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Assessment of Copper and Columbite Mineralization Potential in Gaya and Its Environs Northwestern Nigeria Using Aeromagnetic and Geological Mapping Approach

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Abstract: This study uses high-resolution aeromagnetic data (NGSA sheet no.) to assess the copper and columbite mineralization potential of Gaya and its surroundings in northwestern Nigeria. 82integrated with the published geological map of the area. The geological map shows documented occurrences of columbite at Gaya and Bunin Kudu, and of copper minerals near Ajingi, within a basement terrain comprising porphyritic granite (coarse porphyritic biotite and biotite-hornblende granite) flanked by the Chad Formation (sandstone, clay, and limestone). The aeromagnetic data were processed to generate the Total Magnetic Intensity (TMI), regional field, residual field, Analytic Signal Amplitude (ASA), and First Vertical Derivative (FVD) maps, while lineaments were automatically extracted using the Centre for Exploration Targeting (CET) tool in Oasis Montaj. Results show total magnetic intensity ranging from 33724.9 nT to 34179.1 nT, with high-amplitude analytic signal zones (up to 0.592 nT/m) and dense NE-SW to NW-SE trending lineaments coinciding with the mapped porphyritic granite terrain and the documented columbite and copper mineral occurrence points. This spatial coincidence between known mineral occurrences, structurally complex magnetic zones, and porphyritic granite lithology is interpreted as confirming the structural and lithological controls on copper and columbite mineralization in the area, and is used to extend the known occurrence zones into adjoining structurally similar, previously unsampled parts of the study area. The study recommends targeted ground geochemical and mineralogical follow-up over the extended anomaly zones to validate these additional geophysically inferred targets.

Keywords: Aeromagnetic, Copper, Columbite, Lineament, Analytic signal, Mineralization potential, Gaya, Northwestern Nigeria.

I. INTRODUCTION

Nigeria hosts a wide range of solid mineral resources distributed across its geological terrains, and the Nigerian Geological Survey Agency has catalogued approximately 34 major mineral occurrences with considerable investment potential (NGSA, 2004). Among these, copper and columbite-tantalite are of particular economic significance: columbite (a niobium-bearing oxide mineral, (Fe,Mn)Nb2O6) has historically been mined in commercial quantities from Nigeria's Younger Granite ring complexes and associated pegmatites, while copper commonly occurs as chalcopyrite within structurally controlled, hydrothermally altered zones of Nigeria's Precambrian basement complex.

Airborne magnetic surveys have long been established as an effective tool for delineating the structural features (faults, contacts, fractures, and lineaments) and basement lithological boundaries that control the emplacement of such mineral occurrences, particularly where they coincide with granitic and pegmatitic intrusions or fault-controlled hydrothermal pathways (Adebisi et al., 2024; Ekwok et al., 2022). Studies elsewhere in Nigeria's Younger Granite province and Pan-African basement terrain have consistently shown that high-amplitude magnetic anomalies mark granite/pegmatite structures prospective for cassiterite-columbite mineralization (Sunday et al., 2026; Salawu et al., 2025), while NE-SW and NW-SE trending lineaments, reactivated from Pan-African shear zones, are commonly associated with base-metal sulphide and hydrothermal mineral occurrences (Lawal et al., 2024; Fatoba & Kehinde, 2025). Recent studies in the North-Central Precambrian Basement Complex have similarly used integrated Source Parameter Imaging, Euler deconvolution, analytic signal, and 3D inversion modelling to delineate structurally hosted columbite, tantalite, and base-metal deposits at depths of 150-800 m along NE-SW, NW-SE, and E-W fault and fracture networks (Ndatuwong et al., 2025), while comparable work in northwestern Nigeria's Kano-Katsina basement terrain has used Total Magnetic

Intensity, First Vertical Derivative, Source Parameter Imaging, and lineament extraction to delineate NE-SW and NW-SE trending structures controlling mineralization in a basement setting directly comparable to the present study area (Abdullahi et al., 2025). Jos Plateau columbite-lode and pegmatite occurrences, likewise, are documented to be hosted within granitic and pegmatitic environments where hydrothermal enrichment of niobium and tantalum minerals is structurally controlled (Olomo et al., 2025), while copper, lithium, and lead-zinc exploration targets elsewhere in Nigeria's basement complex have similarly been mapped using integrated aeromagnetic and airborne radiometric data (Ekwok et al., 2025).

The published geological map of Gaya and its environs (Fig. 1) documents columbite occurrences at Gaya and Bunin Kudu and a copper mineral occurrence near Ajingi, hosted within a porphyritic granite (coarse porphyritic biotite and biotite-hornblende granite) terrain that is flanked to the east by the Chad Formation (sandstone, clay, and limestone). This confirms that the area is a genuine, documented host for both commodities, though the full structural extent of the mineralized zones beyond the mapped occurrence points has not previously been assessed using aeromagnetic data.

Beyond these regional structural studies, several recent investigations have specifically targeted the geophysical and geochemical expression of copper- and columbite-related mineralization within Nigeria’s basement and granitic terrains, providing direct analogues for the present study area.

Abraham et al. (2022) applied Euler deconvolution, analytic signal, source parameter imaging, and 3D inversion of aeromagnetic data to delineate niobium-, tantalum-, and tin-bearing structures within granitic rocks of northern Nigeria, confirming that Nb-Ta (columbite-tantalite) mineralization is consistently associated with discrete, high-amplitude magnetic anomalies and structurally controlled dyke- and sill-like intrusive bodies. Similarly, Olasehinde et al. (2024) used aeromagnetic mapping of basement structures in northwestern Nigeria, the region encompassing the present study area, to identify structurally controlled zones favourable for base-metal mineralization, while Akpaneno and Tawey (2024) combined residual magnetic intensity, first and second vertical derivatives, and analytic signal analysis over the Shanga area (sheet 96) of northwestern Nigeria to delineate and depth-estimate basement mineralization zones in a geological setting directly comparable to Gaya and its environs. At the mineralogical and geochemical scale, Adetunla and Oshin (2024) characterized tantalo-columbite ore and host pegmatites at Awo, southwestern Nigeria, using petrographic, X-ray diffraction, and X-ray fluorescence analyses, confirming niobium-tantalum enrichment and a magmatic, structurally controlled origin consistent with the columbite occurrences documented within the porphyritic granite terrain of the present study area. Collectively, these copper- and columbite-focused studies reinforce the interpretation that structurally complex, high-amplitude magnetic zones coincident with porphyritic and pegmatitic granite terrains, as identified in the present study, are genuine loci of Nb-Ta and Cu-sulphide mineralization rather than incidental magnetic artefacts.

This study therefore applies an integrated aeromagnetic and geological mapping approach to assess the structural and lithological controls on the known copper and columbite occurrences in Gaya and its environs, and to identify additional, structurally analogous target zones for follow-up ground exploration.

The aim of this study is to assess the copper and columbite mineralization potential of Gaya and its environs using integrated aeromagnetic and geological mapping methods. The specific objectives are to: (i) process and enhance the aeromagnetic data to delineate subsurface structural features; (ii) map lineament trends and their relationship to the mapped lithological units and documented mineral occurrence points; and (iii) integrate the structural and lithological evidence to extend the known copper and columbite occurrence zones into structurally comparable, unsampled parts of the study area.

II. GEOLOGIC SETTING OF THE STUDY AREA

The study area lies between longitudes 9°0'0"E to 9°30'0"E and latitudes 11°30'0"N to 12°0'0"N, covering Gaya, Ajingi, Albasu, Takai, Bunin Kudu, and surrounding local government areas in the Kano sector of northwestern Nigeria. As shown on the geological map (Fig. 1), the western part of the study area is underlain by porphyritic granite, comprising coarse porphyritic biotite and biotite-hornblende granite, while the eastern and central parts are covered by the Chad Formation, comprising sandstone, clay, and limestone. Documented columbite occurrences are mapped at Gaya and at Bunin Kudu, both located at or near the contact between the porphyritic granite and the Chad Formation, while a copper mineral occurrence is mapped near Ajingi, within the porphyritic granite terrain.

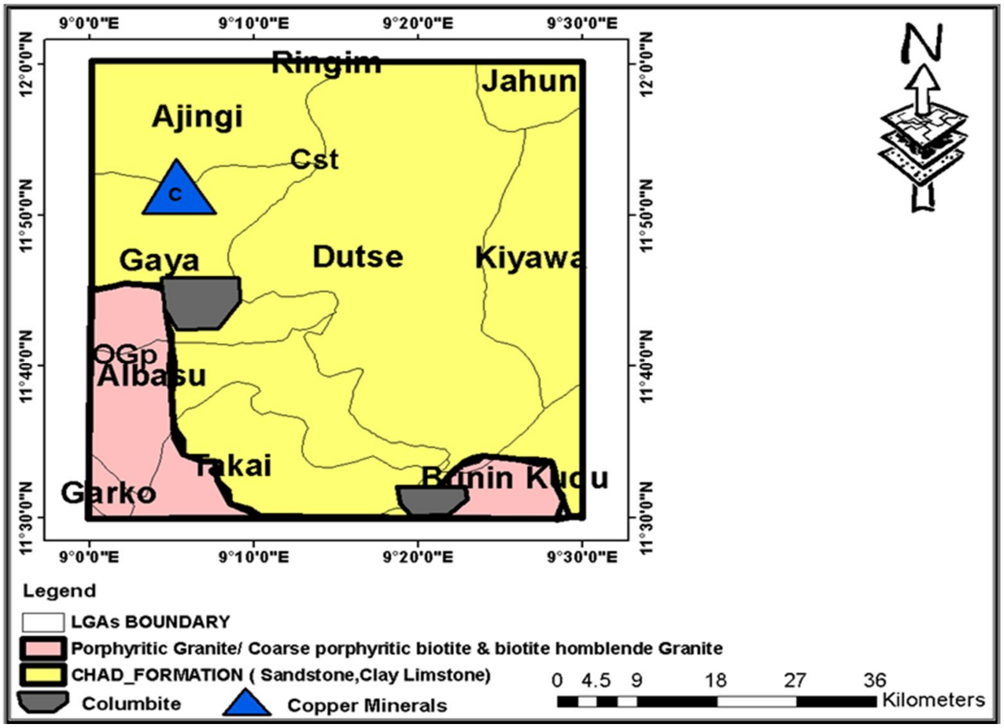

Figure 1: Geological map of Gaya and its environs, (Base map: NGSA2025.)

This lithological and occurrence pattern, porphyritic granite hosting both columbite and copper mineral occurrences, is consistent with regional exploration models elsewhere in Nigeria's Younger Granite and Pan-African basement terrains, in which porphyritic and pegmatitic granite bodies host Nb-bearing (columbite) minerals, and structurally complex granite-basement contacts host Cu-bearing sulphide occurrences.

III. MATERIALS AND METHODS

A. *Theory of Method*

Aeromagnetic exploration for mineralization is based on the principle that variations in the total magnetic field of the Earth reflect contrasts in the magnetic susceptibility and remanent magnetization of subsurface rocks, which in turn reflect lithological boundaries and structural features such as faults, fractures, and intrusive contacts that commonly localize hydrothermal and pegmatitic mineralization (Telford et al., 1990; Dentith & Mudge, 2014). The processing sequence applied in this study, comprising computation of the magnetic anomaly, regional-residual separation, and Analytic Signal Amplitude, First Vertical Derivative, and automated lineament extraction, follows standard potential-field theory summarized in Equations (1) to (7) below.

The Total Magnetic Intensity (TMI) recorded during the survey represents the magnetic anomaly field, ΔT, obtained by removing the International Geomagnetic Reference Field (IGRF) from the observed total field intensity:

$$\Delta T(x, y) = T_o^{bs}(x, y) - T^{IGRL}(x, y) \qquad (1)$$

Where $T_o^{bs}(x, y)$ is the observed total magnetic field intensity at position (x, y), and $T^{IGRL}(x, y)$ is the corresponding computed IGRF value at the same location and survey epoch (Telford et al., 1990).

Regional-residual separation was carried out by fitting a first-order polynomial trend surface, R(x, y), to the gridded TMI data, such that the observed field, T(x, y), is expressed as the sum of a smooth regional component and a residual component:

$$T(x, y) = R(x, y) + Res(x, y) \qquad (2)$$

$$R(x, y) = a_0 + a_1 x + a_2 y \qquad (3)$$

Where a_0, a_1, and a_2 are the polynomial coefficients determined by least-squares fitting to the TMI grid. The residual field, which isolates the short-wavelength anomalies associated with near-surface structural and lithological contrasts from the broad regional trend, is then obtained as:

$$Res(x, y) = T(x, y) - R(x, y) \qquad (4)$$

(Telford et al., 1990; Dentith & Mudge, 2014).

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The Analytic Signal Amplitude (ASA), A(x, y), was computed from the residual magnetic field following Nabighian (1972):

$$A(x,y) = \sqrt{\left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2\right]} \qquad (5)$$

Where $\partial T/\partial x$ and $\partial T/\partial y$ are the horizontal derivatives of the magnetic field in the x and y directions, respectively, and $\partial T/\partial z$ is the vertical derivative, computed in the frequency domain. Because the analytic signal amplitude peaks directly over the edges of magnetic source bodies irrespective of the direction of magnetization, the ambient field inclination, or remanent magnetization effects, it provides a robust means of locating structural and lithological contacts (Nabighian, 1972).

The First Vertical Derivative (FVD) enhances shallow, short-wavelength magnetic sources relative to deeper, broader ones, and was computed by Fourier transformation of the magnetic field:

$$F\left[\frac{\partial T}{\partial z}\right] = |k|.\,F[T(x,y)] \qquad (6)$$

Where F denotes the Fourier transform, and $k = \sqrt{(kx^2 + ky^2)}$ is the radial wavenumber, with kx and ky the wavenumbers in the x and y directions, respectively. The First Vertical Derivative map was then recovered by applying the inverse Fourier transform to the right-hand side of Equation (6) (Telford et al., 1990).

Lineaments were extracted from the enhanced (residual, ASA, and FVD) magnetic maps using the Centre for Exploration Targeting (CET) grid analysis tool, which applies multi-scale edge detection based on the local horizontal gradient of the magnetic field:

$$G(x,y) = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2} \qquad (7)$$

to automatically identify, vectorize, and classify linear and curvilinear trends corresponding to faults, fractures, and lithological contacts within the magnetic data, which were subsequently compared with the mapped lithological boundaries and documented mineral occurrence points on the geological map (Fig. 1) (Ndatuwong et al., 2025; Abdullahi et al., 2025).

B. Data Acquisition and Processing

High-Resolution Aeromagnetic Data (HRAD) covering the study area (Gaya, sheet 82) were obtained from the Nigerian Geological Survey Agency (NGSA), acquired by Fugro Airborne Services on behalf of the Federal Government of Nigeria between 2003 and 2010. The data were flown at a mean terrain clearance of 80 m and a flight-line spacing of 500 m along NW-SE trending lines, oriented across the regional structural grain of the area. The published geological map of the study area (Fig. 1) was used to provide lithological context and to locate the documented columbite and copper mineral occurrence points for comparison with the processed magnetic data. Data processing and enhancement were carried out using Oasis Montaj (Geosoft) software, and lineaments were automatically extracted using the Centre for Exploration Targeting (CET) tool.

The acquired magnetic data were gridded at 100 m spacing using the minimum curvature technique to produce the Total Magnetic Intensity (TMI) map. A first-order polynomial regional-residual separation was applied to isolate the regional field and the residual field associated with near-surface structures and lithological contrasts. The Analytic Signal Amplitude (ASA) was computed from the residual field to highlight the edges and amplitude contrast of magnetic source bodies independent of remanent magnetization, while the First Vertical Derivative (FVD) was computed via fast Fourier transformation to sharpen shallow structural features such as faults and fractures.

Lineaments were then automatically delineated from the enhanced magnetic maps using the CET tool, and their trends were compared against the mapped lithological boundaries and mineral occurrence points on the geological map.

IV. RESULTS AND DISCUSSION

A. Total Magnetic Intensity, Regional Field, and Residual Field

The Total Magnetic Intensity (TMI) map (Fig. 2) shows values ranging from 33724.9 nT (minimum) to 34179.1 nT (maximum), indicating a magnetically heterogeneous basement terrain. Magnetic highs (pink to magenta zones) are concentrated in the northwestern, central, and southeastern parts of the map, coinciding broadly with the mapped porphyritic granite terrain that hosts the documented columbite and copper mineral occurrences shown in Figure 1. The regional field map (Fig. 3), obtained from first-order polynomial fitting, shows a smooth trend increasing from northwest (33999-34012 nT) to southeast (34062-34067 nT), reflecting the broad basement architecture across which the residual anomalies of structural and lithological interest are superimposed.

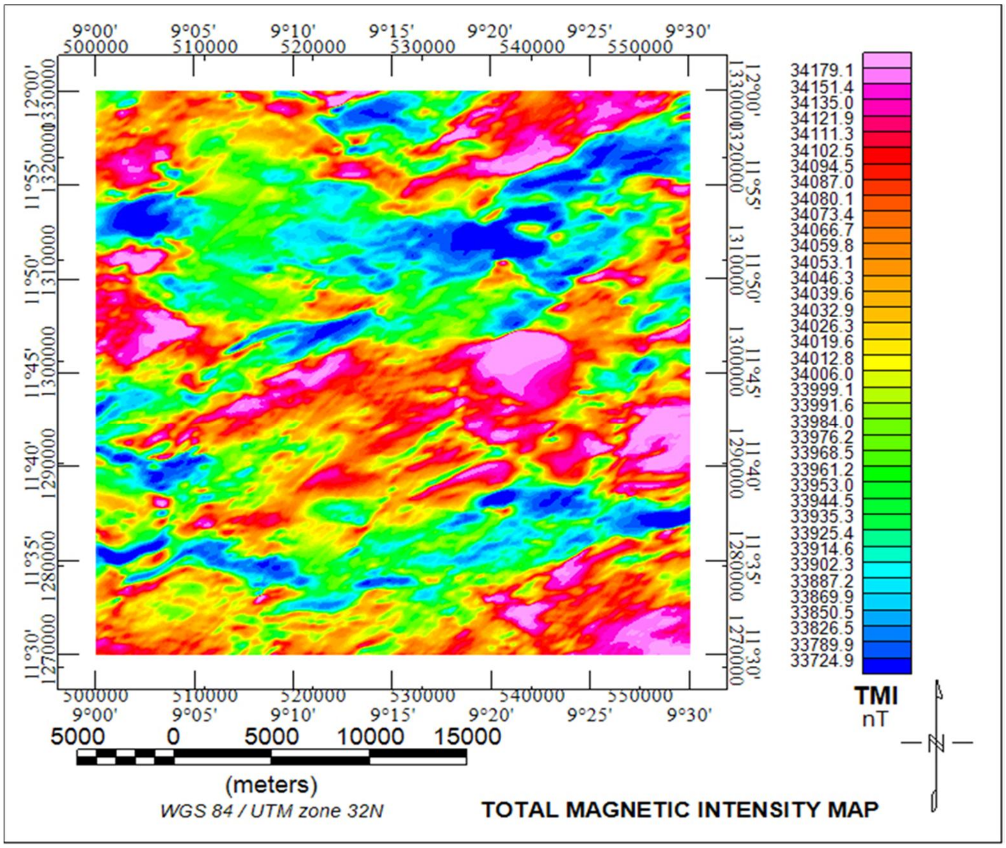

Figure 2: Total Magnetic Intensity (TMI) map of the study area.

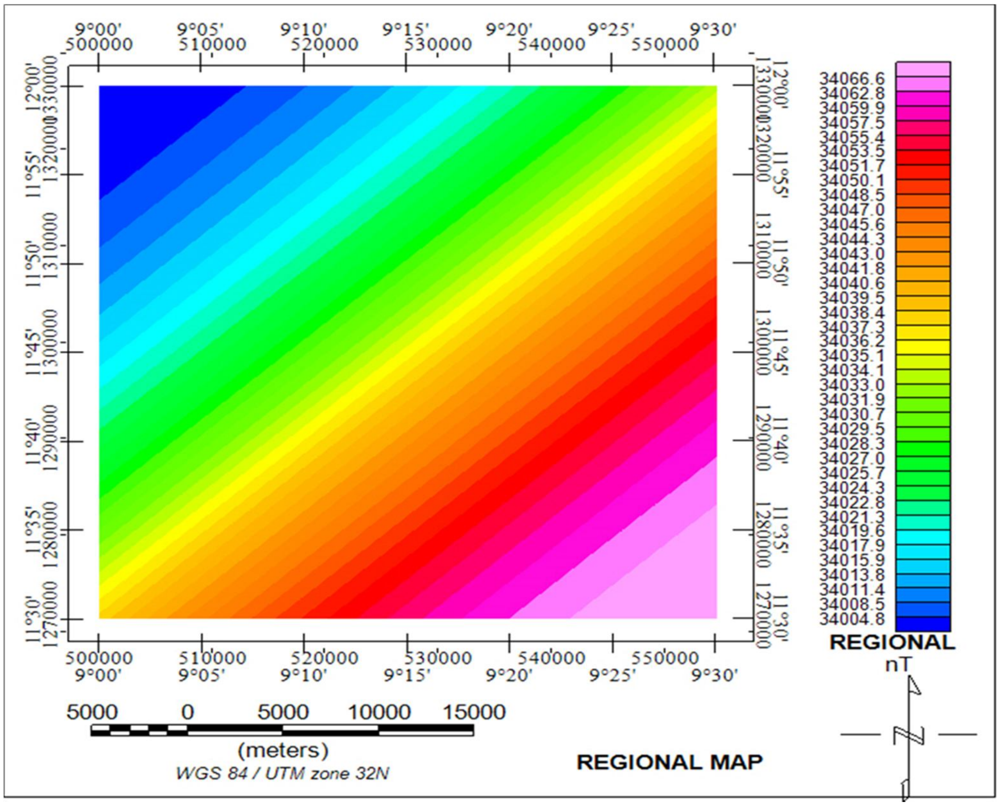

Figure 3: Regional magnetic field map of the study area,

Subtracting the regional field (Fig. 3) from the Total Magnetic Intensity (Fig. 2) yields the residual magnetic field map (Fig. 4), with values ranging from -308.6 nT to 139.7 nT. The residual map isolates the short-wavelength, near-surface magnetic response of structural and lithological contrasts from the broad regional trend, and shows discrete, structurally complex highs (pink to magenta) and lows (blue) trending broadly NE-SW to NW-SE across the western, central, and southeastern parts of the study area. These residual anomaly patterns coincide with the mapped porphyritic granite terrain and the documented columbite and copper mineral occurrence points shown in Figure 1, and form the basis for the Analytic Signal Amplitude and First Vertical Derivative enhancements presented in the following sections.

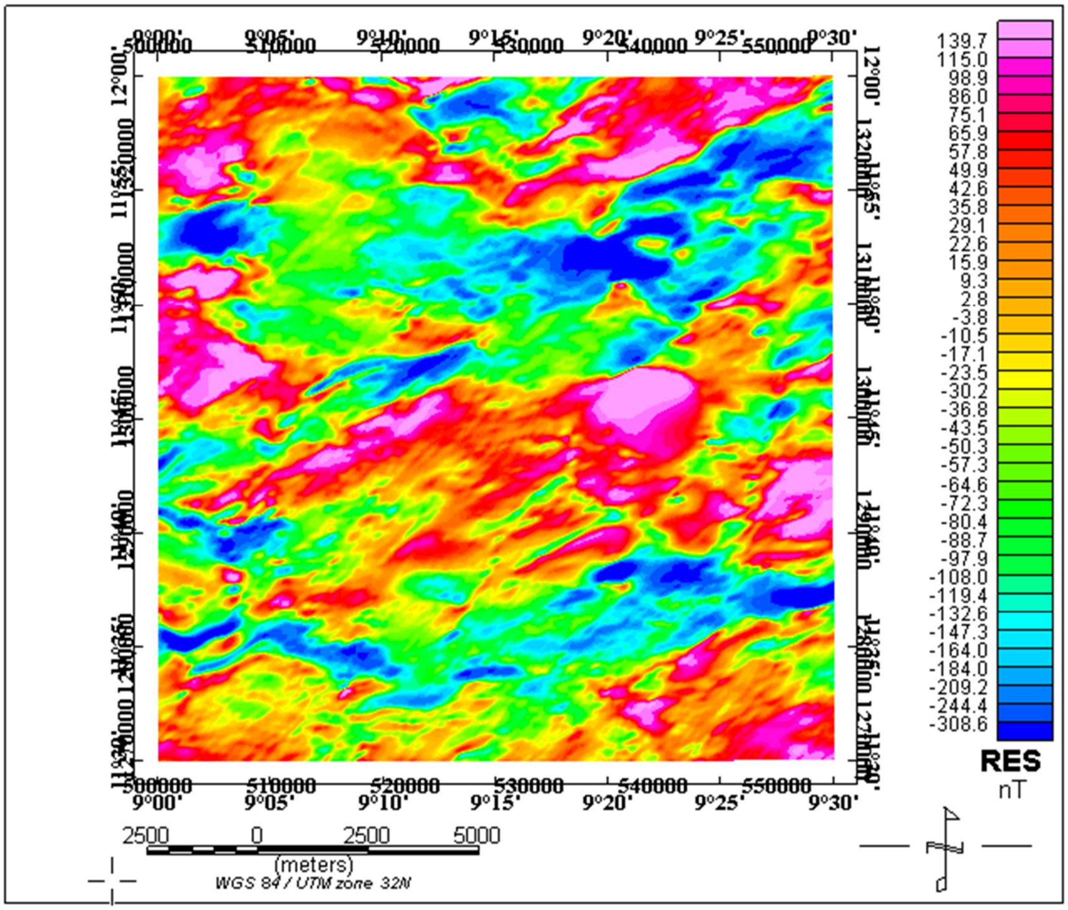

Figure 4: Residual magnetic field map (RES) of the study area,

B. Analytic Signal Amplitude

The Analytic Signal Amplitude (ASA) map (Fig. 5), derived from the residual magnetic field, ranges from 0.031 nT/m to 0.592 nT/m. High-amplitude zones (orange, red, and pink) form elongate, structurally complex belts trending broadly NE-SW to NW-SE across the western and central parts of the study area, spatially coincident with the porphyritic granite terrain and the documented columbite occurrence at Gaya and the copper mineral occurrence near Ajingi. These zones are interpreted as marking structurally and lithologically favourable ground for both columbite (Nb-bearing pegmatitic/porphyritic granite) and copper (structurally hosted sulphide) mineralization, consistent with the deposit-type associations recognized in comparable Nigerian basement and Younger Granite terrains (Abdullahi et al., 2025; Olomo et al., 2025). This is consistent with the widely reported use of analytic signal amplitude, independent of remanent magnetization effects, as a robust discriminator of mineralized intrusive and structural contacts in Nigerian basement exploration studies (Ndatuwong et al., 2025; Adebisi et al., 2024). Structurally comparable high-amplitude zones extending southward and eastward of the mapped occurrence points, away from the currently sampled localities, are identified as priority extensions of the known mineralized trend.

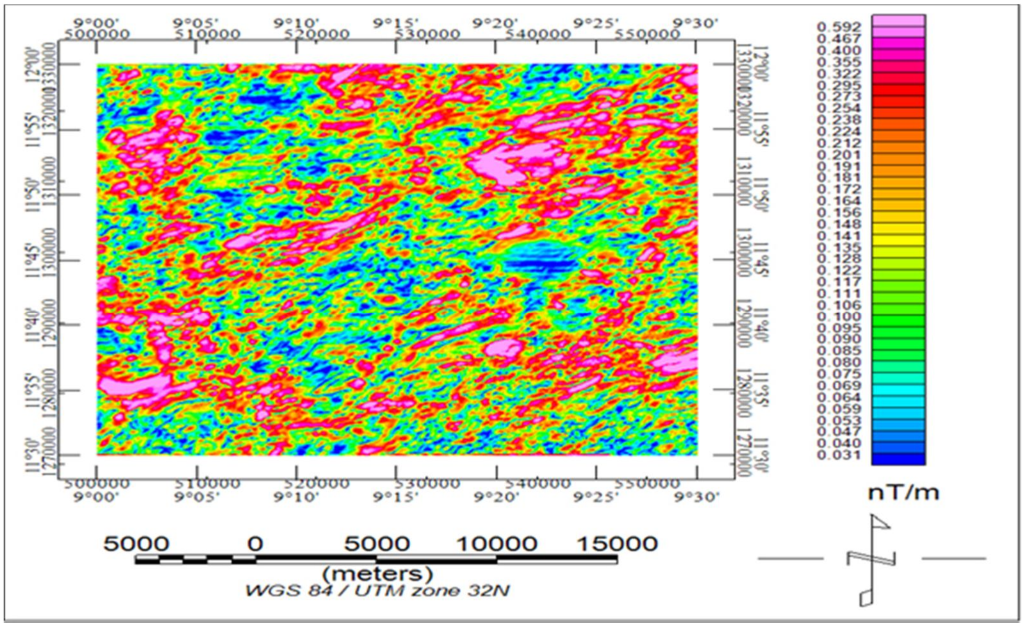

Figure 5: Analytic Signal Amplitude (ASA) map of the study area.

C. First Vertical Derivative and Lineaments

The First Vertical Derivative (FVD) map (Fig. 6), with values ranging from -0.371 nT/m to 0.315 nT/m, sharpens shallow structural features across the study area, revealing a dense network of short-wavelength anomalies concentrated in the central and northeastern parts of the map. Lineaments extracted using the CET tool (Fig. 7) correlate closely with the FVD anomaly pattern, showing a dominant NE-SW trend with a secondary NW-SE trend, and a particularly dense lineament network in the central part of the study area, between Gaya, Ajingi, and Bunin Kudu, exactly the zone bracketed by the three documented mineral occurrence points on the geological map (Fig. 1). This NE-SW/NW-SE lineament pattern mirrors the dominant structural trends reported from CET-based lineament extraction and FVD analysis in comparable Nigerian basement terrains, including the Ijebu-Ode basement (Fatoba & Kehinde, 2025), the Sokoto Basin (Magawata et al., 2025), the Kwara basement (Adebisi et al., 2024), and the Kano-Katsina basement immediately adjoining the present study area (Abdullahi et al., 2025), where these same lineament trends have been shown to control gold, base-metal, and hydrothermal mineral occurrences. This spatial relationship supports the interpretation that both the columbite and copper mineral occurrences are structurally controlled, localized along the intersection of NE-SW and NW-SE trending basement lineaments within the porphyritic granite terrain.

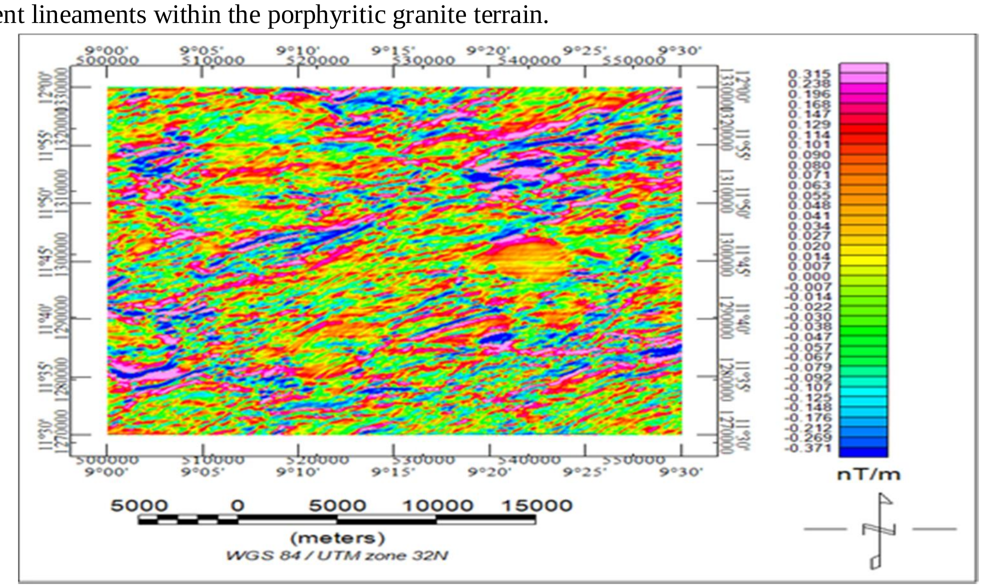

Figure 6: First Vertical Derivative (FVD) map of the study area.

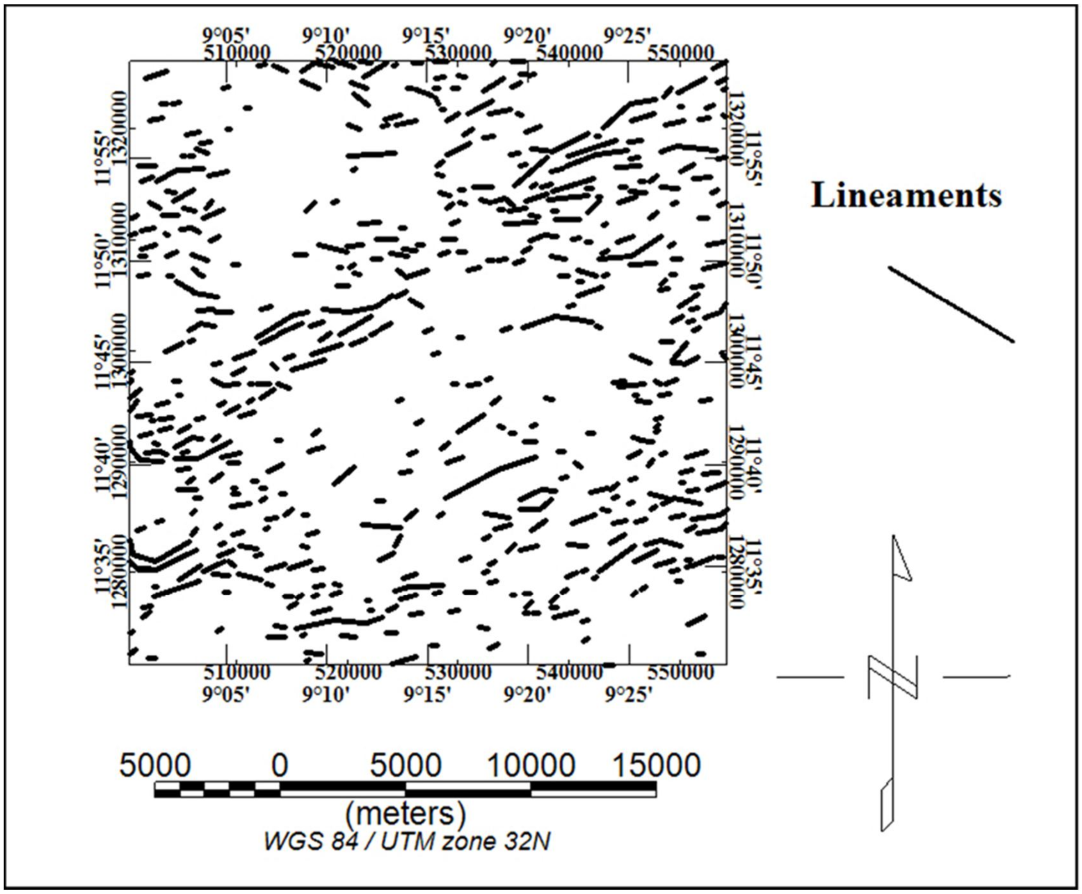

Figure 7: Lineament map of the study area, extracted using the Centre for Exploration Targeting (CET) tool.

D. Integrated Structural and Lithological Interpretation

Integration of the magnetic structural results with the geological map (Fig. 1) shows a consistent spatial association between (i) the porphyritic granite terrain, (ii) zones of high analytic signal amplitude, (iii) dense NE-SW and NW-SE trending lineaments, and (iv) Documented columbite occurrences at Gaya and Bunin Kudu and the copper mineral occurrence near Ajingi. Because this association is anchored to actual, mapped mineral occurrence points rather than regional analogy alone, it provides direct, area-specific evidence that the structurally complex, lineament-dense zones of the porphyritic granite terrain are genuinely favourable for both columbite and copper mineralization. This approach, using the coincidence of structural (analytic signal, lineament density) and lithological evidence layers around known occurrence points to extend and rank prospective target zones, follows a validation strategy comparable to that used in recent integrated aeromagnetic-Aeroradiometric mineralization potential mapping elsewhere in Nigeria, where mineralization potential maps derived from analytic signal, lineament density, and radiometric ratio layers were validated directly against known active mining site coordinates (Bawallah et al., 2024). It is also consistent with regional-scale evidence that copper, lithium, lead-zinc, and iron-ore targets in Nigeria's basement complex are structurally controlled and can be mapped using the same aeromagnetic processing sequence applied here (Ekwok et al., 2025), and with basement-wide evidence that columbite and tantalite mineralization in Nigeria's Younger Granite and Pan-African terrains is consistently associated with structurally complex, high-amplitude magnetic zones within granitic and pegmatitic host rocks (Okuo & Agho, 2024; Olomo et al., 2025). On this basis, structurally and lithologically comparable zones identified between and beyond the three known occurrence points, particularly the densely lineament ground bracketed by Gaya, Ajingi, and Bunin Kudu, are proposed as priority extensions of the known mineralized trend, warranting ground follow-up.

It is emphasized that, while the known occurrence points confirm the presence of columbite and copper mineralization in the area, the extended target zones proposed here are geophysical and lithological inferences of structural and lithological favourability; ground geochemical sampling, mineralogical analysis, and petrographic study of the extended anomaly zones are required to validate these additional targets.

V. CONCLUSION AND RECOMMENDATION

This study has used an integrated aeromagnetic and geological mapping approach to assess the copper and columbite mineralization potential of Gaya and its environs, northwestern Nigeria, anchored to documented occurrence points at Gaya, Bunin Kudu, and Ajingi.

The Total Magnetic Intensity, Analytic Signal Amplitude, First Vertical Derivative, and lineament results reveal a structurally complex, magnetically heterogeneous basement terrain, with a dominant NE-SW lineament trend and a secondary NW-SE trend, particularly dense in the zone bracketed by the three known mineral occurrence points. The coincidence of high-amplitude magnetic anomalies, dense lineament networks, and the porphyritic granite terrain with the known columbite and copper occurrences confirms the structural and lithological controls on mineralization in the area, and defines additional target zones structurally analogous to the known occurrences.

It is recommended that ground geochemical soil and rock sampling, petrographic and mineralogical analysis, and, where feasible, ground magnetic and gravity surveys be carried out over the extended anomaly zones identified in this study, particularly between Gaya, Ajingi, and Bunin Kudu, to validate these additional geophysically inferred copper and columbite mineralization targets.

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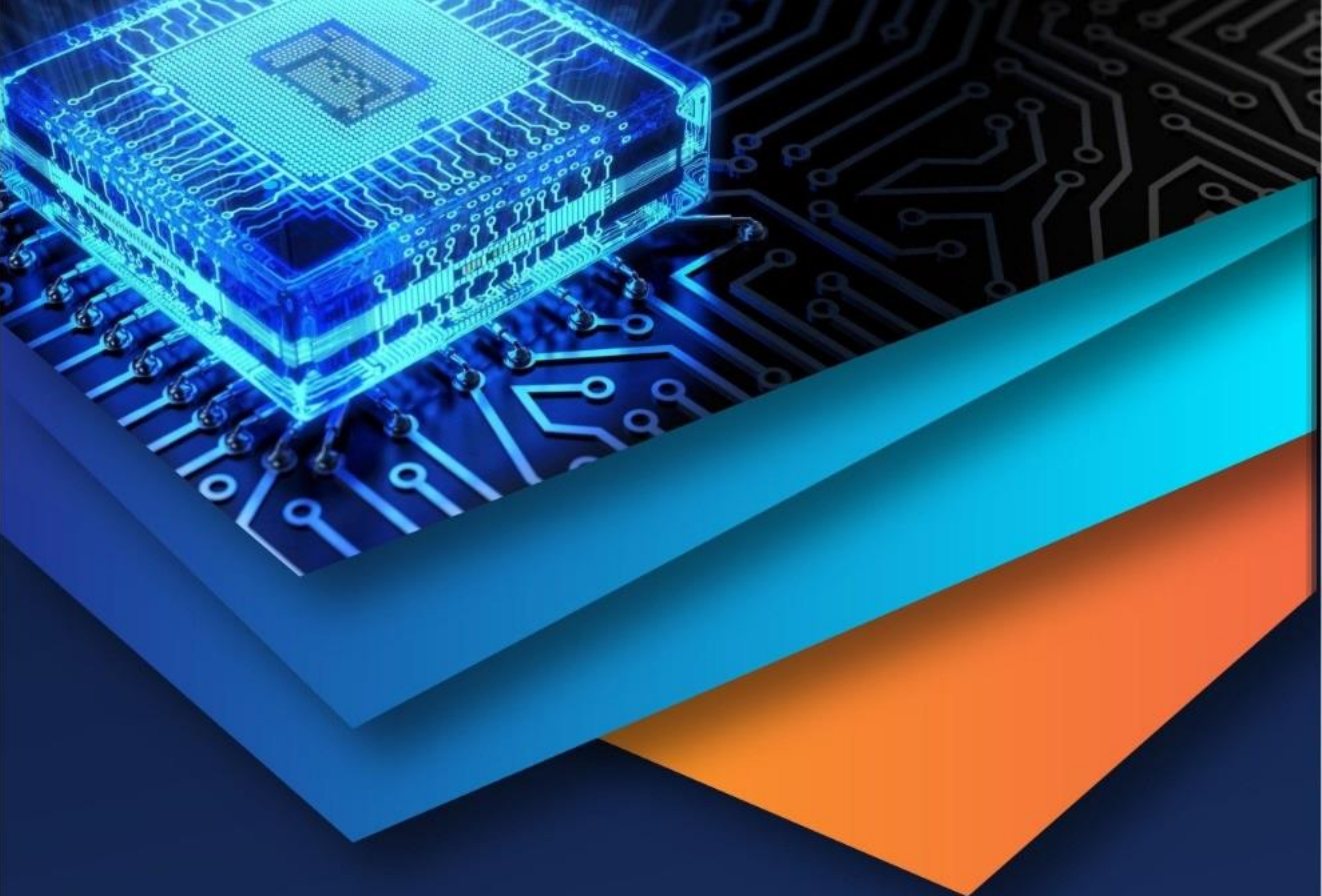

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