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Structural Interpretation of Aeromagnetic Data for Regional Controls on Gold Mineralization in Northwestern Nigeria

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Abstract: The aim of this study is to delineate regional structures associated with gold mineralization in part of northwestern Nigeria using aeromagnetic data. The dataset, comprising Total Magnetic Intensity (TMI), was processed and analyzed using residual anomaly separation, reduction-to-equator (RTE), First Vertical Derivative (FVD), lineament extraction, and Source Parameter Imaging (SPI) techniques. The results show TMI values ranging from 32,893.9 nT to 33,077.5 nT, indicating distinct lithological variations. Residual magnetic anomalies vary between –94.0 nT and 76.3 nT, reflecting both shallow and deep sources. The RTE correction improved anomaly symmetry, while FVD and lineament maps revealed dominant NE–SW and NW–SE structural trends, with subordinate E–W and N–S orientations, concentrated between latitudes 11°30′–12°30′N and longitudes 7°30′–8°30′E. SPI depth estimates range from 143 m to 737 m, with shallow anomalies (150–250 m) located in the south and west, and deeper anomalies (>500 m) concentrated in the northeast.

These findings are significant as they reveal a structurally complex terrain with basement highs, intrusives, and depressions that control mineralization. The delineated structures provide valuable targets for gold exploration and contribute to an improved understanding of the regional tectonic framework.

Keywords: Aeromagnetic data, Lineaments, Regional structures; Source Parameter Imaging; Gold mineralization

I. INTRODUCTION

Airborne geophysical surveys are integral to modern geoscientific investigations, offering rapid and cost-effective coverage compared to conventional ground surveys. Among the available techniques, aeromagnetic surveys are particularly valuable for regional-scale structural studies due to their sensitivity to variations in magnetic susceptibility (Kearey, Brooks, & Hill, 2004).

Aeromagnetic data have been widely applied in mineral exploration because they provide insights into basement configuration, intrusive bodies, and subsurface structures that frequently exert control on mineralization (Okiwelu, Onwuemesi, Anakwuba, Onuba, & Usman, 2013; Olasehinde et al., 2024). In the Nigerian Basement Complex, structural features such as faults, fractures, and shear zones play a fundamental role in gold mineralization, functioning both as conduits for hydrothermal fluids and as favorable loci for mineral deposition (Ejepu, Olasehinde, & Mallam, 2018; Sani, Bala, Haruna, & Umar, 2019; Abubakar et al., 2024).

Hence, understanding their geometry, distribution, and tectonic evolution is essential for delineating potential gold-bearing zones (Adewumi & Salako, 2018; Akpaneno & Tawey, 2024).

Previous research has confirmed that gold mineralization in Nigeria is largely structurally controlled, occurring within schist belts, quartz veins, and alluvial deposits. Significant occurrences have been reported in northwestern and southwestern Nigeria, including the Anka, Bin Yauri, Maru, Okolom–Dogondaji, and Tsohon Birnin Gwari–Kwaga goldfields (Garba, 2000, 2003; Ramadan & Abdel Fattah, 2010; Augie, Salako, Rafiu, & Jimoh, 2024). These findings reinforce the importance of structural analysis as a critical tool in targeting prospective gold zones.

This study, therefore, applies aeromagnetic data to delineate the regional structures that may host gold mineralization in part of northwestern Nigeria. The results are expected to improve the understanding of the structural framework of the area and highlight exploration targets for sustainable resource development.

A. Location Map of the Study Area

The study area is situated within northwestern Nigeria, covering parts of Kano and Katsina States. It extends from latitudes 11°40′N to 12°20′N and longitudes 7°40′E to 8°20′E (Figure 1). The region is accessible through an extensive network of roads linking several towns and settlements. Prominent settlements within the area include Kankia, Kusada, Tsanyawa, Shanono, Bagwai, Gwarzo, Karaye, Bichi, Dawakin Tofa, Kabo, Madobi, Rogo, Kiru, and Bebeji.The area lies within the Nigerian Basement Complex, which is characterized by a variety of Precambrian to Pan-African rocks intruded by younger granitoids. This geologic setting is structurally complex and has been shown to host significant mineralization, particularly gold, which is commonly associated with fractures, faults, and shear zones. The inset map situates the study area within the national framework of Nigeria, while the main map illustrates its settlement distribution and accessibility.

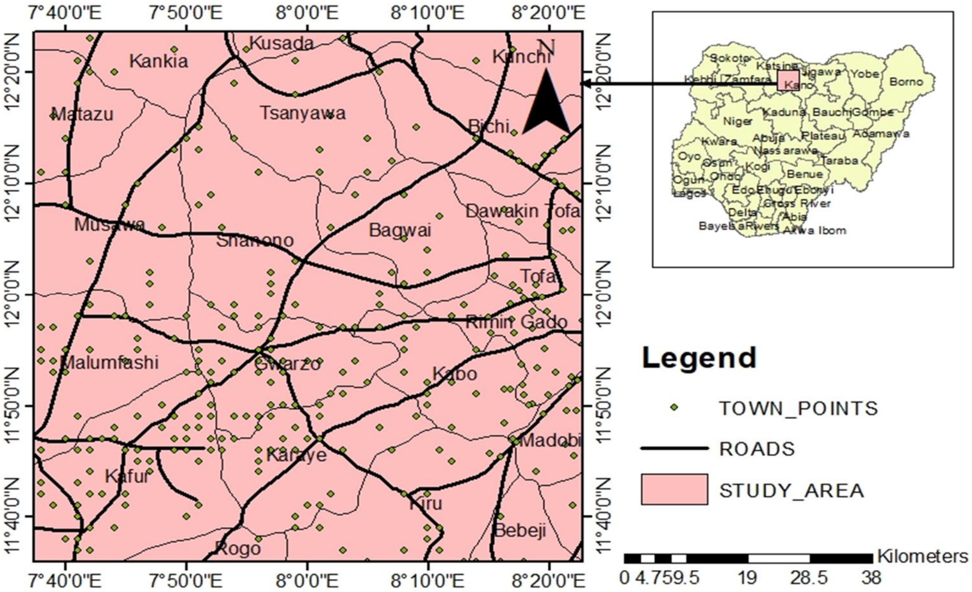

Figure 1: Location Map of the Study Area

B. Geology of the Study Area

It is underlain by rocks of the Nigerian Basement Complex of Pan-African (560 Ma) age, Comprising migmatite, gneiss, undifferentiated schist and phyllite, quartzite, granite-gneiss, and biotite. The Nigerian Basement Complex forms part of the Pan-African mobile belt and lies between the West African and Congo craton and south of the Tuareg shield (Obaje, 2009). The area falls within the Kazaure schist belt, the northern part of Malumfashi schist belt and there surrounding older metasediments/volcanic series, the older granites and migmatite – Gneiss complex

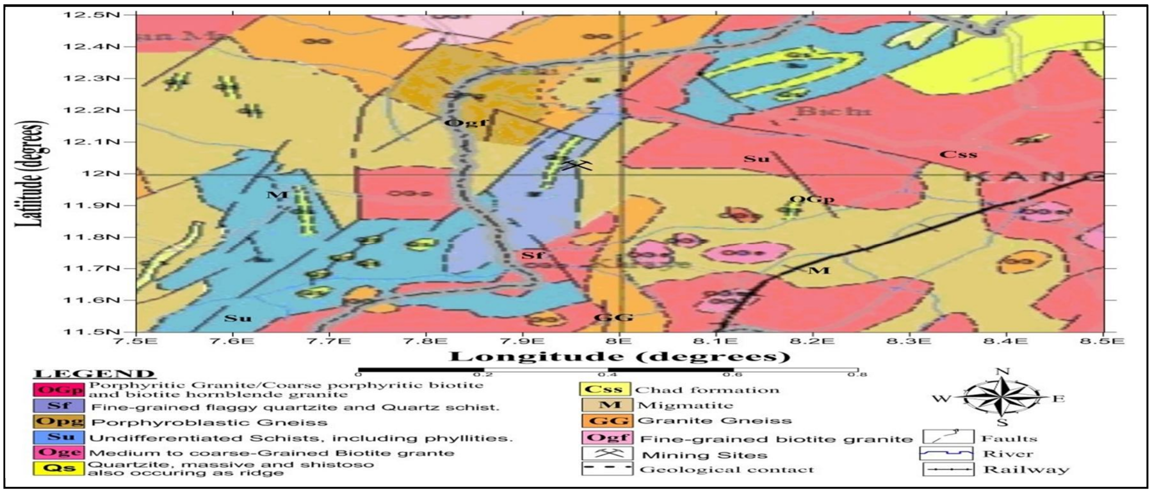

Figure 1: Geological Map of the study area. (Published by NGSA 2006).

C. Theories of Methods Analysis

To enhance structural interpretation, a regional–residual separation was carried out. The residual magnetic field was derived by subtracting the regional component from the TMI using a second-order polynomial fitting based on the least-squares method. This approach, following Ugwu et al. (2013), effectively isolates near-surface anomalies from deeper-seated regional trends, thereby improving the delineation of structures potentially associated with mineralization.

$$r = a_0 + a_1(x - x_{ref}) + a_2(y - y_{ref}) \tag{1}$$

D. Reduction to Magnetic Equator

The RTE was applied to correct for the distortion of magnetic anomalies at low latitudes, thereby centering anomaly peaks over their causative sources. This enhances the interpretation of basement architecture, including structural lineaments and their orientations, without loss of geophysical significance (Mendonça & Silva, 2003). The TMI was reduced to the equator in accordance with the International Geomagnetic Reference Field (IGRF) using a geomagnetic inclination of –1.4°, a declination of –1.7°, and a standard deviation parameter. The RTE transformation followed the expression of Umera (2011) (Equation 2).

$$L(\theta) = \frac{[\sin(I) - i.\cos(D-\theta)]^2 \times (-cos^2(D-\theta)}{[sin^2(I_a) + cos^2(I_a)cos^2(D-\theta)] \times [sin^2(I) + cos^2(D-\theta)]}, \tag{2}$$

$if\ (|I_a|) < (|I|), I_a = I$.

Where;

I = geomagnetic inclination; Ia = inclination for amplitude correction; D = geomagnetic declination; Sin (I) = amplitude component while icos (I) cos (D-θ) is the phase component Ө =wave number direction

E. First Vertical Derivative (FVD)

The First Vertical Derivative (FVD) map is an important tool for highlighting near-surface magnetic features associated with geological formations. This filtering technique enhances anomalies produced by shallow sources, thereby improving structural interpretation. This expressed mathematically by Remke et al. (2004) as:

$$FVD = \frac{\partial M}{\partial z} \tag{3}$$

F. Analytical Signal (AS) Technique

The Analytic Signal (AS) technique is widely applied in magnetic and gravity data interpretation due to its independence from rock magnetization and susceptibility contrasts. For two-dimensional bodies, it produces a bell-shaped symmetric function, while for three-dimensional sources, the signal amplitude is enhanced. This function and its derivatives are not affected by strike, dip, magnetic declination, inclination, or remanent magnetization. The 3-D analytic signal at any location (x,y)(x, y) is derived from the three orthogonal gradients of the total magnetic field, as expressed by Remke et al. (2004).

$$|A(x,y,z)| = \sqrt{\left(\frac{dT}{dx}\right)^2 + \left(\frac{dT}{dy}\right)^2 + \left(\frac{dT}{dz}\right)^2} \tag{4}$$

Where |A(x, y, z)| is the amplitude of the analytical signal at (x, y, z) and T is the observed magnetic field at (x, y, z).

G. Source Parameter Imaging

The SPI is a depth estimation technique derived from the extension of the complex analytic signal, also referred to as the local wavenumber. The method is applicable to two models: a 2-D sloping contact and a 2-D dipping thin sheet. For a magnetic field TTT, the local wavenumber is defined as given by Thurston and Smith (2000)

$$K(x,y) = \frac{\frac{\partial^2 T}{\partial x \partial z}\left(\frac{\partial T}{\partial X}\right) + \frac{\partial^2 T}{\partial y \partial z}\left(\frac{\partial T}{\partial X}\right) + \frac{\partial^2 T}{\partial^2 z}\left(\frac{\partial T}{\partial X}\right)}{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2} \tag{5}$$

II. METHODOLOGY

In this study, aeromagnetic and satellite gravity data of the area were obtained from the Nigeria Geological Survey Agency (NGSA). The total magnetic intensity (TMI) maps were processed using Oasis Montaj software and subjected to further analytical procedures.

The materials and tools applied include aeromagnetic and satellite gravity data covering the study area, geology and location maps, Geosoft Oasis Montaj, ArcGIS, and Rockwork software packages.

A. Data Analysis

Gridding of aeromagnetic data is a crucial step in data analysis, as imaging, processing, and interpretation require the data to be converted into an evenly spaced two-dimensional (2D) grid. Gridding involves interpolating data into equally spaced cells in a specified coordinate system.

The "minimum curvature" method is used to produce the grids, fitting a minimum curvature surface (the smoothest possible surface that fits the given data values) to the data points. The RANGRID GX of the Oasis Montaj™ software is used for this purpose. Gridding the data produces the total magnetic intensity (TMI) grid.

B. Data Interpretation

Since the release of aeromagnetic data in Nigeria by the Nigeria Geological Survey Agency (NGSA), there has been an upsurge of interest in the quantitative and qualitative interpretations of aeromagnetic data (Obiora et al., 2016). Interpretation of aeromagnetic survey data aims at mapping the surface and sub-surface regional structures (intrusive bodies, contacts, faults, basement rocks, and mineralization). This can be performed both qualitatively and quantitatively.

C. Qualitative Interpretation

This involves describing the survey results and explaining the major features revealed by the survey in terms of the likely geological formations and structures that cause the anomalies (Reeves, 2005). This information aims to map surface and subsurface structures, such as intrusives.

The first step in qualitative interpretation is preparing potential field maps or grids, where anomalous values at different stations are plotted, and contours are drawn at appropriate intervals. Computer software like Oasis Montaj is used for contouring, producing colored maps and grids.

D. Structural Trend

Lineaments are significant topographical features or geological structures, often linear or curvilinear, which can be continuous or discontinuous over a considerable distance.

They may arise from fractures, faults, joints, folds, contacts, or other geological processes and are present in igneous, sedimentary, and metamorphic rocks. Lineaments can serve as favorable structural conditions that control mineral deposits in an area (Megwara et al., 2013; Megwara and Udensi, 2014).

E. Quantitative Interpretation

This step involves estimating the depth and dimensions of anomaly sources numerically (Reeves, 2005). The study uses several quantitative interpretation techniques for aeromagnetic data, including Source Parameter Imaging (SPI) and Euler deconvolution. Initially, mathematical filters are applied, such as polynomial fitting, reduction to pole (RTE), first vertical derivative (FVD), second vertical derivative (SVD), and horizontal derivative (HD).

F. Total Magnetic Intensity

The Total Magnetic Intensity Figure 3 shows the two-dimensional (2D) Total Magnetic Intensity (TMI) map, where color variation highlights magnetic anomalies. High values reflect magnetite-rich zones, while lows denote areas of reduced magnetic susceptibility. The TMI ranges from 32,893.9 nT to 33,077.5 nT, demonstrating clear magnetic heterogeneity.

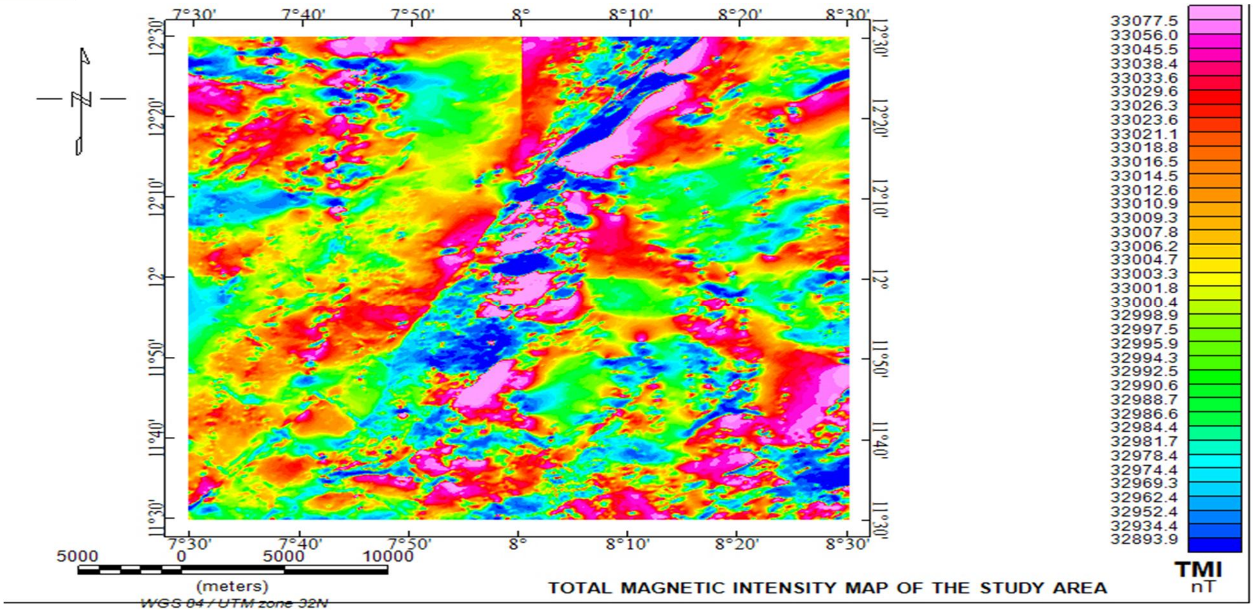

Figure 3 Total Magnetic Intensity map of the study Area

G. *Residual Map*

The residual magnetic intensity map (Figure 4) reveals values between –94.0 nT and 76.3 nT, highlighting both positive and negative anomalies. Positive signatures correspond to magnetic highs associated with surface rocks, while negative values indicate magnetic lows.

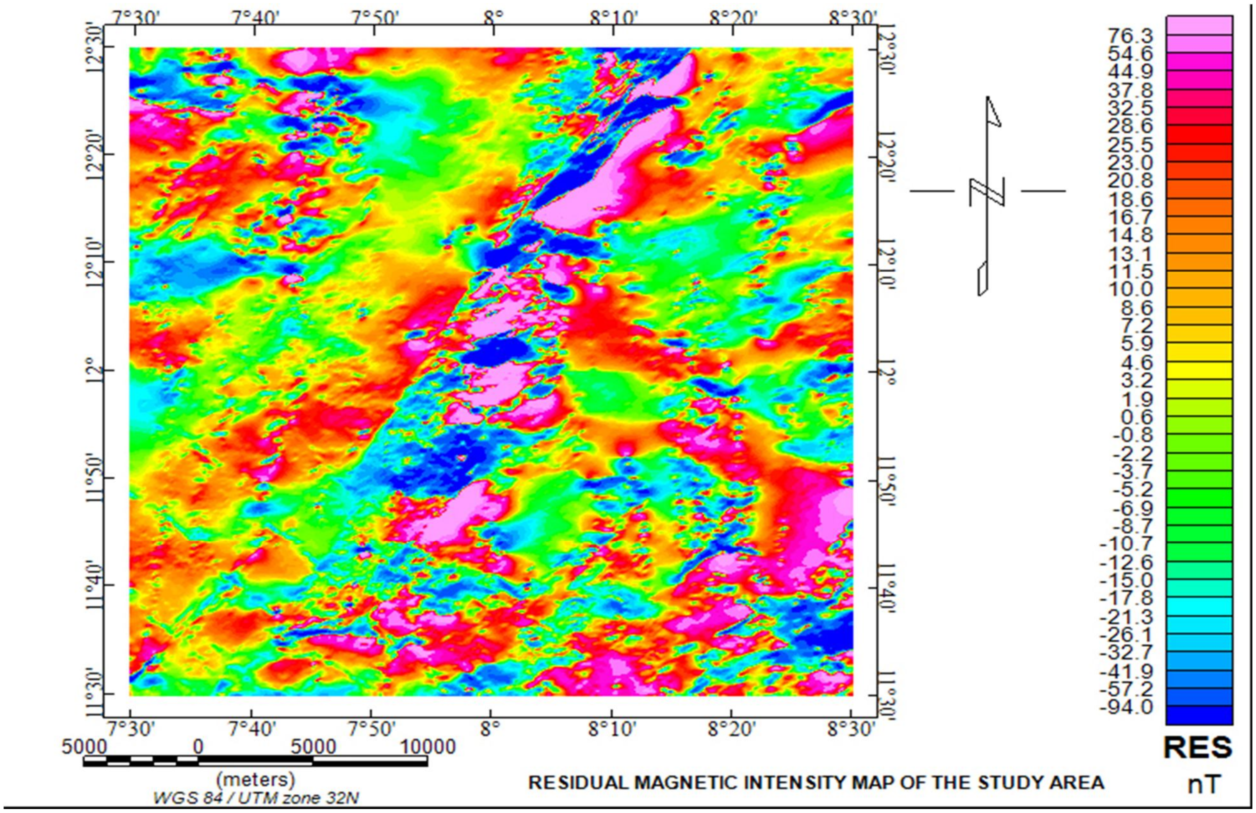

Figure 4 Residual Map of the Study Area

H. Reduction to Magnetic Equator

The Reduced-to-Equator (RTE) assumes magnetization is entirely induced; however, the presence of remanence alters this assumption. In the RTE map (Figure 5), the influence of remnant magnetization is evident, reflected in the reversal of the magnetic field.

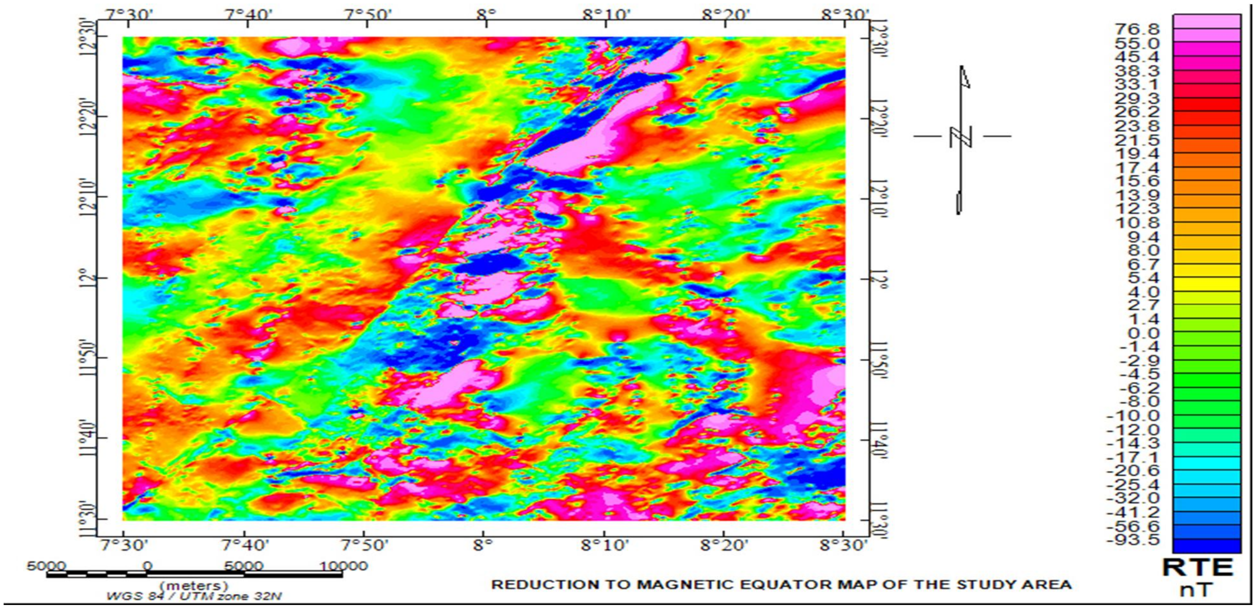

Figure 5 Reduction to Magnetic Equator of the Study Area

I. First Vertical Derivative Shaded Relief

The First Vertical Derivative (FVD) shaded relief Figure 6 highlights structural lineaments within the study area. The mapped lineaments display dominant NE–SW and NW–SE trends, with subordinate E–W and N–S orientations. These structural features suggest zones of faulting and fracturing that control subsurface lithology and possible mineralization. Spatially, the lineaments are concentrated between latitudes 11°30′–12°30′N and longitudes 7°30′–8°30′E, reflecting a structurally complex terrain.

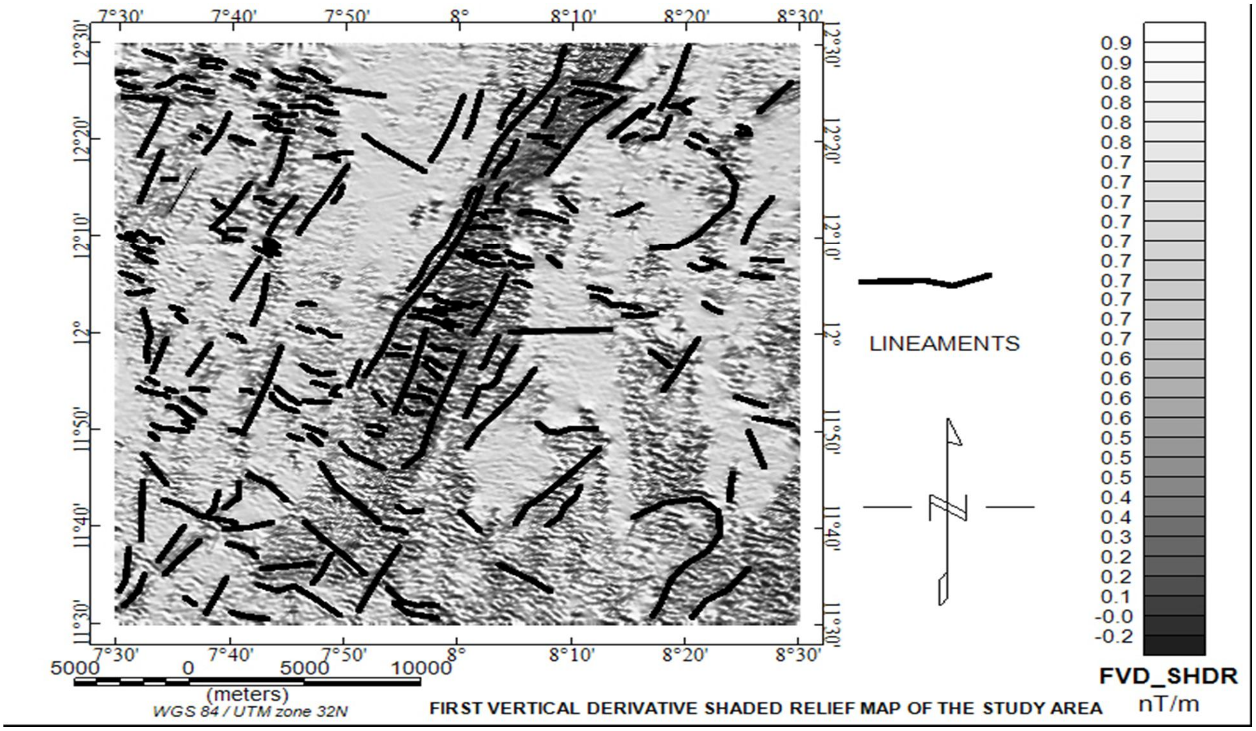

Figure 6 First Vertical Derivative Shaded Relief Map of the Study Area

J. Lineament Map

The lineament Figure 7 of the study area illustrates a dense network of structural features distributed between latitudes 11°30′–12°30′N and longitudes 7°30′–8°30′E. The lineaments show dominant NE–SW and NW–SE orientations, with minor E–W and N–S trends. Their concentration along the central and eastern portions suggests zones of intense deformation, possibly linked to faulting, fracturing, and tectonic activity, which are structurally significant for groundwater flow, mineralization, and crustal evolution.

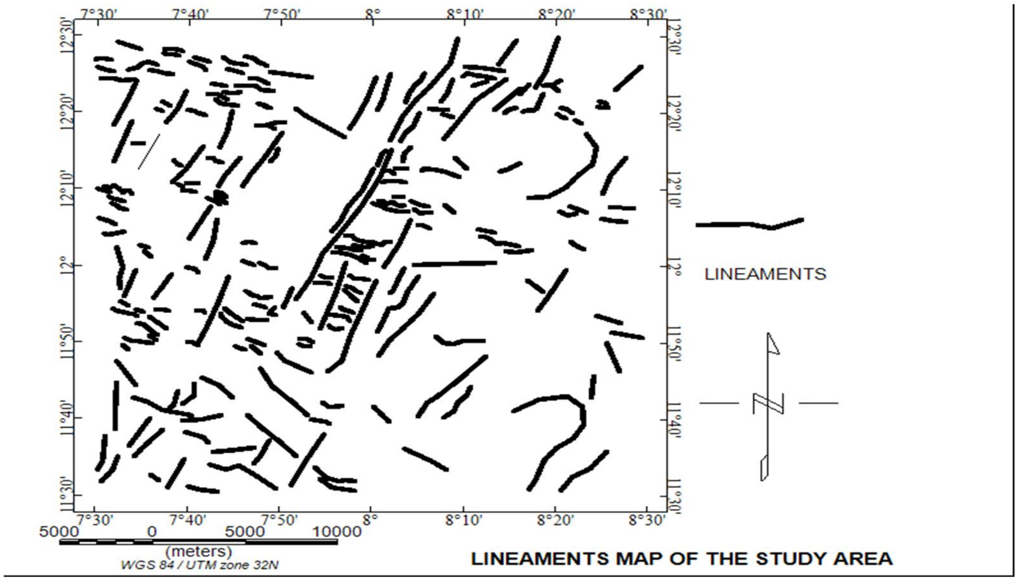

Figure 7 Lineaments Map of the Study Area

K. Source Parameter Imaging Map

The SPI Figure 8 shows depth variations from about 143 m to 737 m. Shallow magnetic sources, mostly between 150–250 m, dominate the southern and western parts of the area (around 7°30′E–7°50′E and 11°30′N–11°50′N). Deeper anomalies, exceeding 500 m, are concentrated in the Northeastern sector (8°10′E–8°30′E and 12°10′N–12°30′N). The central zone around longitude 8°E shows mixed depths with elongated patterns. The main structural trends are NE–SW and N–S, indicating fault-controlled features. Shallow anomalies likely represent basement highs or intrusives, while the deeper zones mark basement depressions that may host sediment accumulation. Overall, the northeast shows deeper structural lows, while the south and west are characterized by shallow intrusives.

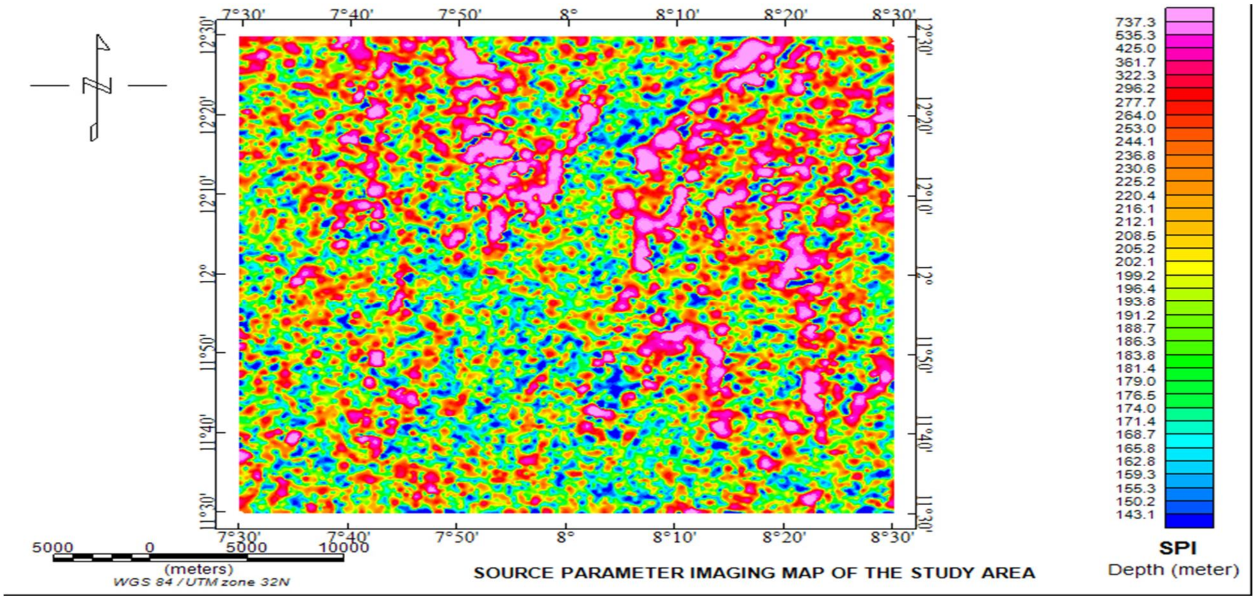

Figure 8 Source Parameter Imaging Map of the Study Area

III. DISCUSSION OF RESULTS

The aeromagnetic interpretation integrates results from the Total Magnetic Intensity (TMI), residual magnetic field, Reduction to the Equator (RTE), First Vertical Derivative (FVD), lineament mapping, and Source Parameter Imaging (SPI). Collectively, these datasets provide insights into the lithological variations, structural architecture, and subsurface framework controlling mineralization within the study area.

The TMI map (Figure 3) ranges from 32,893.9 nT to 33,077.5 nT, highlighting significant magnetic heterogeneity. High-intensity anomalies mark magnetite-rich lithologies or intrusive bodies, while low-intensity zones correspond to rocks of reduced susceptibility, possibly reflecting altered or non-magnetic lithologies. Such contrasts often define basement architecture and intrusive contacts that may localize mineralization (Garba, 2003; Okiwelu et al., 2013).

The residual magnetic intensity map (Figure 4), ranging between –94.0 nT and 76.3 nT, isolates shallow magnetic features by removing regional trends. Positive anomalies are linked to magnetic highs associated with surface or near-surface rocks, whereas negative anomalies delineate magnetic lows that may represent altered or sheared zones. These low anomalies are structurally significant, as faulted and altered rocks frequently act as conduits for hydrothermal mineralizing fluids (Ejepu et al., 2018; Adewumi & Salako, 2018).

Application of RTE filtering (Figure 5) centered anomaly signatures over their causative sources, revealing clearer structural patterns. However, the presence of remanent magnetization caused polarity reversals, consistent with observations in other low-latitude terrains (Mendonça & Silva, 2003). The RTE data emphasize NE–SW and N–S trends, which correspond to regional tectonic fabrics known to influence gold mineralization in northwestern Nigeria (Sani et al., 2019).

The FVD shaded relief map (Figure 6) enhanced short-wavelength anomalies and highlighted structurally controlled features. Dominant NE–SW and NW–SE lineaments, with subordinate E–W and N–S orientations, were observed between latitudes 11°30′–12°30′N and longitudes 7°30′–8°30′E. These orientations reflect tectonic deformation, faulting, and fracturing within the Basement Complex. Such lineaments are critical exploration guides, as they represent structural conduits for fluid migration and zones of potential mineralization (Olasehinde et al., 2024).

The lineament density map (Figure 7) further confirms a structurally complex terrain, with intense deformation concentrated in the central and eastern parts. The dominance of NE–SW and NW–SE lineaments suggests long-lived shear systems consistent with Pan-African tectonics, which are widely recognized as controlling gold occurrences in the Anka and Maru schist belts (Garba, 2000; Augie et al., 2021).

Depth estimates from the SPI analysis (Figure 8) range between 143 m and 737 m. Shallow magnetic sources (150–250 m) are concentrated in the southern and western sectors (7°30′E–7°50′E; 11°30′N–11°50′N) and are interpreted as basement highs or intrusives. These features are structurally favorable for gold mineralization due to their role in channeling hydrothermal fluids. In contrast, deeper anomalies (>500 m) occur in the northeast (8°10′E–8°30′E; 12°10′N–12°30′N), marking basement depressions that may host sedimentary accumulations or act as traps for mineralizing fluids. The central zone (~8°E) displays mixed depths (250–500 m) with elongated patterns, reflecting tectonic complexity and possible structural transitions.

Overall, the integration of TMI, residual, RTE, FVD, lineament, and SPI data reveals a structural framework dominated by NE–SW and N–S trends, with mineralization potential concentrated along zones of intense deformation and basement highs adjacent to depressions. These findings align with earlier studies that emphasize the role of shear zones, intrusives, and structural lows in hosting gold mineralization within the Nigerian Basement Complex (Ramadan & Abdel Fattah, 2010; Abubakar et al., 2024).

IV. CONCLUSION

This study delineates the regional structures associated with gold mineralization in part of northwestern Nigeria using aeromagnetic data, including TMI, residual separation, RTE, FVD, lineament analysis, and SPI. The Total Magnetic Intensity (TMI) ranges between 32,893.9 nT and 33,077.5 nT, reflecting clear lithological variations. Residual anomalies vary from –94.0 nT to 76.3 nT, distinguishing shallow and deep magnetic sources. The reduced-to-equator (RTE) correction enhanced anomaly positioning, improving structural interpretation. The First Vertical Derivative (FVD) and lineament maps delineated dominant NE–SW and NW–SE fault trends, with subordinate E–W and N–S orientations, concentrated between latitudes 11°30′–12°30′N and longitudes 7°30′–8°30′E, suggesting zones of intense deformation favorable for mineralization. Source Parameter Imaging (SPI) revealed depth variations from 143 m to 737 m, with shallow sources (150–250 m) concentrated in the south and west, while deeper anomalies (>500 m) dominate the northeast. These results highlight a structurally complex terrain in which basement highs, intrusives, and deep depressions provide favorable conditions for gold mineralization, thereby identifying priority exploration targets within the study area.

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