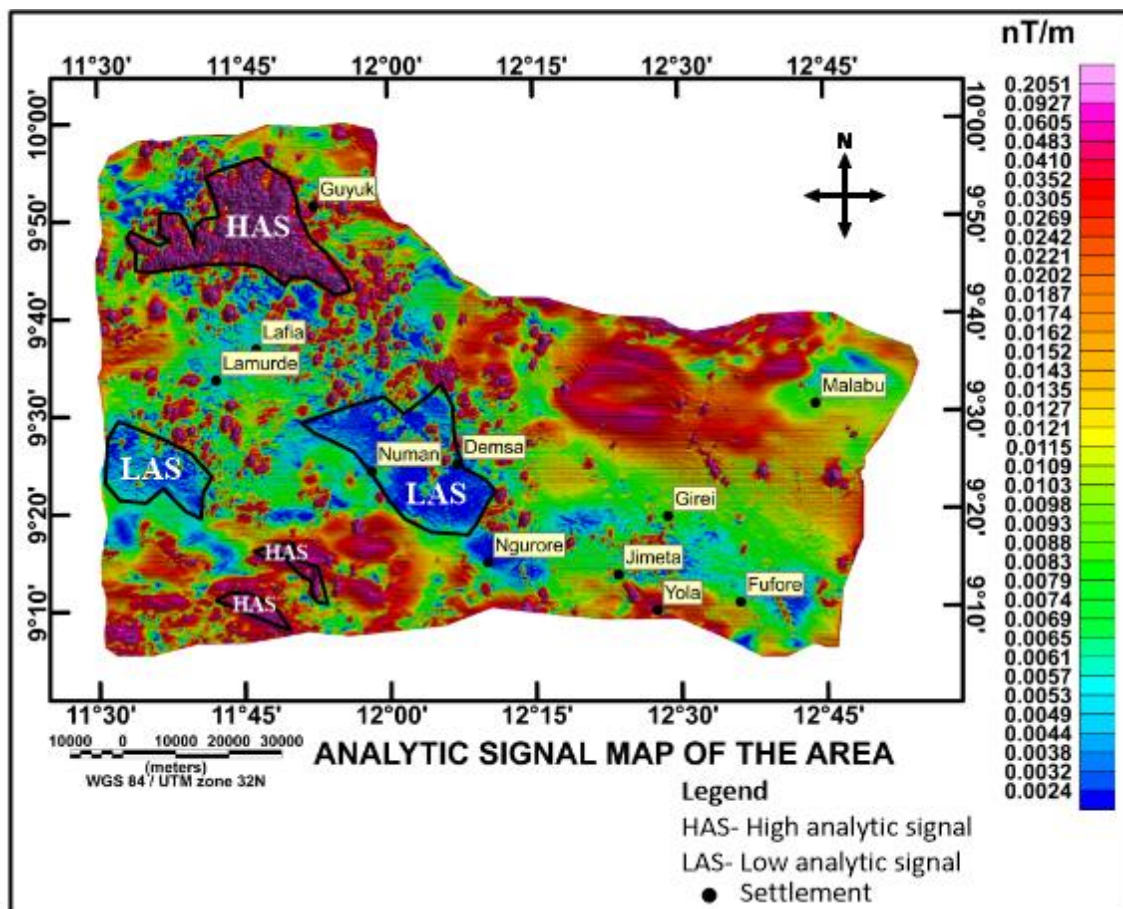


Figure 9: Analytic Signal (AS) map

Lineament Extraction

To produce the lineament map, the peaks of the HGM were overlaid with the zero-contour lines of the TDR (Figure 10). A strong spatial correlation between HGM maxima and TDR zero contours was observed, indicating

major structural features. These coincident features represent geological lineaments representing faults, fractures, and lithological contacts within the research area. The lineaments were then extracted from QGIS 3.38.3.

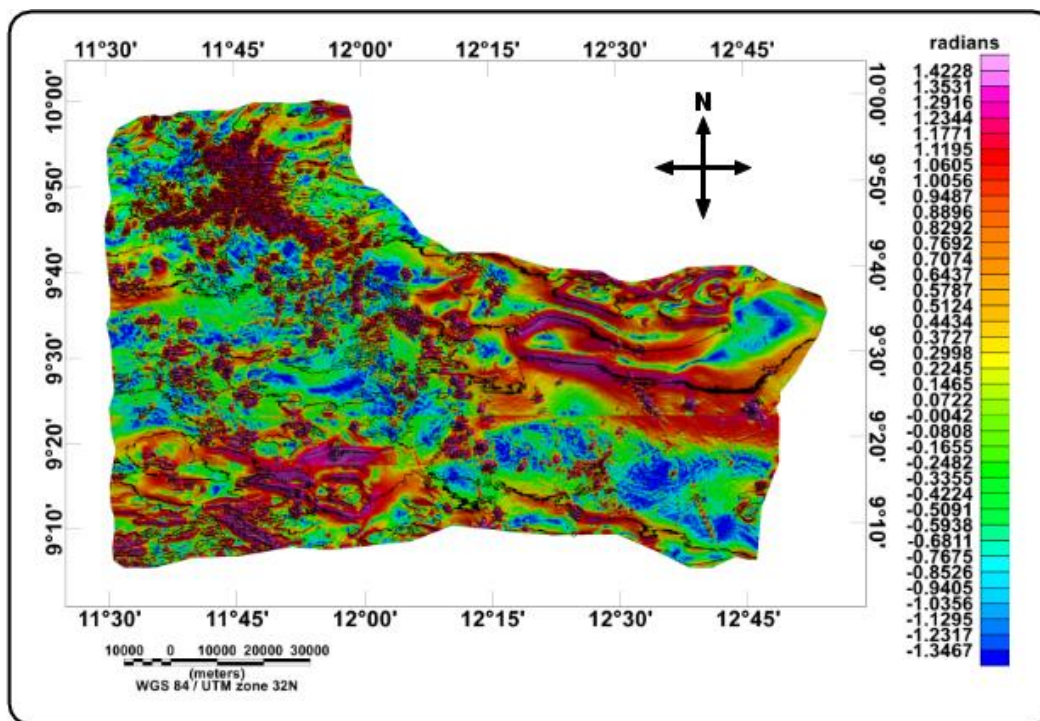


Figure 10: Peaks of HGM plotted on the TDR map of the study area. The peaks are located on zero contour lines of the TDR map

The aeromagnetic lineament map (Figure 11a) reveals a well-developed network of linear features interpreted as faults, fractures, and lithological boundaries within the subsurface. The lineament analysis shows dominant NW-SE and N-S structural trends with a subsidiary NE-SW orientation, as depicted by the rose diagram. These orientations likely reflect major fault and fracture systems that have developed in response to regional

tectonic stresses. Numerous studies demonstrate that such structural features, particularly faults, fractures, and their intersections, act as essential conduits for fluid migration and mineralizing processes because they enhance permeability and focus fluid flow into dilatant zones and intersection loci (McCaffrey et al., 1999). The rose diagram (Figure 11b) highlights the NW-SE and N-S as well as the NE-SW trends.

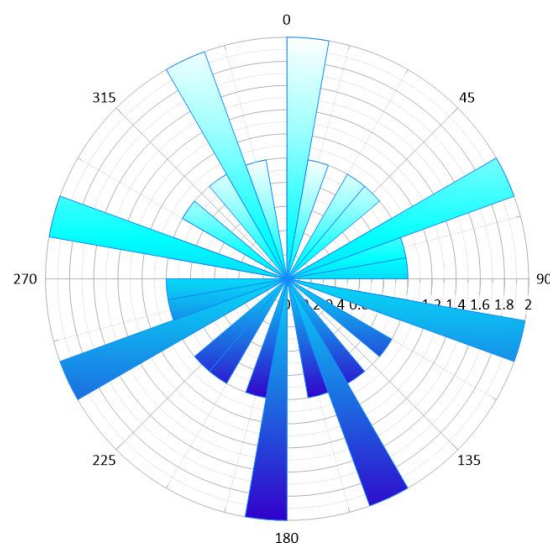
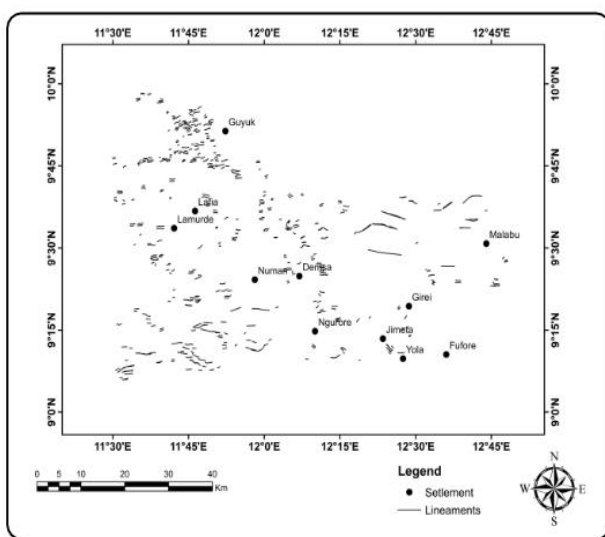


Figure 11: a. Structural Lineaments Map of the Study Area Extracted from Aeromagnetic Data b. Rose Diagram Extracted from lineaments

The lineament map was superimposed on the analytic signal to show the correlation between high analytic signal values and structural features within the research area in Figure 12. The Analytic Signal (AS) map reveals strong correlations between high-intensity zones and tectonic lineaments, indicating significant magnetic anomalies linked with geological features including faults, igneous intrusions, and zones of mineral deposits (Akpaneno, 2024; Blakely, 1996; Nabighian et al., 2005). The red and pink areas represent regions with the highest analytic signal magnitudes (0.0162 nT/m to 0.2051 nT/m), typically marking areas of abrupt magnetic contrasts, such as fault lines or geological boundaries (Reid et al., 1990). These high-intensity regions align with linear features on the map, representing tectonic

lineaments or fracture systems, suggesting active tectonic activity and structural features that may control fluid migration or mineral deposition (Akpaneno, 2024; Ogah et al., 2014; Thompson, 1982). Conversely, the green and blue regions, with lower analytic signal magnitudes (0.0024 nT/m to 0.0109 nT/m), correspond to areas with uniform magnetic properties, often reflecting sedimentary formations or stable geological units (Blakely, 1996). The correlation between high-intensity zones and linear anomalies underscores the presence of faults and tectonic boundaries, making the map a useful tool for identifying structural features and potential areas for exploration of minerals (Ogah et al., 2014; Reid et al., 1990).

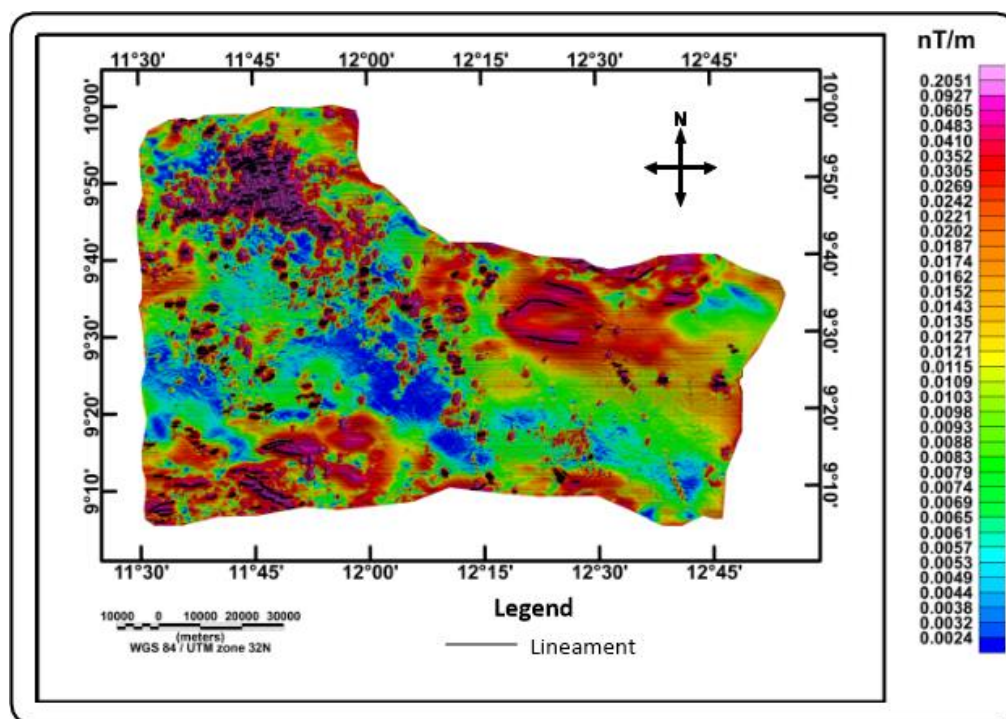


Figure 12: The lineament map was superimposed on the Analytic signal

CONCLUSION

The aeromagnetic analysis carried out effectively delineated potential mineralization zones and revealed the structural controls influencing their distribution. High-intensity magnetic anomalies, particularly in the northern and southeastern parts of the research area, are linked to magnetite-rich intrusions and structurally complex zones. Dominant NW-SE and N-S lineaments, along with subsidiary NE-SW trends, reflect major fault and fracture systems that serve as pathways for mineralizing fluids. The strong correlation between lineaments and Analytic Signal highs confirms the critical role of structural features in controlling mineralization. The study highlights the potential of aeromagnetic surveys as a non-invasive, cost-effective

tool for mapping subsurface geological structures, aiding in identifying prospective areas for the exploration of minerals. Future exploration in the Yola Arm, guided by these findings, may lead to the discovery of untapped mineral resources, contributing to the region's economic development.

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