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# Structural Implications of High-Resolution Aeromagnetic Surveys in the Riruwai Complex, North Central Nigeria

A. Olasehinde[1]*, J. Barka[1], R. P. Tabale[1], A. Yusuf[1], M. N. Mboringong[1], S. I. Bute[1] and J. K. Ogunmola[2]

[1]Department of Geology, Gombe State University, P.M.B 127, Gombe, Gombe State, Nigeria.
[2]Department of Geology, University of Jos, P.M.B 2084, Jos, Plateau State, Nigeria

Corresponding Author: yinka@gsu.edu.ng

## ABSTRACT

Exploratory and mineral data collection is crucial for boosting investor confidence in the Nigerian mining sector and promoting the development of mineral resources in Nigeria. Geological structures play a vital role in mineral exploration, and high resolution aeromagnetic data analysis over the Riruwai Complex was utilized to identify these structures and their impact on mineralization. The enhancement techniques applied include Analytical Signal (AS) and Tilt Derivatives (TDR). The analytic signal of the reduced-to-the-equator anomaly highlighted the edges of highly altered rocks within the complex, corresponding to the biotite granite, Kaffo albite arfvedsonite granite, and Kaffo riebeckite porphyry-bearing granites. This was also accompanied by clusters of positive intensity values ranging from 0.68 to 1.39 nT/m, attributed to highly evolved, late-stage, low-density residual fluid-rich magmatic material, emplaced as granites in a separate magmatic phase following an initial eruption of less evolved volcanic material. Tilt Derivatives (TDR) accentuated the structural lineaments, which play a significant role in the enrichment of U, Th, Zr, Sn, Nb, and the exsolution of fluorine-bearing fluids during the late magmatic stage, concentrating in fissures and fractures. This study demonstrates that structural interpretation based on aeromagnetic data is an effective approach for mineral exploration.

**Keywords:** Aeromagnetic data, Analytic signals, Tilt Derivatives, Riruwai Complex, Mineral exploration

## INTRODUCTION

Despite the mining sectors significant past contributions to Nigeria's economy and its rich mineral resources, the sector has experienced stagnated growth for many years. However, recent developments signal a potential turnaround. To achieve the ambitious 3% growth target set for 2025, considerable efforts and intensified exploration are needed. Magnetic methods, essential for geological interpretation, play a key role in identifying geological structures and potential mineralization zones. These structures are crucial for exploring and mapping mineralized areas. The Younger Granite Province in north-central Nigeria, featuring anorogenic Mesozoic granites (Bowden & Kinnaird, 1978; Pointer, et al., 1988; Ogunleye, Ike & Garba, 2004; Ashano & Umeji, 2010; Girei et al., 2019), includes the Riruwai Complex. This complex is a prime example of the full cycle of ring complex magmatic activity within Nigeria’s Younger Granite (Jacobson & Macleod, 1977; Ogunleye, Garba, & Ike, 2006). Located between latitudes 10° 40’N to 10° 50’N and longitudes 8° 40’E to 8° 50’E, approximately 140 km south of Kano, the Riruwai Younger Granite Complex is a prominent feature.

Data collection has significantly boosted confidence in Nigeria’s mining sector and enhanced the promotion of its mineral resources. This study explores the structural insights and implications of high-resolution aeromagnetic data over the Riruwai Complex to support mineral exploration.

## GEOLOGY

The distribution of Mesozoic alkaline ring complexes, magmatic migration, and associated structures has been extensively studied (Black & Liegeois, 1993; Ike, 1983; Kinnaird & Bowden, 1991). The Riruwai Complex (Figure 1) is a prime example of a complete cycle of ring complex magmatic activity within Nigeria's Younger Granite Province. The complex's evolution began with an initial volcanic stage, characterized by substantial acid lavas and pyroclastic flows, with occasional basalt flows (Jacobson & Macleod, 1977). This volcanism led to the formation of a large cauldron or caldera, approximately 13 km in diameter, where most volcanic materials accumulated. The extrusive volcanic rocks are well-preserved in the north-western half of the complex, while the underlying vent structures are visible in the south-east and extreme north-west.

At the end of the volcanic cycle, a large quartz-fayalite-porphyry plug was emplaced in the center of the Dutsen Shetu vent complex. During the subsequent plutonic phase, a peripheral ring-dyke of granite-porphyry and central granite plutons of biotite and arfvedsonite granite were emplaced beneath the volcanic layers. Erosion has exposed all major units of the cycle, revealing their structural relationships. The lavas are confined within peripheral ring-faults, likely preserved due to down-faulting. Subsidence during the volcanic stage and subsequent ring-dyke intrusion probably contributed to this preservation.

The early development of the ring-fault provided a pathway for lava to reach peripheral vents. Studies (Abaa,1976; Jacobson & Macleod, 1977; Turner & Bowden, 1979; Ogunleye et al., 2006; Girei, 2019) have detailed the geology of the Riruwai Complex and the cassiterite mineralized lode, which extends 5 km east-west, at a depth of over 400 meters, and dips south at 85°.

## MATERIALS AND METHODS

### Aeromagnetic Data

Geophysicists can uncover information about geological structures, even those hidden entirely beneath the earth's surface using magnetic measurements (Ofuegbu, 1985; Dobrin & Savit, 1988; Iliya & Bassey, 1993; Alkali & Gaiya, 2011; Akanbi & Mangset, 2011; Olasehinde, et al., 2012). These measurements are typically taken from aircraft flying along closely spaced, parallel flight lines, with additional lines flown perpendicularly to aid in data processing. The collected data are then processed into a digital aeromagnetic map. Using computer programs, geologists can develop interpretations or models from these data. Aeromagnetic maps are valuable because rocks exhibit varying degrees of magnetism, allowing the outlines of magnetic structures to be traced over considerable distances.

The high spectral resolution aeromagnetic data for Riruwai sheet 126 were acquired by Fugro Airborne Surveys on behalf of the Nigerian Geological Survey Agency (NGSA) in 2005. The survey featured a flight line spacing of 400 m and a terrain clearance of 80 m, covering almost 2 million line-km. Data acquisition involved up to seven aircraft simultaneously and required innovative approaches for survey planning, instrument calibration, data compilation, and grid merging during the multiyear and multi-season campaigns (Nigerian Geological Survey Agency [NGSA], 2005).

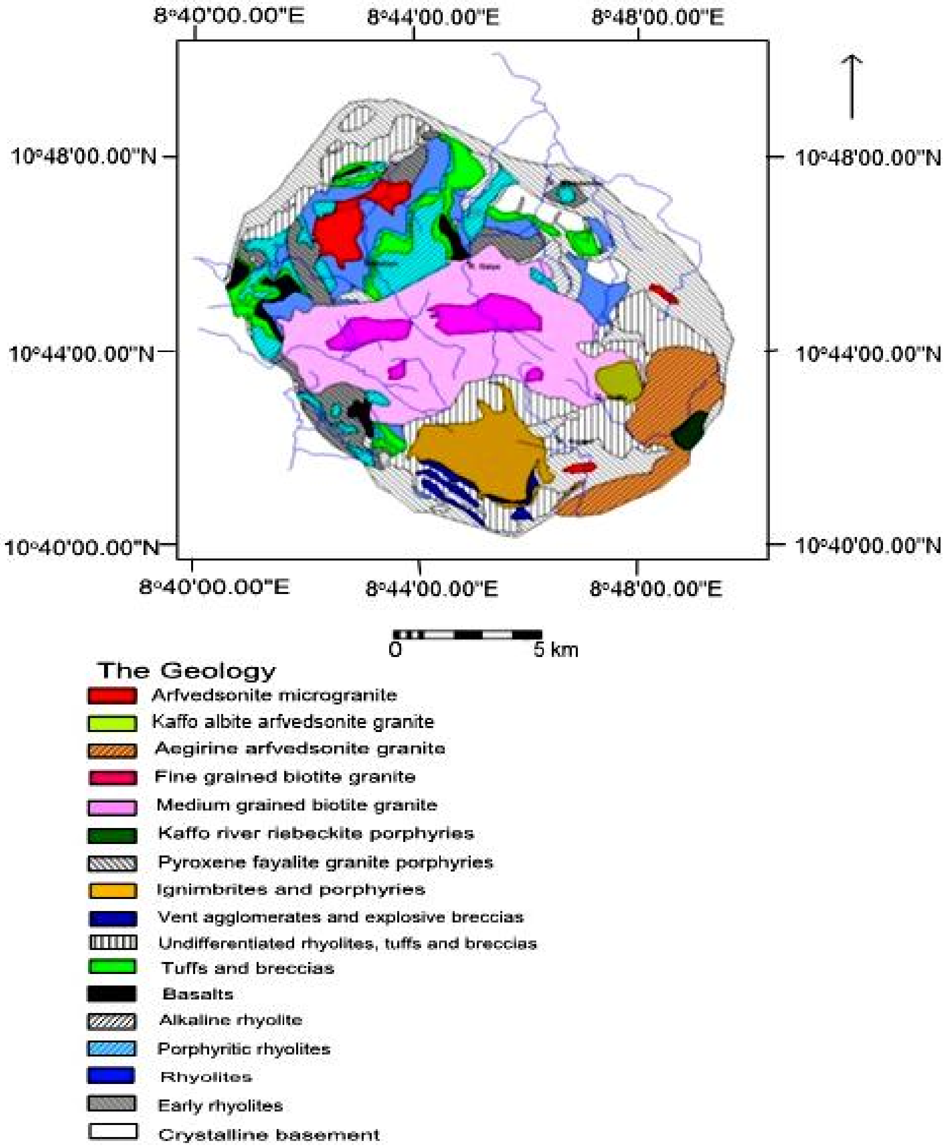

**Figure 1:** Geological Map of the Riruwai Complex, modified after Ogunleye, *et al.* (2006)

## Analytical Signal

The magnetic derivatives are calculated in the x,y,z direction, and the square root of the sum of the square of the derivatives gives the analytical signal (Roest, et al., 1992; Akingboye, 2018). It is also called the total gradient method.

The analytic signal is formed by the horizontal and vertical gradient of the magnetic anomaly.

In the 3-D case, the analytic signal is given by:

$$A\ (x,y) = \frac{\partial yM}{\partial x}\hat{\imath} += \frac{\partial yM}{\partial x}\hat{\jmath} += \frac{\partial yM}{\partial z}\hat{k} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ (1)$$

where $\hat{\imath}, \hat{\jmath}$ and $\hat{k}$ are unit vectors in the x,y,z directions respectively , and M is the magnitude of the magnetic anomaly. In the frequency domain equation (1) can be written as:

$$\hat{t}F[A(x,y)] = \widehat{h}.\nabla F[M] + iz.\nabla FM \ldots\ldots\ldots\ldots \text{(2)}$$

where ∇ is the gradient operator in frequency domain.

$(ik_x\hat{x} + i\dot{k}_y\hat{y} + |\ddot{k}|\widehat{z})$; $\hat{\imath} = \widehat{x} + \hat{y} + \hat{z}$ $and$ $\widehat{h} = \hat{x} + \hat{y}$ (Akingboye, 2018; Roset, et al., 1992)

The horizontal derivative and vertical derivaties of the anomaly are the real and imaginary and imaginary parts of equation (1) and (2) respectively.

The amplitude of the analytic signal

$$|A(x,y)| = \sqrt{\left[\frac{\partial M}{\partial x}\right]^2 + \left[\frac{\partial M}{\partial y}\right]^2 + \left[\frac{\partial M}{\partial z}\right]^2} \ldots\ldots\ldots\ldots \text{(3)}$$

The analytical signal transform was applied to the residual data of the study area utilizing Geosoft's Oasis Montaj software, which employs a Fast Fourier Transform (FFT) algorithm to efficiently compute the derivatives and subsequently generate the analytical signal.

## Tilt Derivative

The ratio of the vertical gradient to the total horizontal derivative which is always positive has been defined as the tilt angle (Miller & Singh, 1994). The Tilt derivative (TDR) is defined as-

$$\text{Tilt derivative } TDR = \tan^{-1}\left[\frac{VDR}{THDR}\right] \ldots\ldots\ldots\ldots \text{(4)}$$

The tilt angle always falls within the range -π/2 < Tilt < π/2, meaning the depth of the source does not affect the transformation. As a result, the tilt derivative can resolve magnetic sources at all depths, whether shallow or deep. This is particularly beneficial when deeper sources are present among numerous shallow ones. The Tilt Derivative Response (TDR) produces a maximum that peaks over the anomaly (Ogunmola et al., 2015). By limiting the arctangent component of the expression to between +1.57 and -1.57, an automatic gain control (AGC) is introduced, which amplifies low-amplitude signals. This makes the tilt derivative a highly effective method (Verduzco, Fairhead, Green, & MacKenzie, 2004). In this study, the tilt method was applied to the residual data using Geosoft's Oasis Montaj software.

## RESULTS AND DISCUSSION

### The Geodynamics

The Total Magnetic Intensity (TMI) map reveals a pattern of low magnetic values trending northeast and eastward in the mid-northern and southern regions of the complex, while higher magnetic values are concentrated in the central area (Figure 2). In the Reduction to Equator of the Total Magnetic Intensity (RTE-TMI) image (Figure 3), magnetic anomaly peaks are centered over their sources, using a geomagnetic inclination of 11.595 and declination of 2.097 (from IGRF), improving the clarity of inclined and aligned structures. The residual magnetic map (Figure 4) displays anomalies ranging from -221.05 to 205 nT, indicating both high and low residual magnetic variations in the region. This suggests the presence of both intrusive and extrusive mineral bodies. Notably, high residual

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magnetic anomalies, ranging from 38.26 to 205 nT, occur over intrusives such as Biotite granite in the center, Kaffo albite arfvedsonite granite in the southeast, and Pyroxene fayalite granite porphyries in the extreme north. These elevated magnetic responses are likely attributed to the significant magnetic content in these rocks. On the other hand, low residual magnetic anomalies, ranging from -211.05 to 11.75 nT, are predominantly found in volcanic rocks north and south of the Biotite granite boundary.

Applying the Tilt Derivative (TDR) to the residual RTE data (Figure 5) enhances anomaly detection, aligning peaks over magnetic sources. The TDR (Figure 6) emphasizes structural lineaments in the magnetic map, highlighting NE-SW trending anomalies as dominant features (Profiles AB and CD in Figure 7). These anomalies correspond to major structural trends in Nigeria's Younger Granite Province (Kogbe, 1989; Alkali & Gaiya, 2011; Raimi et al., 2014). The magnetic lineaments, which appear as narrow belts of low anomaly (2 to 5 km), reflect significant tectonic trends that extend across the Younger Granite Provinces (Odeyemi et al., 1999) and likely represent regional structures responsible for the emplacement of the Riruwai Complex. The residual magnetic map corresponds well with both the TMI and RTE-TMI maps, indicating that regional magnetic anomalies dominate over residual anomalies.

The analytic signal of the reduced equator anomaly distinctly outlines rock unit boundaries through anomaly patterns. Highly altered rocks, such as Biotite granite and Kaffo albite arfvedsonite granite, exhibit clusters of positive intensity values ranging from 0.68 to 1.39 nT/m. The magnetic lineaments emphasized by the TDR and analytic signal reveal a predominant NE-SW regional anomaly pattern within the Complex, aligning with the structural fabric of Nigeria's Basement Complex and paralleling major trends in the Younger Granites Province (Ashano & Olasehinde, 2010; Olasehinde & Ashano, 2014).

This pattern likely represents significant tectonic trends that facilitated volcanic activity and emplacement (Raimi et al., 2014). The low magnetic signal in the Riruwai Complex, similar to that of the Central Lapland Greenstone Belt in Finland (Nykanen, 2008), is associated with fine and medium-grained Biotite granites, Kaffo albite arfvedsonite granite, and Kaffo riebeckite porphyry-bearing granites. This anomaly likely reflects highly evolved, late-stage, low-density, fluid-rich magmatic material that was emplaced as granites during a separate magmatic phase following an initial volcanic eruption of less evolved material.

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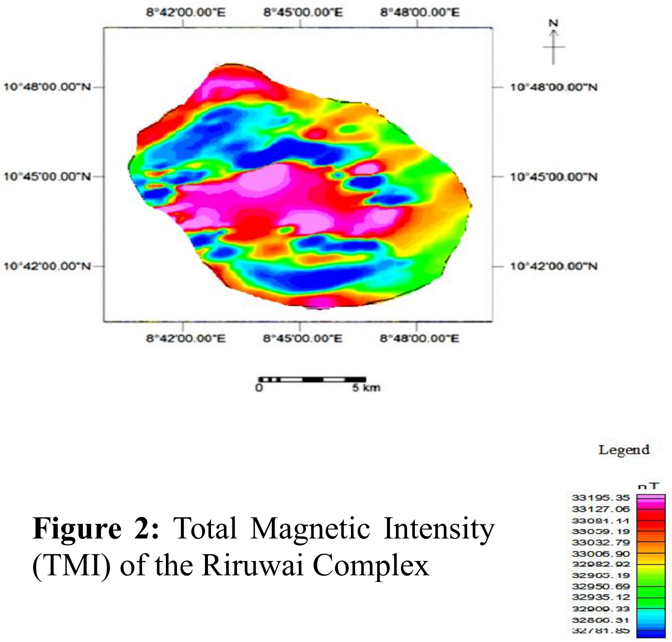

**Figure 2:** Total Magnetic Intensity (TMI) of the Riruwai Complex

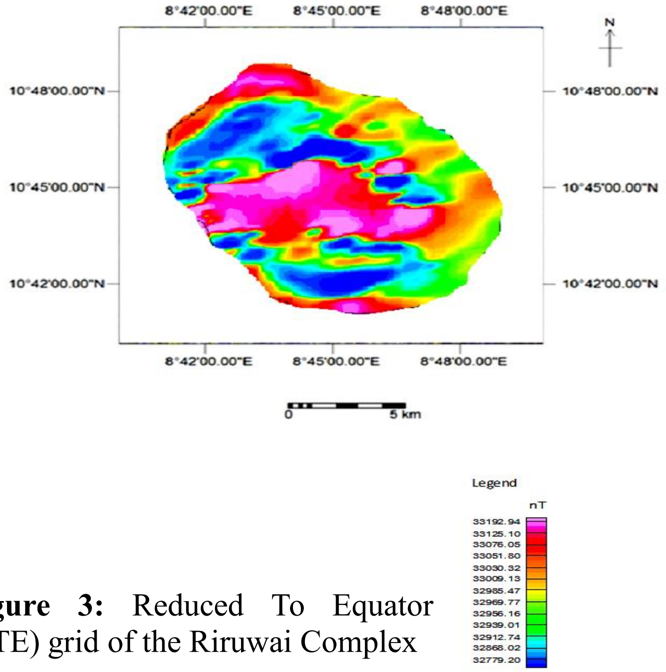

**Figure 3:** Reduced To Equator (RTE) grid of the Riruwai Complex

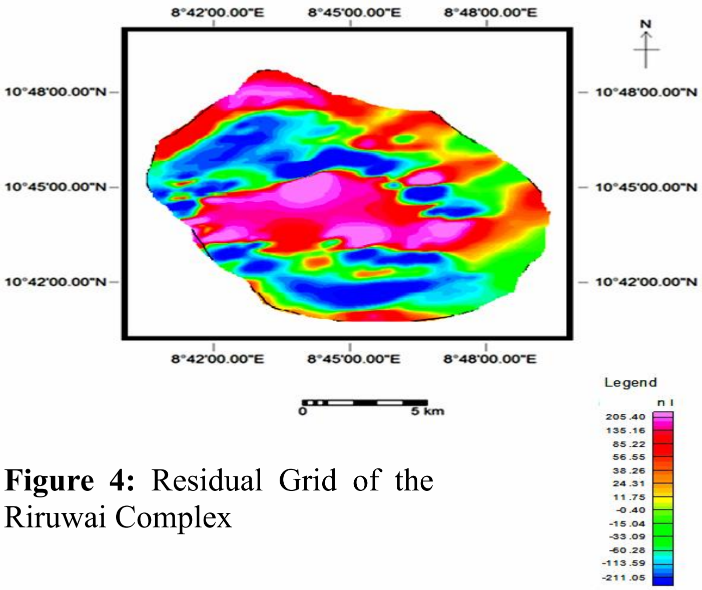

**Figure 4:** Residual Grid of the Riruwai Complex

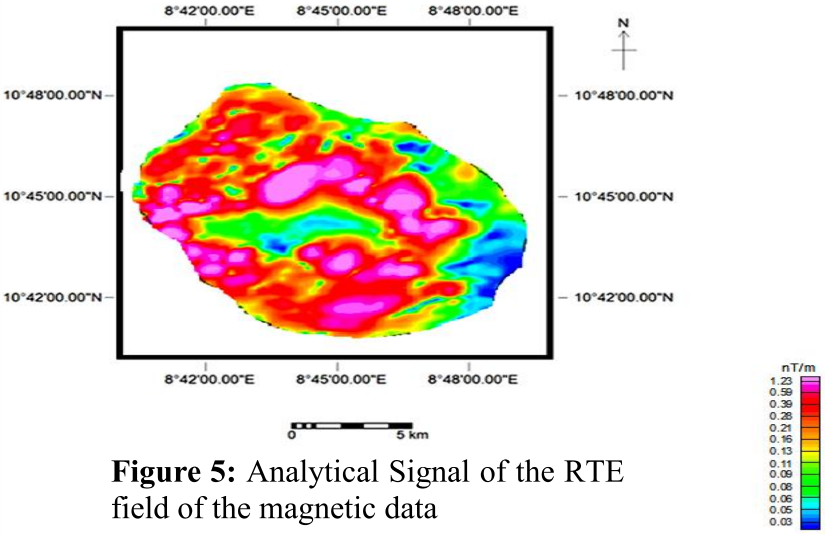

**Figure 5:** Analytical Signal of the RTE field of the magnetic data

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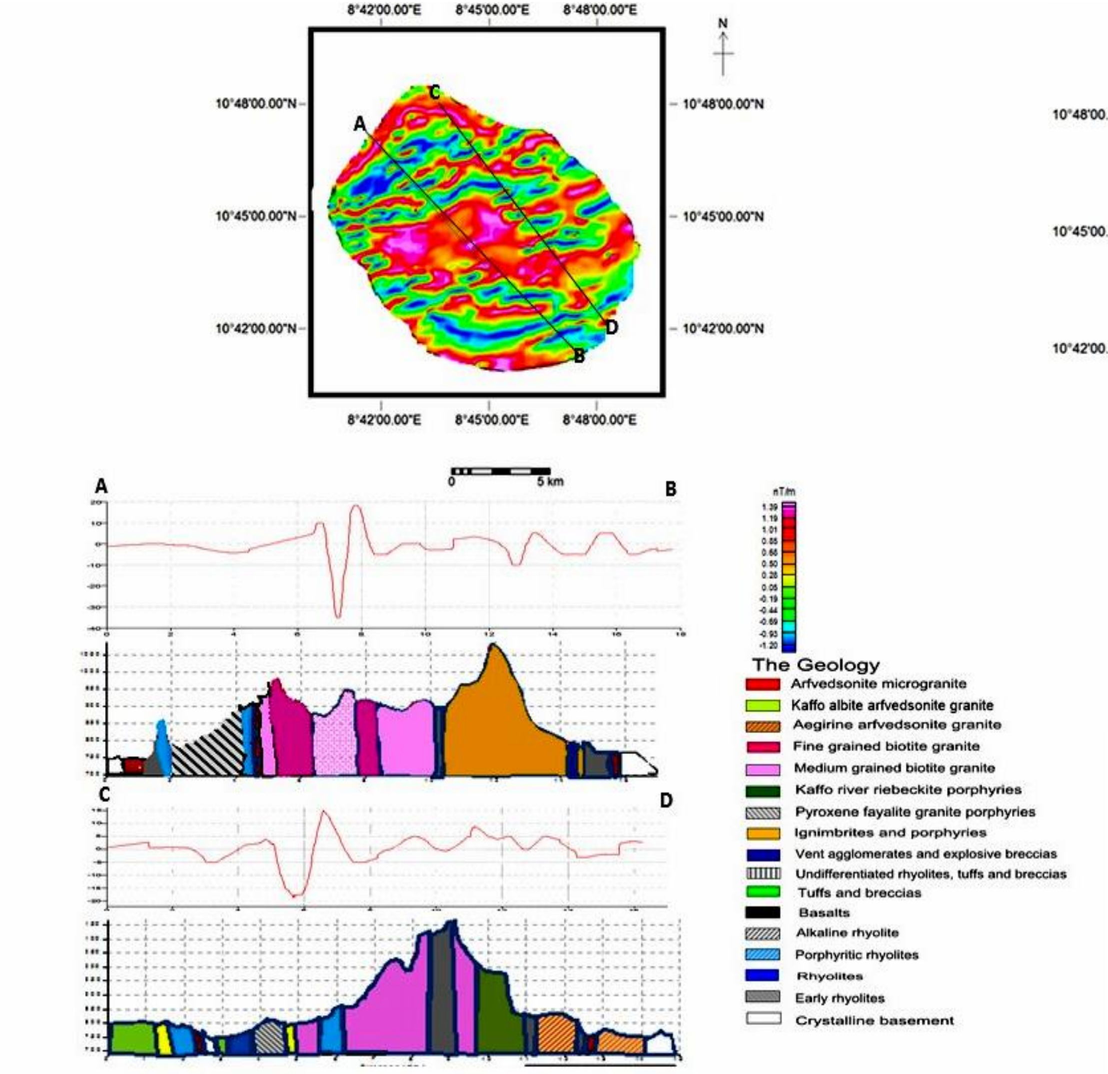

**Figure 6:** Tilt Derivative (TDR) of the Ririwai Complex. Profiles AB and CD of the TDR and the corresponding geology.

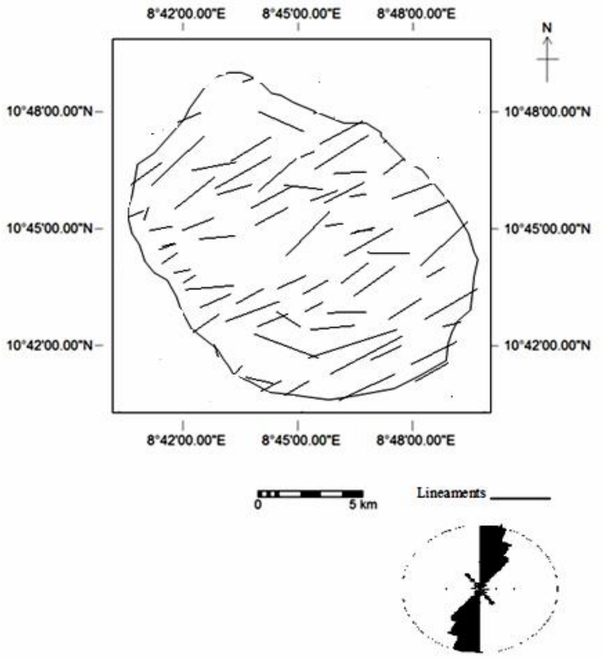

**Figure 7:** Deep seated structures derived from magnetic interpretation of the Riruwai Complex with major direction in the NE.

## Mineral Potentials

Lineament analysis is a crucial tool in mineral exploration, aiming to identify optimal locations for mineral concentration. These zones serve as channels for mineralizing fluids, facilitating their movement. Lineaments play a significant role in providing pathways for highly volatile mineralizing fluids (Bonin, 1986, 2007). This is particularly evident in the biotite and Kaffo arfvedsonite granite, which exhibit high potential for Sn, Nb, U, and Zn mineralization.

Extensive fracture networks enable magma to reach the surface, leading to volcanic eruptions, as observed in the Riruwai Complex. Regions with dense lineaments (Figure 8) correspond to high magnetic zones, indicating that mineralization potential is likely controlled by structural factors. These structures, including joints, veins, dykes, faults, and mineralized lodes (Figures 9-11), display variable trends and enhance hydrothermal movement and concentration of mineralizing fluids.

Field studies (Plate 1-3) have confirmed the presence of various structures, evidencing deformation imprinted on the rocks. The extensively mineralized lode (Imeokparia, 1983) features parallel to sub-parallel or braided quartz veins surrounded by grey greisens, grading outward into reddened wall rock. Occasionally, this transitions through a narrow buff-colored zone into pale pink, equigranular biotite perthite granite (Turner and Bowden, 1979).

The mineralization of the Riruwai Complex (Van Breemen, Pidgeon, & Bowden, 1977; Bonin, 1986; Girei, et al. 2019) reveals a sequence of hydrothermal alteration events. Potash metasomatism initiated the alteration, causing perthic feldspar near fissures to become microclinized. This was followed by early deposition of monazite, zircon, and ilmenite, and later the formation of cassiterite, wolframite, and rutile, culminating in the intrusion of molybdenite (Kinnaird, 1979; 1985).

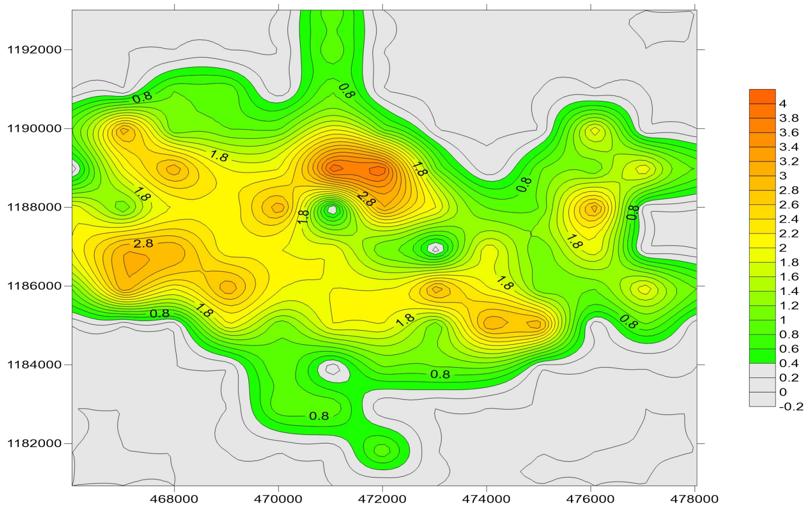

**Figure 8:** Lineaments density contour map showing areas with high concentrations which are targets during mineral exploration.

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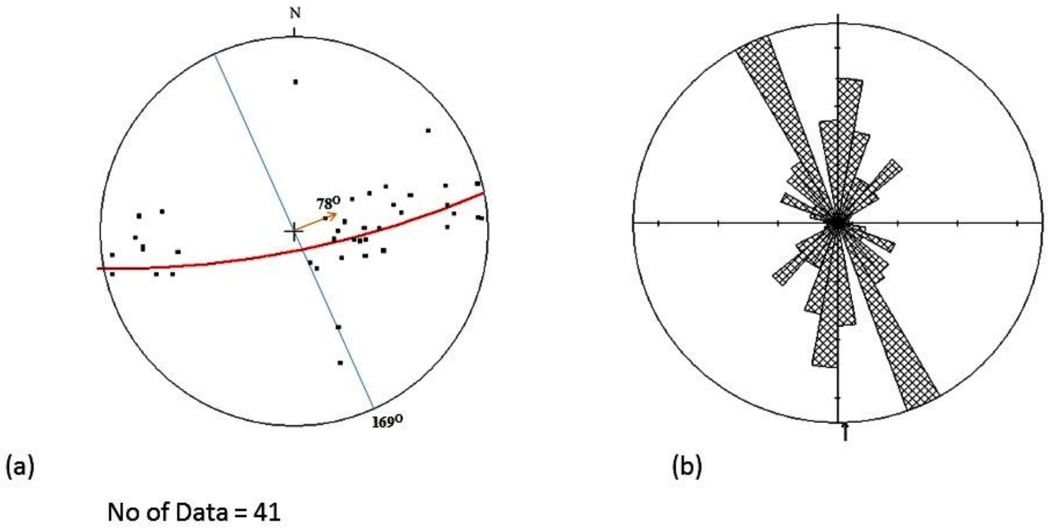

**Figure 9(a):** Pole to Fractures in the Fine Grained Biotite Granite of the Riruwai Complex on the Equal Area is N169° and with dip of about 78° to the E (b) Rose plot for fractures in the Fine Grained Biotite Granite with the major trend in the NW-SE and minor NE-SW direction.

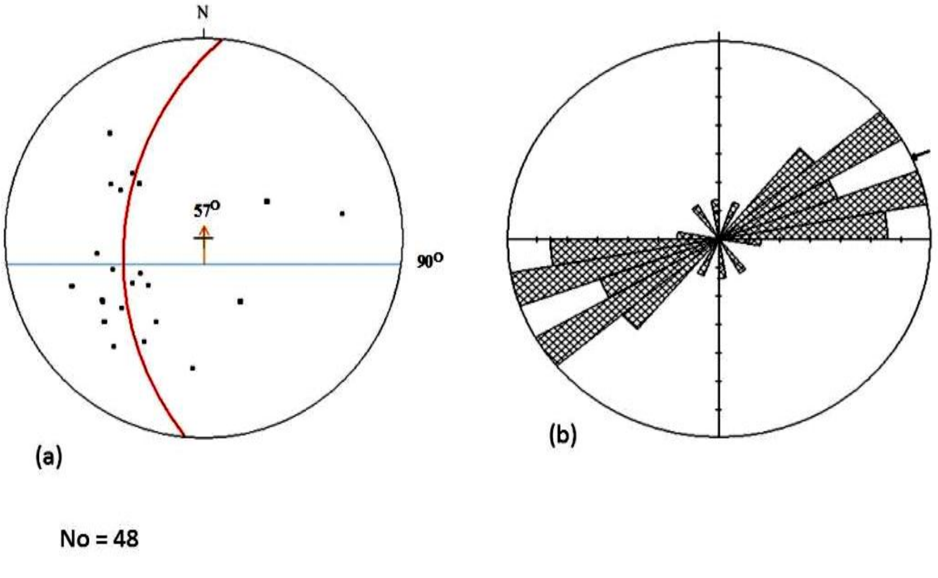

**Figure 10(a):** Pole to Fractures in the Medium Grained Biotite Granite of the Riruwai Complex on the Equal Area is N90°E and with Average dip of about 57° (b) Rose plot for fractures on the Medium Grained Biotite Granite with the major trends in the NE-SW direction.

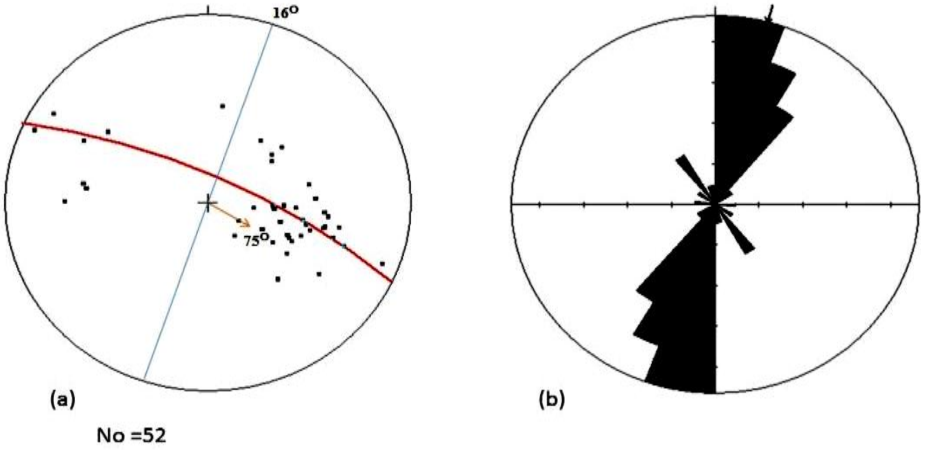

**Figure 11(a):** Pole to Fractures in the Kaffo Albite Arfvedsonite Granite of the Riruwai Complex on the Equal Area is N16°E and with dip of about 75° to the SE (b) Rose plot for fractures in the Kaffo Albite Arfvedsonite with major trend in the NE-SW direction.

Plate 1; A Typical quartz vein trending N-S within the Biotite Granite.

Plate 2; Typical joints trending NE-SW within the Kaffo Riebeckite Porphyry bearing Granite.

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Plate 3; Fractures within the the Kaffo Albite Arfvedsonite. NE-SW and E-W directions.

## CONCLUSION

The tilt derivative of the analytical signal reveals a prominent NE-SW regional anomaly pattern within the Complex, coinciding with the emplacement of the Riruwai Younger Granite. This pattern aligns with the NE-SW structural fabric of Nigeria's Basement Complex, reflecting the regional tectonic stress field. Low magnetic analytical signals are characteristic of the fine and medium-grained biotite granites, Kaffo albite arfvedsonite granite, and Kaffo riebeckite porphyry-bearing granites within the Complex. This anomaly is likely attributed to the presence of highly evolved, late-stage, low-density residual fluid-rich magmatic material, which is associated with significant rare-metal mineralization (Sn, U, Th, Nb). This mineralization is influenced by late-stage crystallization and the role of fluorine in mineral transport. A strong correlation exists between known mineral occurrences and favorable exploration targets, as evidenced by magnetic maps and geological data. We propose that enhancing aeromagnetic data in future studies will introduce new techniques in structural analysis and mineral exploration, leading to improved discovery and characterization of mineral deposits.

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