# Structural Control of Metallic Mineralization Using Integrated Aeromagnetic and Trace Element Geochemical Data in the Ikole–Itapaji Basement Complex, Southwestern Nigeria.

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## ABSTRACT

The Ikole–Itapaji Basement Complex of southwestern Nigeria is part of the Precambrian Nigerian Basement Complex and possesses considerable potential for structurally controlled metallic mineralization. This study integrated high-resolution aeromagnetic data with trace element geochemistry to delineate mineralization zones and identify prospective exploration targets. Twenty representative rock samples were analyzed for trace elements using Inductively Coupled Plasma–Mass Spectrometry (ICP–MS) following partial multi-acid digestion (HCl, $HNO_3$, and $HClO_4$) combined with lithium metaborate fusion to ensure complete dissolution of refractory silicate minerals and accurate trace element determination. High-resolution aeromagnetic datasets were processed using Total Magnetic Intensity (TMI), Reduction-to-Equator (RTE), First Vertical Derivative (FVD), Analytical Signal (AS), Euler Deconvolution, and lineament density analyses. Pearson correlation and factor analyses were employed to evaluate elemental associations and mineralization controls. The aeromagnetic results revealed dominant NE–SW, NW–SE, and E–W structural trends comprising faults, fractures, and shear zones that controlled hydrothermal fluid migration. Euler deconvolution identified shallow to moderately deep magnetic sources concentrated around Itapaji, Bolorunduro, and parts of Ikole. Factor analysis extracted two significant components explaining 92.04% of the total variance, comprising a lithological association (Cu–Ni–Co–Fe–Zn–Mn) and a hydrothermal pathfinder association (As–Th–Ag–Pb). Pearson correlation analysis confirmed strong positive relationships among Cu, Ni, Co, Fe, and Zn, indicating a common geological origin. The integrated interpretation demonstrates that trace element enrichment is spatially associated with major basement structures, confirming structural control of sulphide mineralization. The Itapaji–Bolorunduro corridor and adjoining parts of Ikole were identified as the most prospective exploration targets. The study demonstrates that integrating aeromagnetic and trace element geochemical datasets provides a reliable framework for mineral prospectivity mapping within the Nigerian Basement Complex.

**Keywords:** Aeromagnetic data; trace element geochemistry; metallic mineralization; structural control; ICP–MS; Ikole–Itapaji Basement Complex.

## INTRODUCTION

The increasing global demand for strategic and base metals has intensified mineral exploration within Precambrian crystalline basement terrains, which host economically significant deposits of gold, copper, lead, zinc, iron, rare earth elements (REEs), lithium, tin, niobium, tantalum, and uranium. As near-surface mineral resources become progressively depleted, mineral exploration has increasingly shifted towards integrated exploration strategies capable of identifying concealed mineralization beneath weathered regolith and structurally complex basement rocks. Consequently, modern exploration programmes now combine geological, geophysical, geochemical, and remote sensing techniques to improve target definition, reduce exploration uncertainty, and enhance the success rate of mineral discovery (Govett, 1983; Rose et al., 1979; Rollinson, 1993; Talapatra, 2020; Olade, 2020).

The Nigerian Basement Complex forms part of the Pan-African Mobile Belt of West Africa and comprises the Migmatite–Gneiss Complex, metasedimentary schist belts, Older Granites, and late-stage pegmatitic intrusions emplaced during the Pan-African Orogeny (Ajibade & Fitches, 1988; Rahaman, 1988; Ajibade & Wright, 1989). These lithological assemblages have undergone multiple episodes of deformation, metamorphism, magmatism, and hydrothermal activity, resulting in the development of regional faults, fractures, folds, shear zones, and lithological contacts that constitute favourable conduits for mineralizing fluids (Olade & Elueze, 1979; Omosanya et al., 2015). Consequently, structural architecture has become one of the most important controls governing the localization, migration, and concentration of metallic mineralization within the Nigerian Basement Complex.

Among modern exploration techniques, high-resolution aeromagnetic surveying has proven particularly effective for imaging subsurface geological structures concealed beneath weathered overburden. Variations in magnetic susceptibility enable the delineation of lithological boundaries, basement fabrics, faults, fractures, shear zones, folds, intrusive contacts, and magnetic lineaments that commonly influence hydrothermal fluid migration and ore deposition (Blakely, 1995; Anudu et al., 2014; Akinlalu et al., 2018; Ilugbo et al., 2020; Faruwa et al., 2021; Ogah & Abubakar, 2024). Enhanced magnetic derivatives such as the analytic signal, total horizontal derivative, tilt derivative, first vertical derivative, and lineament extraction techniques have significantly improved the interpretation of structural controls on mineralization within crystalline basement terrains (Ajakaiye et al., 1985; Akingboye & Ogunyele, 2017).

Trace element geochemistry provides complementary information on the geochemical processes responsible for ore formation. Pathfinder elements including Cu, Pb, Zn, Ni, Co, As, Ag, Mn, and Fe commonly become enriched during hydrothermal alteration and sulphide mineralization, making them valuable indicators of concealed ore systems (Govett, 1983; Rose et al., 1979; Rollinson, 1993). Recent advances in Inductively Coupled Plasma–Mass Spectrometry (ICP–MS), combined with lithium metaborate fusion and multi-acid digestion techniques, have substantially improved analytical precision for trace element determination in crystalline basement rocks (Senda et al., 2014; Chen et al., 2024). When interpreted alongside aeromagnetic structural information, trace element distributions provide a robust framework for distinguishing lithological geochemical signatures from structurally controlled hydrothermal mineralization.

Southwestern Nigeria has received considerable research attention because of its favourable geological setting and significant mineral resource potential. Previous investigations have successfully employed geological mapping, geophysical surveys, petrography, geochemistry, and remote sensing techniques to characterize basement lithologies and identify prospective mineralized zones (Talabi et al., 2018; Alagbe & Amosun, 2021; Amosun & Alagbe, 2020; Lukman et al., 2024). Likewise, recent aeromagnetic studies have demonstrated the importance of structural lineaments and basement deformation in controlling metallic mineralization across various parts of the Nigerian Basement Complex (Anudu et al., 2014; Akinlalu et al., 2018; Faruwa et al., 2021; Ogah & Abubakar, 2024).

More recently, integrated investigations conducted within the Ikole–Itapaji Basement Complex have significantly improved the understanding of its geology and mineral prospectivity. Ayodele et al. (2026) demonstrated the effectiveness of integrating geological mapping with aeromagnetic and remote sensing datasets for litho-structural characterization of the area. Ige et al. (2026) further highlighted the significance of geological structures in controlling hydrothermal alteration and mineralization, while Iwabi et al. (2026) integrated airborne radiometric and trace element geochemical data to delineate hydrothermal alteration zones and identify prospective targets for metallic mineralization. These recent studies collectively demonstrate that mineralization within the Ikole–Itapaji Basement Complex is strongly influenced by lithology, deformation, and hydrothermal processes.

Despite these advances, the direct relationship between subsurface magnetic structures and trace element enrichment has not been comprehensively investigated within the study area. Previous studies have generally examined aeromagnetic structures or geochemical anomalies independently, with limited emphasis on integrating both datasets to establish the structural controls governing metallic mineralization. Consequently, the influence of faults, fractures, shear zones, and magnetic lineaments on the spatial distribution of economically significant trace elements remains insufficiently constrained.

This study therefore integrates high-resolution aeromagnetic data with trace element geochemistry to evaluate the structural controls on metallic mineralization within the Ikole–Itapaji Basement Complex, Southwestern Nigeria. By combining magnetic structural interpretation with trace element distribution patterns, the study provides a more comprehensive understanding of the geological processes responsible for mineralization and identifies structurally favourable targets for future mineral exploration.

The specific objectives of the study are to:

1. Delineate The Major Subsurface Geological Structures Using High-Resolution Aeromagnetic Data;
2. Characterize The Spatial Distribution of Trace Elements Associated with Metallic Mineralization;
3. Evaluate The Relationship Between Aeromagnetic Lineaments and Trace Element Anomalies;
4. Identify Structurally Controlled Hydrothermal Mineralization Zones Through Integrated Interpretation of Aeromagnetic and Geochemical Datasets;
5. Assess The Influence of Lithology and Deformation on Metallic Mineralization Within the Ikole–Itapaji Basement Complex; And
6. Delineate Priority Targets for Future Detailed Mineral Exploration.

**The study Area**

Figure 1 presents the geographical location of the Ikole–Itapaji–Ake-Ako study area within Ekiti State, southwestern Nigeria. The inset map of Nigeria shows the position of Ekiti State within the southwestern region of the country, while the highlighted rectangle delineates the precise location of the study area. The area lies within the Precambrian Basement Complex of southwestern Nigeria**,** which forms part of the Pan-African mobile belt situated between the West African and Congo Cratons. The Nigerian Basement Complex is characterized by widespread migmatite–gneiss complexes, Pan-African granitoids, charnockitic bodies, pegmatites, and minor metasedimentary rocks that have undergone multiple episodes of deformation, metamorphism, and magmatism (Rahaman, 1988).

The enlarged topographic map shows that the study area extends approximately between latitudes 7°47′N and 8°05′N and longitudes 5°26′E and 5°34′E, covering an estimated surface area of about 590 km². The contour pattern indicates a rugged and undulating terrain characterized by numerous hills, ridges, and valleys, which are typical geomorphological features of crystalline basement terrains. Closely spaced contour lines represent steep slopes and elevated ridges, whereas widely spaced contours indicate relatively gentle slopes and low-lying areas. Such topographic variations are largely controlled by differences in lithology, weathering resistance, and structural deformation within the basement rocks (Ojo et al., 2024).

The drainage pattern displayed on the map is predominantly dendritic, indicating that stream development is mainly controlled by the regional slope and the relatively homogeneous crystalline bedrock. However, local variations in stream orientation may reflect the influence of fractures, joints, and faults that commonly characterize the Nigerian Basement Complex. Structural discontinuities frequently serve as zones of weakness that guide surface drainage and facilitate groundwater movement and hydrothermal fluid circulation (Adetunla et al., 2025).

The road network shown on the map indicates that the study area is relatively accessible through major and minor roads linking Ikole-Ekiti, Itapaji, and Ake-Ako. This accessibility facilitated detailed geological mapping, structural measurements, and representative rock-sample collection during the field investigation. The combination of

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extensive rock exposures, rugged topography, and well-developed drainage provides favourable conditions for geological mapping and mineral exploration within the area (Ajibade & Rahaman 1987).

Overall, the location and physiographic characteristics illustrated in Figure 1 indicate that the Ikole–Itapaji–Ake-Ako area possesses the geological and structural attributes typical of the southwestern Nigerian Basement Complex. The presence of resistant crystalline rocks, pronounced topographic relief, and structurally controlled drainage provides a favourable geological framework for investigating the petrogenesis, geochemical evolution, and mineralization potential of the basement rocks

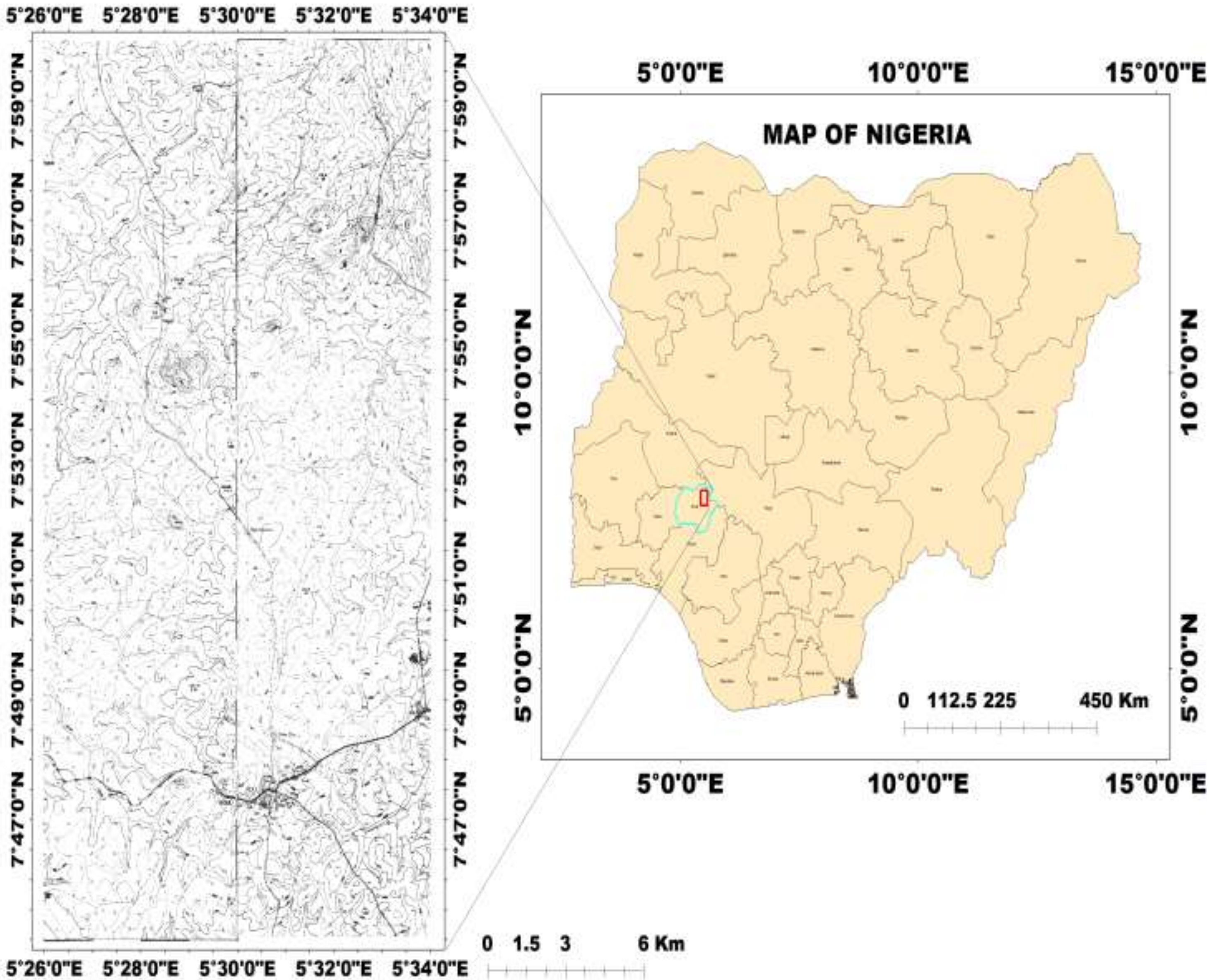


**Figure 1. Location and topographic map of the Ikole–Itapaji–Ake-Ako area, Ekiti State, southwestern Nigeria, illustrating the geographical extent, drainage network, road accessibility, and topographic relief of the study area.**

## Geological setting

The study area is located within southwestern Nigeria, forming part of the Precambrian Basement Complex of the West African Craton. This crystalline basement terrain is distinct from the surrounding sedimentary basins,

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including the Sokoto Basin, Chad Basin, Bida Basin, and the Benue Trough, which are largely composed of Cretaceous-to-Tertiary sediments (Ojo et al., 2024). The southwestern region, including the Ikole–Itapaji axis, is dominated by crystalline rocks that have undergone extensive tectono-metamorphic evolution. The Nigerian Basement Complex evolved through multiple orogenic events, notably the Liberian, Eburnean, and Pan-African cycles, which resulted in widespread deformation, metamorphism, and granitoid emplacement (Adetunla et al., 2025). These processes led to the development of major lithological units, including the migmatite–gneiss complex, schist belts, and Pan-African granitoids.

In the study area, migmatite–gneiss and granitic rocks are predominant, with minor metasedimentary occurrences. Structurally, the area is characterized by well-developed faults, fractures, and foliations, predominantly trending NE–SW and NW–SE, reflecting the imprint of Pan-African deformation (Ogah & Abubakar, 2024). These structures are critical in controlling hydrothermal fluid flow and mineral deposition.

Mineralization within the Basement Complex is commonly associated with quartz veins, pegmatites, and shear zones. The presence of granitic and pegmatitic intrusions within the Ikole–Itapaji area further suggests favourable conditions for mineralization. Recent studies have demonstrated the effectiveness of integrated geophysical methods in delineating such structurally controlled mineralized zones (Salako et al., 2024). The geological framework of the study area reflects a complex interplay of lithology and structure, providing a suitable environment for mineralization and justifying integrated geophysical and remote sensing investigations (Fig. 2)

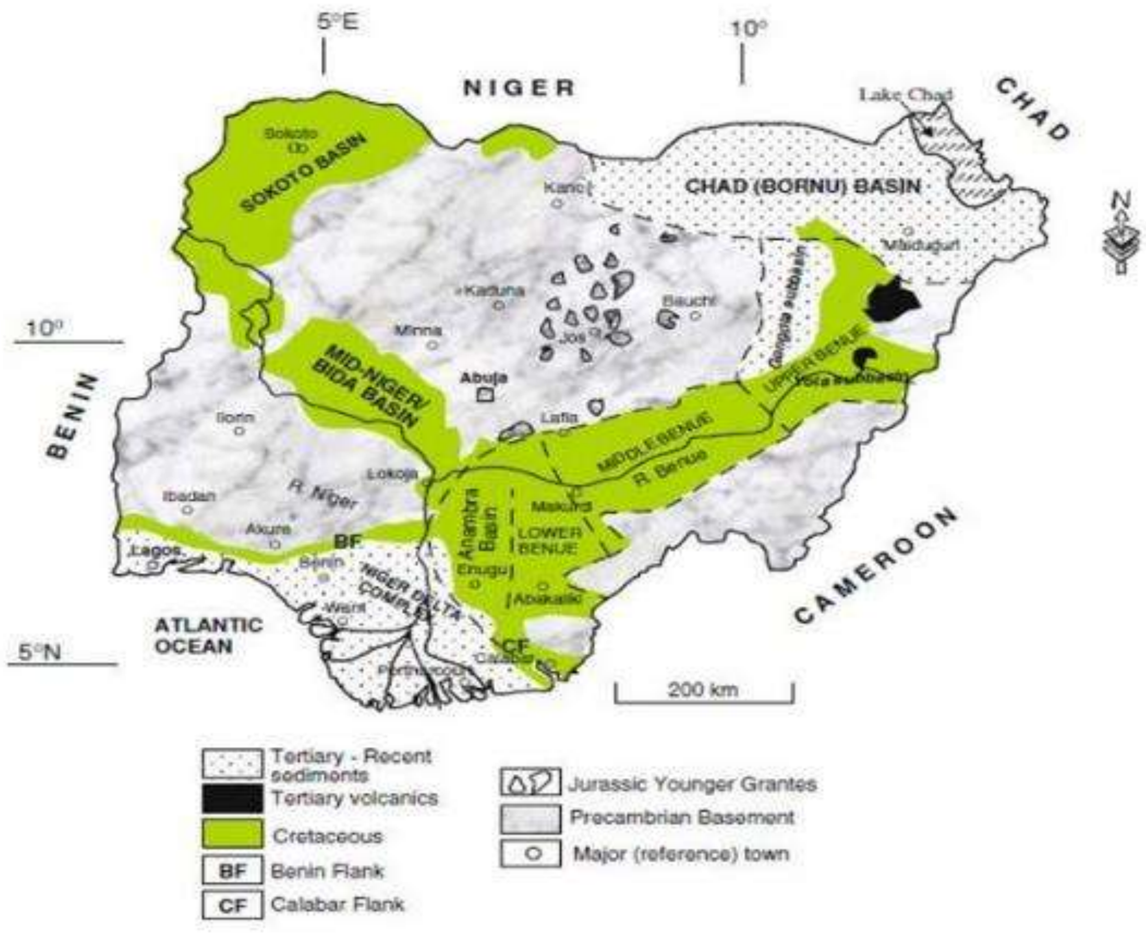


**Figure 2: Geological map of Nigeria showing the distribution of major lithological units, including the**

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**Precambrian Basement Complex and surrounding sedimentary basins (Sokoto, Chad, Bida, and Benue Trough). The study area (Ikole–Itapaji, southwestern Nigeria) is located within the Basement Complex**.

The topographic map Figure 3 illustrates the spatial distribution of geological sampling locations across the Ikole–Itapaji–Bolorunduro–Odo Oro–Ake-Ako area. The sampling points are well distributed throughout the study area, extending from the southern part around Ikole and Odo Oro through Bolorunduro to the northern sectors around Itapaji and Ake-Ako. This broad spatial coverage ensures that all the major lithological units identified within the study area are adequately represented and provides a reliable basis for subsequent geological, structural, petrographic, and geochemical investigations (Ogah & Abubakar, 2024).

The density of sampling points is noticeably higher around the Itapaji, Ake-Ako, and northern portions of the study area, where rugged topography and relatively high elevations provide abundant fresh basement rock exposures.

These elevated terrains expose crystalline rocks with minimal weathering, thereby facilitating direct observation of lithological contacts, structural features, and representative rock sampling. Conversely, relatively fewer sampling locations occur around Odo Oro and the southern part of Ikole, where the terrain is comparatively gentle and extensive soil development, vegetation cover, and weathered overburden locally obscure the basement rocks, thereby reducing outcrop availability (Ojo et al., 2024).

The sampling locations are distributed across ridges, hillslopes, valleys, and gently undulating terrains, thereby minimizing spatial bias and ensuring that lithological variations are examined under different geomorphological settings.

This distribution also enhances the recognition of structural elements such as foliations, joints, fractures, quartz veins, folds, and lineaments that are commonly better exposed on elevated and dissected terrains. The widespread distribution of sampling points therefore improves the reliability of structural interpretations and provides adequate coverage for correlating lithological variations with topographic expression across the study area (Salako et al., 2024).

Furthermore, the sampling strategy captures the spatial occurrence of the major crystalline rock units, including migmatite, granite gneiss, coarse porphyroblastic gneiss, granite, pegmatite, and charnockite, thereby ensuring that the petrographic and geochemical datasets are representative of the geological diversity of the Ikole–Itapaji–Ake-Ako Basement Complex. The comprehensive distribution of the sampling points also provides a sound framework for evaluating mineralogical variations, petrogenesis, tectonic evolution, and mineralization potential across the study area (Adetunla et al., 2025).

Overall, the spatial distribution of the sampling locations demonstrates a systematic and representative sampling strategy that adequately covers the entire study area. The combination of extensive geographical coverage, representation of all major lithological units, and sampling across different topographic settings provides a robust foundation for geological mapping, structural analysis, petrographic characterization, geochemical evaluation, and interpretation of the tectonometamorphic evolution of the Ikole–Itapaji–Bolorunduro–Odo Oro–Ake-Ako area within the Precambrian Basement Complex of southwestern Nigeria (Oyinloye 2011).

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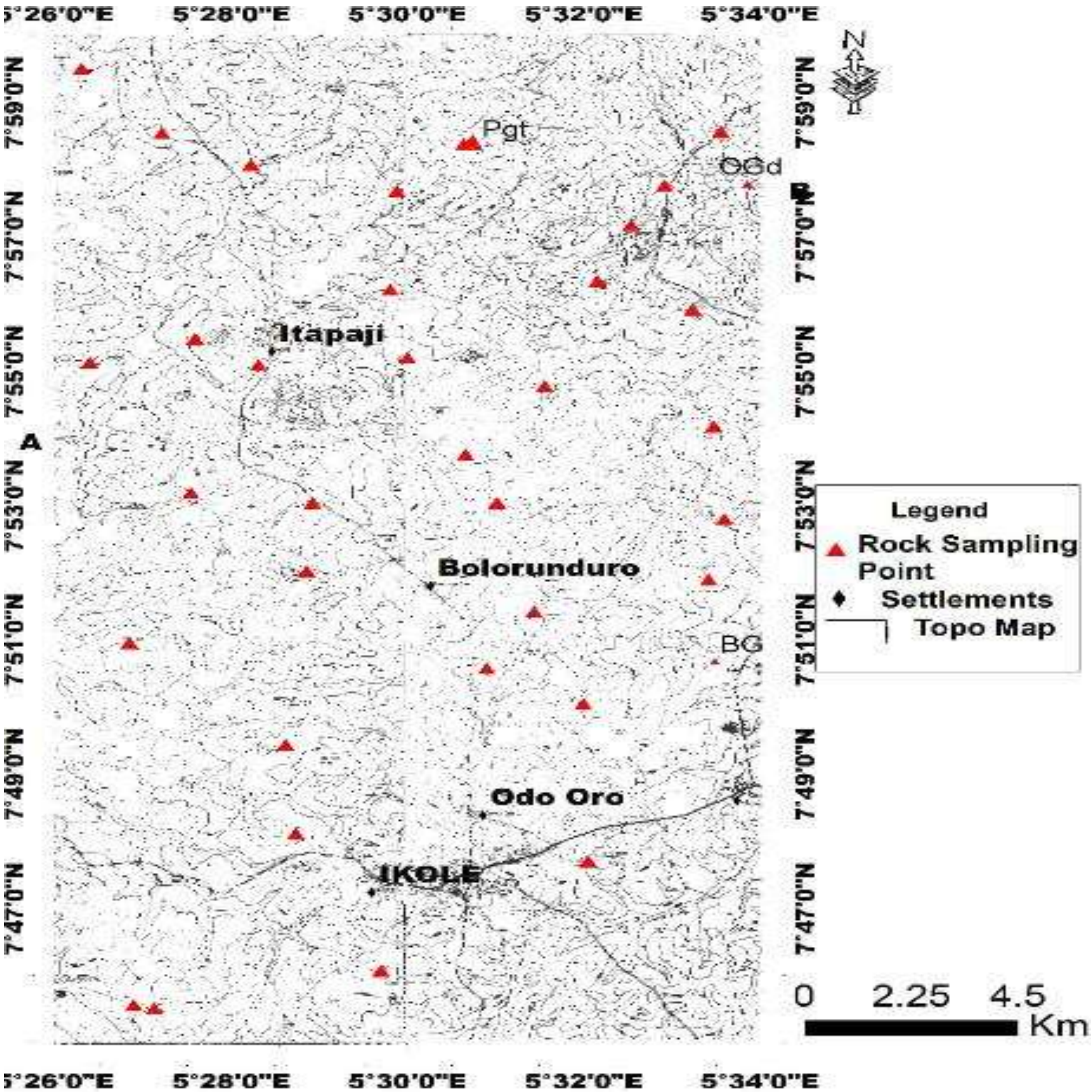


**Figure 3. Topographic map of the Ikole–Itapaji–Ake-Ako area, Southwestern Nigeria, showing the distribution of geological sampling points used for geological mapping, structural measurements, and petrographic investigations. The sampling locations provide representative coverage of the major basement rock units across the study area.**

The geological map and accompanying cross-section Figure 4 reveals that the Ikole–Itapaji–Ake-Ako area is underlain predominantly by rocks of the Precambrian Basement Complex comprising migmatite (Mg), granite gneiss (GG), charnockite (Ch), granodiorite (OGd), and minor pegmatite intrusions. The spatial distribution of these lithologies indicates a complex geological history involving high-grade metamorphism, partial melting, magmatic emplacement, and crustal reworking during the Pan-African tectonothermal event.

The geological map shows that granite gneiss constitutes the dominant lithological unit**,** occupying a large proportion of the central and northern parts of the study area. This unit extends continuously from Itapaji through Bolorunduro and towards the northeastern portion of the map, suggesting that granite gneiss forms the principal basement framework of the area. Field and petrographic evidence indicate that the granite gneiss is characterized by quartz, feldspar, biotite, and muscovite assemblages typical of amphibolite- to granulite-facies metamorphism.

Migmatite occurs extensively in the southern portion of the study area around Ikole and Odo Oro. The broad distribution of migmatite suggests widespread partial melting and anatexis within the basement rocks. The gradational contact observed between migmatite and granite gneiss indicates that both lithologies share a common tectonometamorphic history, with migmatite representing zones of more intense partial melting and metamorphic reworking (Rahaman, 1988; Oyinloye, 2011).

The charnockite body exposed in the southwestern portion of the map occurs as a relatively restricted lithological unit. Its limited areal extent suggests emplacement or preservation as an isolated body within the surrounding granite gneiss terrain. Charnockitic rocks are generally associated with deep crustal processes and high-temperature metamorphism, indicating that parts of the study area experienced elevated thermal conditions during crustal evolution (Adetunla et al., 2025).

The granodiorite body located in the northeastern section of the map forms a discrete intrusive mass. The cross-section demonstrates that the granodiorite extends to depth and is not merely a superficial exposure. This geometry suggests emplacement as a plutonic body intruding the surrounding granite gneiss. The presence of pegmatite veins associated with the granodiorite further supports late-stage magmatic differentiation and residual melt emplacement during the final stages of crystallization **(**Alagbe & Amosun 2021**).**

The geological cross-section along A–B Figure 4 illustrates the subsurface relationships between the major lithological units. Granite gneiss occupies most of the intermediate crustal section and overlies a broad migmatitic basement. The undulating contact between granite gneiss and migmatite suggests an irregular basement surface produced by differential melting, metamorphic segregation, and prolonged crustal evolution. The continuity of the migmatite beneath much of the section indicates that it forms the oldest exposed basement unit within the area.

The cross-section further demonstrates that the granodiorite intrusion cuts the surrounding granite gneiss in the northeastern segment of the profile. This intrusive relationship indicates that the granodiorite is younger than the host granite gneiss. The pegmatite body shown within the granodiorite represents a later magmatic phase formed by crystallization of residual silica-rich melts. Such pegmatitic intrusions are common products of highly evolved granitic systems and frequently host economically important rare-element minerals (Adetunla et al., 2025).

From a geological evolution perspective, the study area records multiple stages of crustal development. The migmatites represent the oldest basement components formed through high-grade metamorphism and partial melting. These were subsequently reworked and transformed into granite gneiss during regional metamorphic events. Charnockitic bodies were emplaced or developed under high-temperature conditions, while granodioritic magmatism and pegmatitic intrusions represent younger intrusive phases associated with crustal melting and magmatic differentiation. Collectively, these lithological relationships indicate prolonged Precambrian crustal evolution culminating in widespread Pan-African tectono-metamorphism (Rahaman, 1988; Oyinloye, 2011).

The geological architecture depicted by the map and cross-section demonstrates that the Ikole–Itapaji–Ake-Ako area forms part of a deeply reworked basement terrane characterized by extensive migmatization, granitoid emplacement, and localized charnockitic development. The intimate association of these lithologies provides evidence of repeated episodes of metamorphism, partial melting, magmatism, and crustal stabilization within the southwestern Nigerian Basement Complex.

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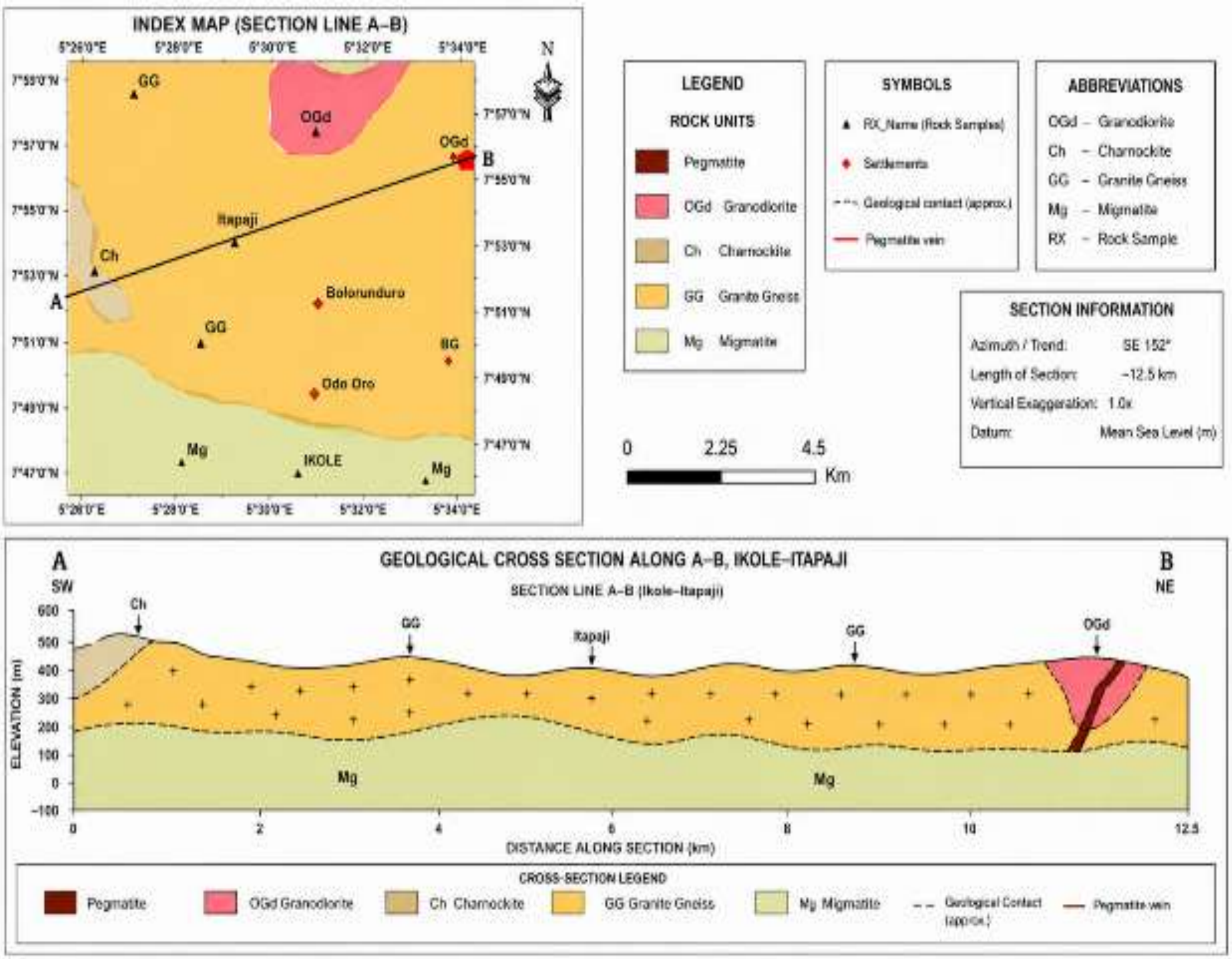


**Figure 4. Geological cross-section along A–B across the Ikole-Itapaji area, showing the subsurface relationships between migmatite, granite gneiss, charnockite, granodiorite, and pegmatite units. The section reveals a migmatitic basement overlain by granite gneiss and intruded by younger granodiorite and pegmatite bodies. The geometry of the rock units reflects prolonged crustal evolution involving metamorphism, partial melting, and magmatic emplacement within the Precambrian Basement Complex.**

# MATERIALS AND METHODS

## Materials

The materials used for this study comprised field equipment, laboratory facilities, high-resolution aeromagnetic datasets, and computer software required for geological mapping, structural investigations, trace element geochemical analyses, aeromagnetic data processing, and spatial data integration. Field equipment included a 1:25,000-scale topographic map of the Ikole–Itapaji–Ake-Ako area, a Brunton compass clinometer, a Garmin GPSMAP 64s handheld Global Positioning System (GPS), geological hammer, chisel, hand lens, measuring tape, sample bags, permanent markers, field notebook, digital camera, and personal protective equipment comprising safety boots, reflective jacket, hand gloves, and a safety helmet. These materials facilitated geological mapping, structural measurements, accurate positioning of outcrops, documentation of field observations, and representative rock sample collection.

Laboratory facilities consisted of a diamond rock-cutting machine, jaw crusher, pulverizing machine, analytical weighing balance, and computer facilities for geochemical data processing, statistical analyses, and graphical presentation of results. Trace element determinations were carried out at ACME Analytical Laboratories (Bureau Veritas Commodities Canada Ltd.), Vancouver, Canada, using Inductively Coupled Plasma–Mass Spectrometry (ICP–MS).

High-resolution aeromagnetic datasets covering Ado-Ekiti Sheet 244 and Ikole Sheet 245 were obtained from the Nigerian Geological Survey Agency (NGSA), Abuja. The datasets were acquired by Fugro Airborne Surveys during the 2006–2007 nationwide airborne geophysical survey commissioned by the Nigerian Geological Survey Agency (NGSA, 2006). The survey was conducted at a nominal terrain clearance of approximately 80 m with a flight-line spacing of 150 m, tie-line spacing of 1500 m, and a map scale of 1:100,000. The Total Magnetic Intensity (TMI) data were gridded at 250 m cell resolution and provide detailed information on subsurface lithological variations, basement structures, faults, fractures, shear zones, and magnetic lineaments associated with mineralization.

Geosoft Oasis Montaj™ 8.4HJ and ArcGIS 10.7 software packages were used for aeromagnetic processing, structural interpretation, spatial analysis, and integration of the aeromagnetic and trace element datasets.

**Geological Field Investigation and Sampling**

The study commenced with a reconnaissance survey of the Ikole–Itapaji–Ake-Ako area using a 1:25,000-scale topographic map to obtain preliminary information on accessibility, drainage pattern, topography, and the distribution of rock exposures. The reconnaissance exercise provided the basis for planning geological traverses and ensuring adequate spatial coverage during detailed field investigations.

Detailed geological mapping was subsequently undertaken along accessible roads, footpaths, stream channels, farm tracks, and exposed rock outcrops. Lithological characteristics including colour, texture, grain size, mineral composition, weathering characteristics, and field relationships were carefully observed and documented. Structural features including foliations, joints, fractures, folds, mineral lineations, quartz veins, and shear zones were identified, while their strike and dip were measured using a Brunton compass clinometer. The geographical coordinates and elevations of each outcrop were recorded using a Garmin GPSMAP 64s handheld GPS receiver, and representative field photographs were obtained to document important geological features. These field observations provided the geological framework for subsequent interpretation of the aeromagnetic and geochemical datasets.

A total of thirty-five (35) fresh rock samples representing the major lithological units encountered during geological mapping, including migmatite, granite gneiss, coarse porphyroblastic gneiss, granite, pegmatite, and charnockite, were collected from different locations across the study area. Following detailed megascopic examination, twenty (20) representative samples were selected for trace element geochemical analyses based on the following criteria:

1. Representation of all major lithological units identified during geological mapping.
2. Freshness of the rock samples, with preference given to fresh, unweathered, and minimally altered specimens.
3. Lithological and mineralogical diversity to adequately represent compositional variability across the study area.
4. Megascopic textural variability, including differences in grain size, mineral fabric, and weathering characteristics.
5. Structural characteristics, particularly representative foliations, mineral banding, folds, quartz veins, fractures, and shear fabrics.
6. Adequate spatial distribution across the study area.
7. Elimination of duplicate samples exhibiting similar lithological, mineralogical, and structural characteristics from the same locality to avoid analytical redundancy.

This sampling strategy ensured that the analysed samples adequately represented the lithological, structural, and geochemical variability of the crystalline basement rocks.

### Trace Element Geochemical Analysis

Fresh portions of the selected rock samples were cleaned to remove weathered surfaces before being reduced to smaller fragments using a jaw crusher and subsequently pulverized into fine homogeneous powders. The pulverized samples were packaged and submitted to ACME Analytical Laboratories (Bureau Veritas Commodities Canada Ltd.), Vancouver, Canada, for trace element analyses.

Trace element determinations were carried out using Inductively Coupled Plasma–Mass Spectrometry (ICP–MS) following partial multi-acid digestion with hydrochloric acid (HCl), nitric acid ($HNO_3$), and perchloric acid ($HClO_4$), combined with lithium metaborate fusion. The lithium metaborate fusion technique ensured complete dissolution of refractory silicate minerals, whereas the multi-acid digestion enhanced the extraction and accurate determination of trace elements within the crystalline basement rocks (Senda et al., 2014).

Quality assurance and quality control (QA/QC) procedures included the analysis of certified reference materials, analytical blanks, duplicate samples, and internal laboratory standards to ensure analytical accuracy, precision, and reproducibility.

### Aeromagnetic Data Processing

The high-resolution aeromagnetic dataset comprising the Total Magnetic Intensity (TMI) grid for Ado-Ekiti Sheet 244 and Ikole Sheet 245 was processed using Geosoft Oasis Montaj™ 8.4HJ. The TMI data were corrected for the Earth's main magnetic field using the International Geomagnetic Reference Field (IGRF) to isolate local magnetic anomalies associated with subsurface geological structures.

$$\Delta B\ (x,y) = TMI\_observed\ (x,y) - IGRF \qquad (1)$$

The corrected magnetic data were used to generate the Total Magnetic Intensity map representing lithological variations and basement structural features.

Regional and residual magnetic components were separated using low-order polynomial fitting to enhance shallow magnetic anomalies associated with faults, fractures, and shear zones.

$$\Delta T\_residual\ (x,y) = \Delta T\_observed(x,y) - \Delta T\_regional(x,y) \qquad (2)$$

This enhances shallow structures such as faults and fractures.

Reduction to the Equator (RTE) was subsequently applied to compensate for the low magnetic latitude of southwestern Nigeria and reposition magnetic anomalies directly above their causative sources, thereby improving structural interpretation.

The Analytical Signal (AS) was computed to enhance the edges of magnetic bodies irrespective of magnetization direction according to:

$$AS = \sqrt{[(\partial M/\partial x)^2 + (\partial M/\partial y)^2 + (\partial M/\partial z)^2]} \qquad (3)$$

Analytical Signal amplitudes were used to delineate lithological contacts, faults, fractures, and structural lineaments associated with metallic mineralization.

Euler Deconvolution was further applied to estimate the depth and geometry of magnetic sources using appropriate structural indices for basement structures.

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$$(x - x_0)(\partial M/\partial x) + (y - y_0)(\partial M/\partial y) + (z - z_0)(\partial M/\partial z) = N(B - M) \qquad (4)$$

Where ($x_0$, $y_0$, $z_0$) represent the source location and $N$ is the structural index. This provides depth solutions and structural control of mineralization.

The resulting Euler solutions were interpreted together with mapped lineaments to establish the structural controls on metallic mineralization.

### Statistical Analysis

Pearson correlation coefficient analysis was performed to evaluate elemental relationships and identify geochemical associations among the analysed trace elements. Factor analysis was subsequently employed to determine the principal geochemical processes controlling elemental distribution and to distinguish lithological signatures from hydrothermal mineralization-related associations.

### Integration of Aeromagnetic and Trace Element Data

The processed aeromagnetic products and trace element geochemical data were integrated within the ArcGIS 10.7 environment to investigate the spatial relationships between magnetic structures and trace element enrichment. Structural lineaments interpreted from the aeromagnetic data were compared with the distribution of economically significant trace elements to identify structurally controlled mineralization.

Areas where magnetic lineaments, faults, fractures, shear zones, and lithological contacts coincided with elevated concentrations of Cu, Pb, Zn, Ni, Co, Ag, As, Fe, Mn, and Th were interpreted as favourable targets for hydrothermal mineralization. This integrated approach provided a comprehensive framework for evaluating the structural controls on metallic mineralization and delineating priority targets for future detailed mineral exploration within the Ikole–Itapaji Basement Complex.

## RESULTS AND DISCUSSION

### Aeromagnetic data

The Total Magnetic Intensity (TMI) map Fig. 5 reveals variations in magnetic field intensity across the study area, reflecting differences in lithology, magnetic mineral composition, and basement structural architecture. High magnetic anomalies (approximately 19 nT to 96 nT) are concentrated around Bolorunduro and parts of Itapaji**,** and are interpreted to represent magnetically susceptible basement rocks, including granite gneiss and localized mafic-rich lithologies containing appreciable quantities of ferromagnetic minerals such as magnetite (Blakely, 1995; Ogah & Abubakar, 2024; Ige et al., 2025). Moderate magnetic anomalies (approximately 1 nT to 19 nT) dominate the surrounding areas and are attributed to granitic gneisses and other intermediate basement lithologies exhibiting moderate magnetic susceptibility (Akinlalu et al., 2018; Adetunla et al., 2025).

Low magnetic anomalies (approximately −234 nT to −23 nT) occurring around Odo Oro and Ikole are interpreted to reflect quartz-rich migmatitic rocks and felsic lithologies characterized by low magnetic susceptibility. These subdued magnetic responses may also indicate deeply weathered or altered basement rocks in which magnetic minerals have been depleted through prolonged weathering processes (Rahaman, 1988; Blakely, 1995).

The spatial distribution of the magnetic anomalies exhibits dominant NW–SE and NE–SW structural trends, reflecting the regional tectonic fabric of the Nigerian Basement Complex. These magnetic lineaments are interpreted as faults, fractures, shear zones, and lithological contacts developed during the Pan-African tectonic evolution. Such structures have been widely recognized as important controls on basement architecture and have significant implications for mineral exploration because they provide favourable pathways for hydrothermal fluid migration (Ajibade & Fitches, 1988; Anudu et al., 2014; Ilugbo et al., 2020; Ige et al., 2025**).**

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The concentration of high magnetic anomalies along these structural trends suggests zones of enhanced basement deformation and possible structural complexity. Consequently, the TMI map provides valuable information for delineating lithological boundaries, identifying major structural features, and recognizing areas of increased mineral exploration potential within the Ikole–Itapaji Basement Complex (Ogah & Abubakar, 2024; Adetunla et al., 2025; Iwabi et al., 2026**).**

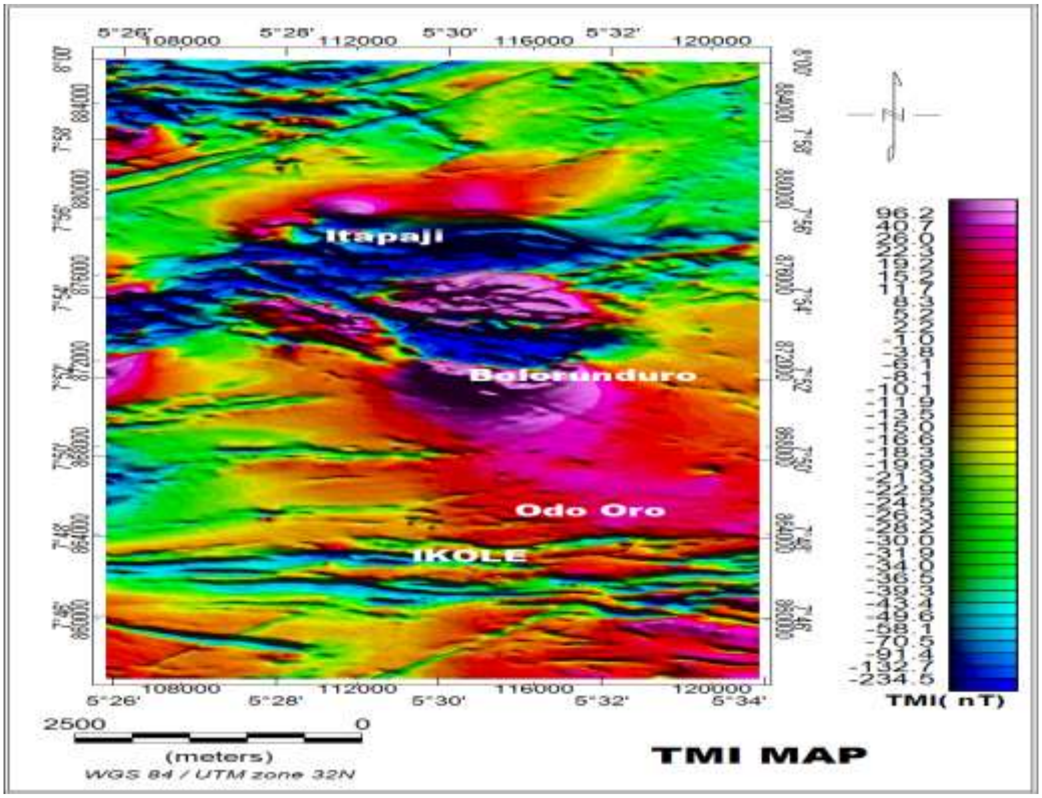


**Figure 5. Total Magnetic Intensity (TMI) anomaly map of the study area showing variations in magnetic signatures associated with subsurface lithological and structural features. High and low magnetic anomalies reflect contrasts in rock types and magnetic susceptibility. The map serves as the baseline for subsequent filtering and structural interpretation**

Reduced to Equator (RTE) magnetic anomaly map corrects for the asymmetry of magnetic anomalies at low magnetic latitudes by repositioning magnetic responses directly above their causative bodies, thereby improving the accuracy of lithological and structural interpretation in low-latitude regions (Blakely, 1995; Ogah & Abubakar, 2024). The map reveals distinct spatial variations in magnetic intensity across the study area, reflecting differences in lithology, magnetic susceptibility, and subsurface structural configuration. High-amplitude magnetic anomalies (approximately 23 to 93 nT), particularly around Bolorunduro and parts of Itapaji, are interpreted to represent shallow magnetically susceptible basement rocks, including amphibolitic bodies, mafic-rich lithologies, and magnetite-bearing granite gneisses. These pronounced magnetic responses indicate areas of strong magnetic susceptibility contrast and have been widely recognized as favourable zones for mineral exploration within crystalline basement terrains (Akinlalu et al., 2018; Ogah & Abubakar, 2024; Ige et al., 2025).

Moderate magnetic anomalies dominate the central part of the study area and are attributed to granitic and granodioritic rocks exhibiting intermediate magnetic properties. In contrast, low magnetic anomalies (approximately −212 to −40 nT), particularly around Odo Oro and Ikole, are interpreted to reflect felsic lithologies such as migmatites and quartz-rich gneisses, or basement rocks that have undergone intense weathering and hydrothermal alteration, resulting in reduced magnetic susceptibility (Rahaman, 1988; Blakely, 1995).

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The RTE map clearly delineates prominent linear and curvilinear magnetic features trending predominantly NE–SW and NW–SE, corresponding to the principal structural grain of the Nigerian Basement Complex. These magnetic lineaments are interpreted as faults, fractures, shear zones, and lithological contacts developed during the Pan-African tectonic evolution. Such structures have played a significant role in controlling magmatic emplacement and subsequent hydrothermal fluid migration within the basement rocks (Ajibade & Fitches, 1988; Anudu et al., 2014; Ilugbo et al., 2020). The spatial coincidence of high magnetic anomalies with these structural features suggests that tectonic deformation exerted considerable control on the localization of prospective mineralized zones, thereby making these structurally controlled magnetic highs priority targets for detailed mineral exploration (Ogah & Abubakar, 2024; Iwabi et al., 2026) (Fig. 6).

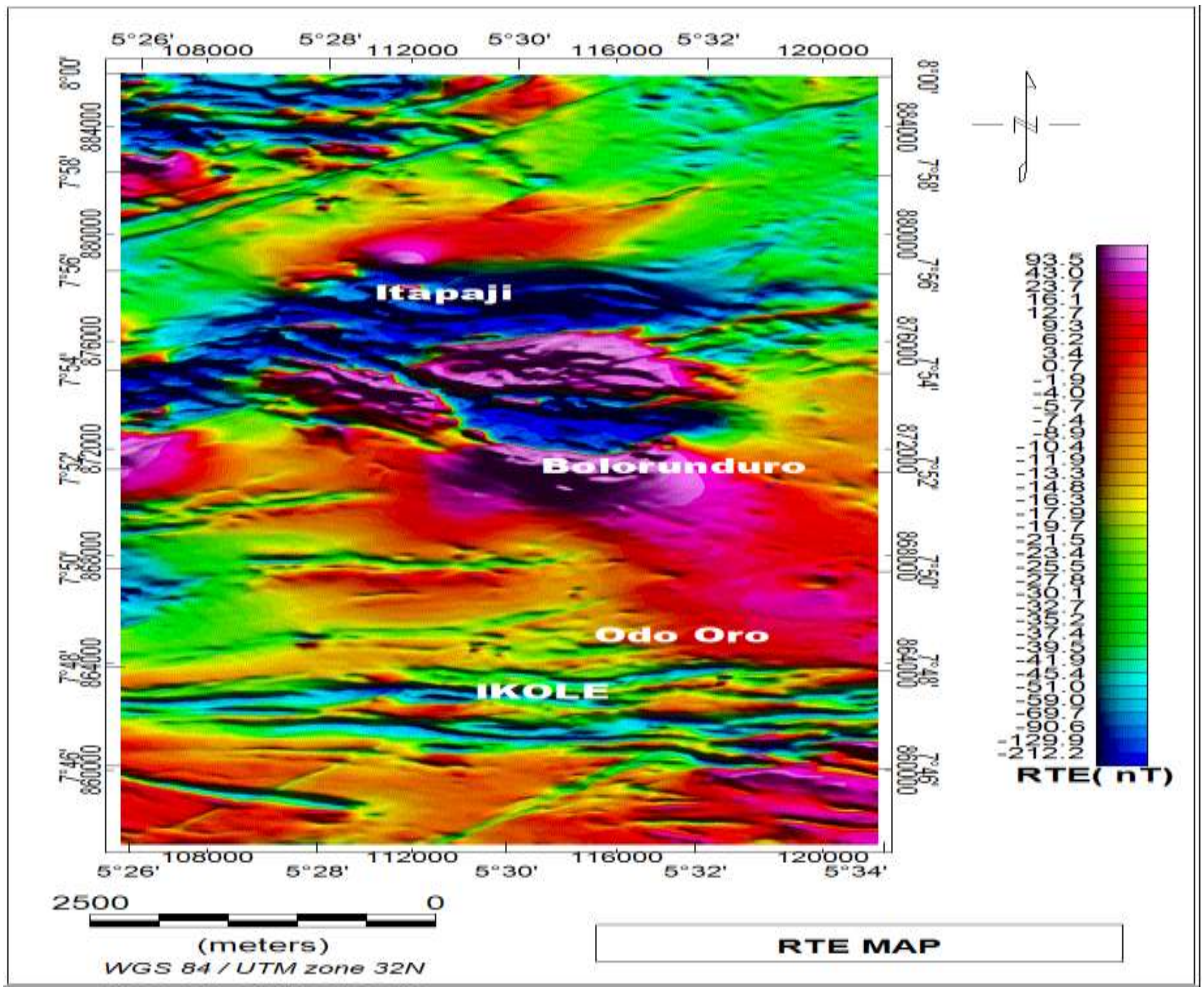


**Figure 6. Reduced to equator (RTE) magnetic anomaly map of the study area showing transformation repositions magnetic anomalies over their causative sources, minimizing dipolar distortion at low latitudes. Enhanced anomaly patterns clearly delineate subsurface structures and lithological variations relevant to mineral exploration.**

An analytical signal (AS) map is an effective tool for delineating subsurface magnetic source boundaries because its amplitude is independent of both the direction of magnetization and the low geomagnetic latitude characteristic of the study area. This property makes it particularly valuable for accurately mapping lithological contacts, faults, and other structural discontinuities within crystalline basement terrains, thereby improving the interpretation of magnetic data for mineral exploration (Blakely, 1995; Ogah & Abubakar, 2024). High analytical signal amplitudes are interpreted as zones underlain by shallow magnetic sources, including magnetite-bearing basement rocks, mafic intrusions, amphibolites, and highly deformed crystalline rocks. These high-amplitude responses indicate sharp

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magnetic susceptibility contrasts and commonly coincide with structurally disturbed zones that may have experienced hydrothermal alteration, making them favourable targets for mineral exploration (Akinlalu et al., 2018; Ogah & Abubakar, 2024; Ige et al., 2025). Conversely, low analytical signal amplitudes are associated with deeper magnetic sources or weakly magnetic lithologies such as migmatites, granitic gneisses, quartz-rich rocks, and weathered basement units. These subdued responses reflect relatively low magnetic susceptibility contrasts and generally indicate areas of limited structural deformation or magnetic mineral content (Rahaman, 1988; Blakely, 1995).

Structurally, the analytical signal map delineates prominent linear high-amplitude trends corresponding to faults, fractures, shear zones, and lithological contacts that characterize the Pan-African Basement Complex. These structural features represent zones of crustal weakness that have facilitated magmatic emplacement and the circulation of hydrothermal fluids responsible for metallic mineralization. Consequently, the analytical signal map provides a reliable framework for identifying structurally controlled exploration targets, particularly where pronounced magnetic gradients coincide with major basement structures (Anudu et al., 2014; Ilugbo et al., 2020; Ogah & Abubakar, 2024; Iwabi et al., 2026) (Fig. 7).

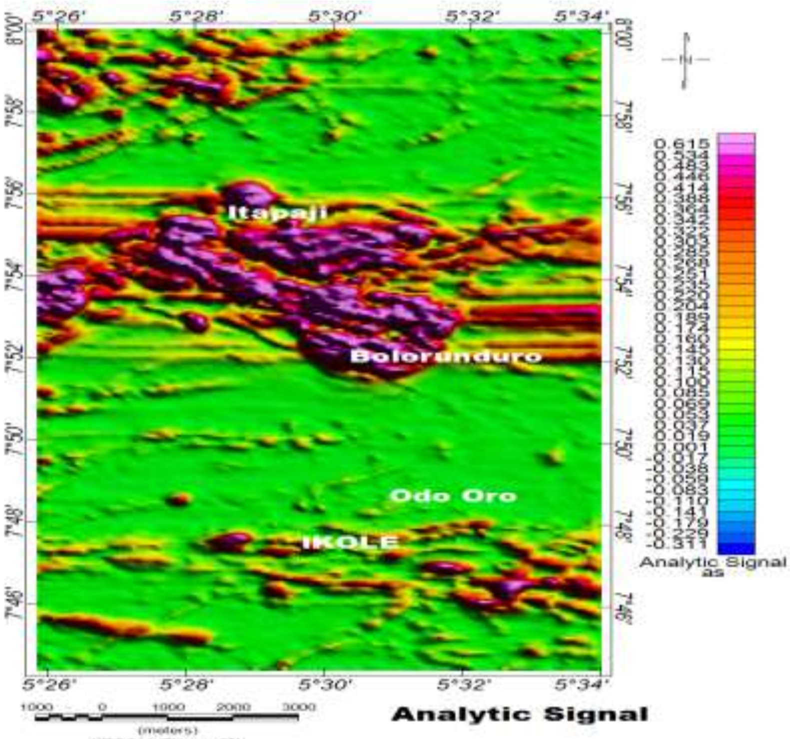


**Figure 7. Analytical Signal (AS) Map. The map highlights the edges and geometry of magnetic sources, with amplitude maxima delineating lithological contacts and structural boundaries. High AS values indicate shallow, highly magnetic bodies, while low values correspond to deeper or weakly magnetic sources. Linear AS trends delineate faults and shear zones that control subsurface structures and mineralization pathway.**

The First Vertical Derivative (FVD) map enhances shallow subsurface features by amplifying high-frequency magnetic anomalies while suppressing deeper regional magnetic responses, thereby improving the delineation of near-surface lithological boundaries and structural discontinuities within the basement complex (Blakely, 1995; Ogah & Abubakar, 2024). The map reveals numerous short-wavelength magnetic anomalies distributed across the study area, indicating significant lithological heterogeneity and structural complexity. High-frequency anomalies occurring around Itapaji and Bolorunduro are interpreted as shallow magnetic sources associated with magnetite-bearing basement rocks, mafic intrusions, amphibolitic bodies, or intensely fractured crystalline rocks. These anomalies are characterized by sharp magnetic gradients that define lithological contacts, faults, fractures, and shear

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zones within the basement terrain (Akinlalu et al., 2018; Ige et al., 2025). In contrast, relatively subdued magnetic responses around Odo Oro and Ikole indicate weakly magnetic or deeply weathered basement rocks, including quartz-rich migmatites and felsic gneisses characterized by relatively low magnetic susceptibility (Rahaman, 1988; Blakely, 1995). The reduced magnetic gradients within these areas suggest comparatively lower structural deformation and fewer shallow magnetic sources.

The FVD map further delineates dominant NE–SW and NW–SE structural trends, which are consistent with the regional tectonic framework of the Nigerian Basement Complex. These magnetic lineaments are interpreted as faults, fractures, shear zones, and lithological contacts developed during the Pan-African orogeny. Such structures constitute important zones of crustal weakness that have influenced basement deformation and provided favourable pathways for hydrothermal fluid circulation. Consequently, the well-defined structural features identified on the FVD map represent important exploration targets because of their potential role in controlling the localization of metallic mineralization (Anudu et al., 2014; Ilugbo et al., 2020; Ogah & Abubakar, 2024; Iwabi et al., 2026) (Fig. 8).

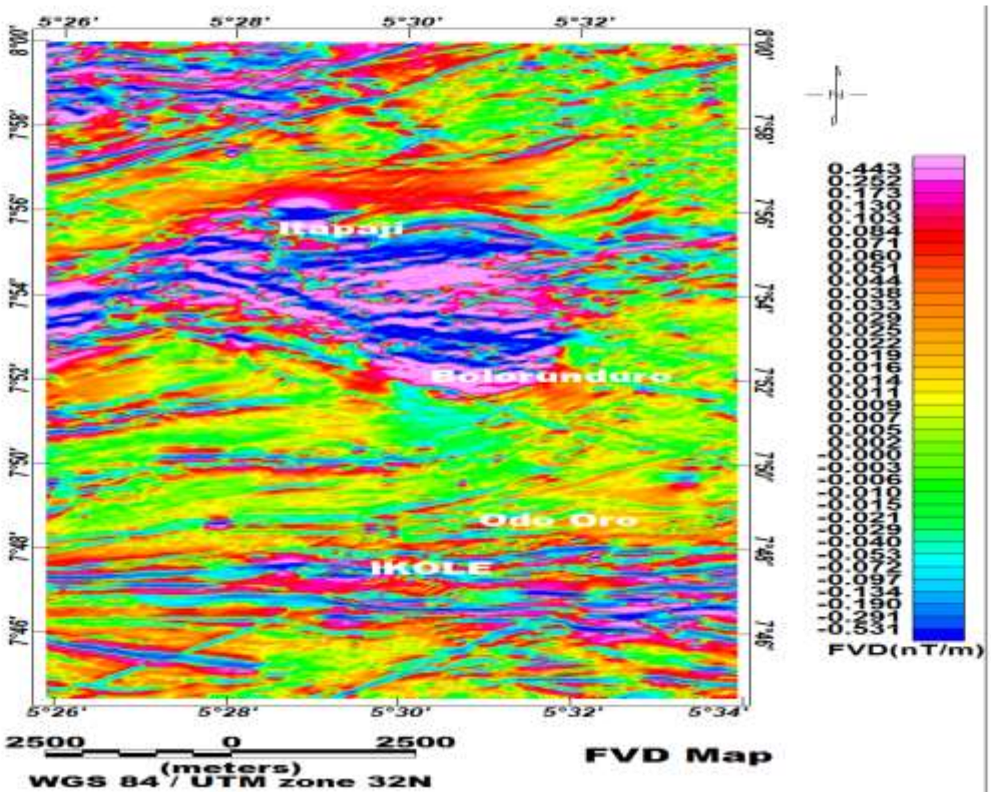


**Figure 8. First Vertical Derivative (FVD) map showing enhanced shallow magnetic anomalies within the study area. The map highlights near-surface geological features including faults, contacts, and lineaments. These structures are important for interpreting subsurface geology and potential mineralization zones.**

The Euler Deconvolution map provides estimates of the locations and depths of magnetic source bodies by solving Euler's homogeneity equation, thereby improving the interpretation of subsurface structures and magnetic source geometries within the study area (Reid et al., 1990; Blakely, 1995). The Euler solutions are widely distributed across the Ikole–Itapaji Basement Complex and occur as distinct clusters that reflect variations in the depth, geometry, and structural disposition of the magnetic sources.

High-density clusters of Euler solutions are concentrated around Itapaji and Bolorunduro, indicating the presence of relatively shallow magnetic bodies that are interpreted as magnetite-bearing basement rocks, mafic intrusions, lithological contacts, or intensely fractured crystalline rocks. The close spacing of these solutions suggests structurally disturbed zones characterized by significant magnetic susceptibility contrasts (Ogah & Abubakar, 2024;

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Ige et al., 2025). Conversely, the relatively sparse and deeper Euler solutions observed around Odo Oro and Ikole are interpreted to represent deeper-seated or weakly magnetic basement rocks, including quartz-rich migmatites, granitic gneisses, and weathered crystalline units with comparatively low magnetic susceptibility (Rahaman, 1988; Blakely, 1995). The greater depth to magnetic sources within these areas reflects reduced structural disruption and a thicker weathered profile.

The Euler solutions exhibit dominant NE–SW and NW–SE alignments, corresponding closely with the structural trends identified from the Reduced-to-Equator and First Vertical Derivative maps. These consistent orientations represent major faults, fractures, shear zones, and lithological contacts that define the structural framework of the Nigerian Basement Complex and reflect the tectonic imprint of the Pan-African orogeny (Ajibade & Fitches, 1988; Anudu et al., 2014; Ilugbo et al., 2020). The concentration of shallow Euler solutions along these structural corridors suggests that they constitute important zones of crustal weakness that have influenced basement deformation and magmatic emplacement. Overall, the Euler Deconvolution map provides reliable estimates of magnetic source depth and geometry, complementing the Total Magnetic Intensity, Reduced-to-Equator, Analytical Signal, and First Vertical Derivative maps. The close spatial association between shallow magnetic sources and major structural lineaments highlights these areas as favourable targets for detailed mineral exploration within the Ikole–Itapaji Basement Complex (Ogah & Abubakar, 2024; Iwabi et al., 2026) (Fig. 9).

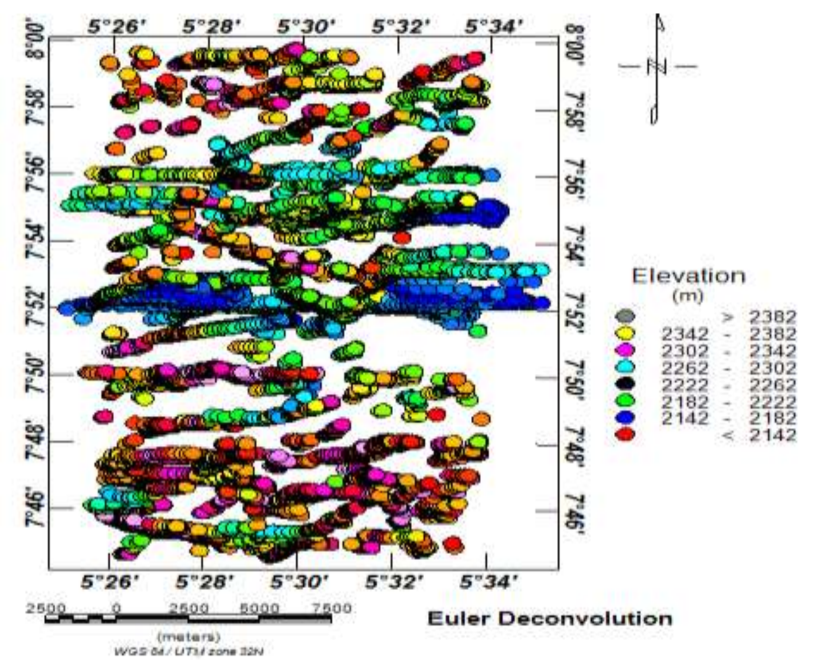


**Figure 9. Euler Deconvolution map showing estimated depths and locations of magnetic source bodies within the study area. The solutions indicate structural features such as faults, contacts, and intrusive bodies. These depth estimates provide insight into subsurface geometry and potential mineralization.**

The lineament density map is an important structural tool for evaluating the intensity of rock fracturing and deformation within the basement complex, thereby providing valuable information on subsurface structural controls and zones of enhanced mineral exploration potential. Areas of high lineament density represent intensely fractured and sheared basement rocks characterized by increased secondary porosity and permeability, conditions that favour the circulation of hydrothermal fluids responsible for metallic mineralization (Ogah & Abubakar, 2024; Ige et al., 2025). In the present study, prominent high-density lineament zones occur around Itapaji and Bolorunduro within the central to northern part of the study area, while another significant cluster is observed around Ikole in the southern sector. These zones are interpreted as areas of intense brittle–ductile deformation that have undergone repeated tectonic reactivation.

Moderate to low lineament density zones are represented by yellow to green colours and correspond to relatively competent or less deformed basement rocks. These areas may also reflect regions where thick weathered overburden obscures underlying structural features, resulting in comparatively lower fracture intensity and reduced permeability for hydrothermal fluid circulation (Rahaman, 1988; Blakely, 1995).

The dominant lineament orientations are predominantly E–W to ENE–WSW, consistent with the regional structural grain of the Nigerian Basement Complex established during the Pan-African orogeny. These structural trends correspond to major faults, fractures, shear zones, and lithological contacts that have controlled the deformation history of the basement rocks and provided favourable pathways for magmatic emplacement and subsequent hydrothermal fluid migration (Ajibade & Fitches, 1988; Anudu et al., 2014; Ilugbo et al., 2020). The coincidence of high lineament density with major structural corridors indicates that these areas constitute zones of enhanced structural complexity and are therefore considered favourable targets for detailed mineral exploration (Ogah & Abubakar, 2024; Iwabi et al., 2026) (Fig. 10).

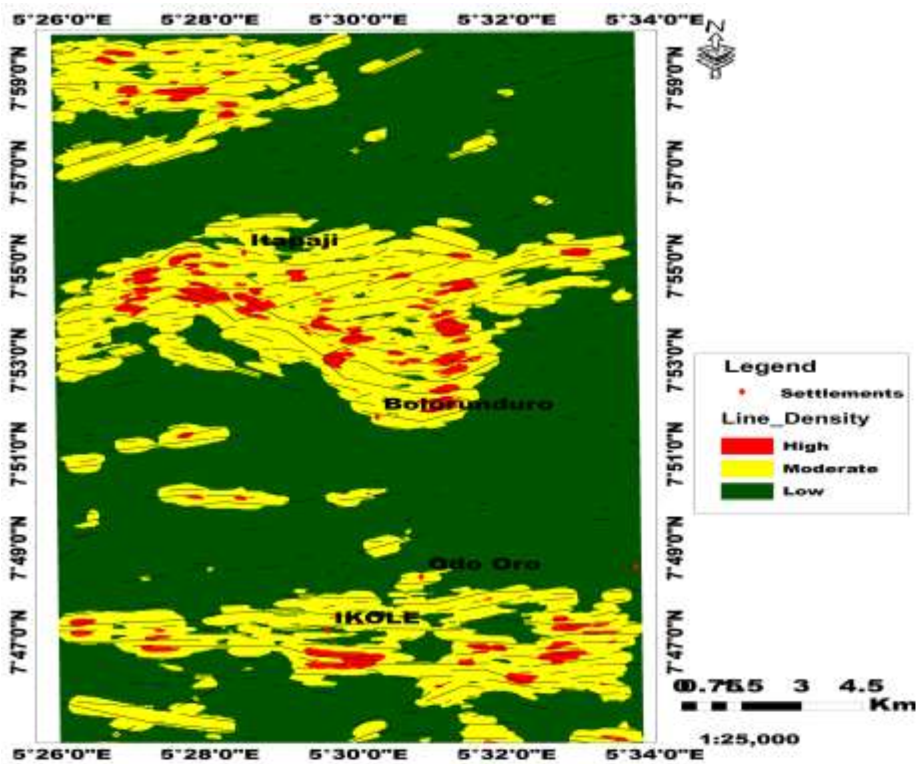


**Figure 10. Lineament Density Map. The map illustrates the spatial distribution and concentration of structural lineaments across the study area, highlighting zones of intense deformation. Areas of high lineament density indicate structurally weak zones with enhanced fracturing and potential fluid flow pathways.**

The integration of the lineament and geological maps reveals a strong spatial relationship between structural features and the underlying lithological units, highlighting the influence of lithology on deformation patterns within the Ikole–Itapaji Basement Complex. Lineaments are predominantly concentrated within competent crystalline rocks, particularly the granite gneiss and migmatite units, which are more susceptible to brittle deformation and fracture development under regional tectonic stresses. This structural behaviour is consistent with the response of competent basement rocks to repeated episodes of deformation associated with the Pan-African orogeny (Rahaman, 1988; Ajibade & Fitches, 1988).

The dominant structural orientations are predominantly E–W to ENE–WSW, especially along the Itapaji–Bolorunduro corridor, reflecting the regional structural grain of the Nigerian Basement Complex. These trends correspond to major faults, fractures, and shear zones that have undergone multiple episodes of tectonic reactivation and have significantly influenced the structural evolution of the study area (Anudu et al., 2014; Ilugbo et al., 2020; Adetunla et al., 2025). In the southern sector around Ikole, E–W trending fractures developed within the migmatitic rocks further demonstrate the strong influence of lithological characteristics on structural development and fracture propagation.

From a mineral exploration perspective, the clustering and intersection of lineaments within the crystalline basement rocks indicate zones of enhanced structural permeability that have likely served as conduits for hydrothermal fluid circulation. These structurally controlled corridors are considered favourable sites for metallic mineralization because repeated deformation increases fracture connectivity and creates pathways for the emplacement of mineralizing fluids. Consequently, the integrated geological and lineament map provides important insight into the structural controls on mineralization and serves as a valuable guide for delineating prospective exploration targets within the study area (Ogah & Abubakar, 2024; Ige et al., 2025; Iwabi et al., 2026) (Fig. 11).

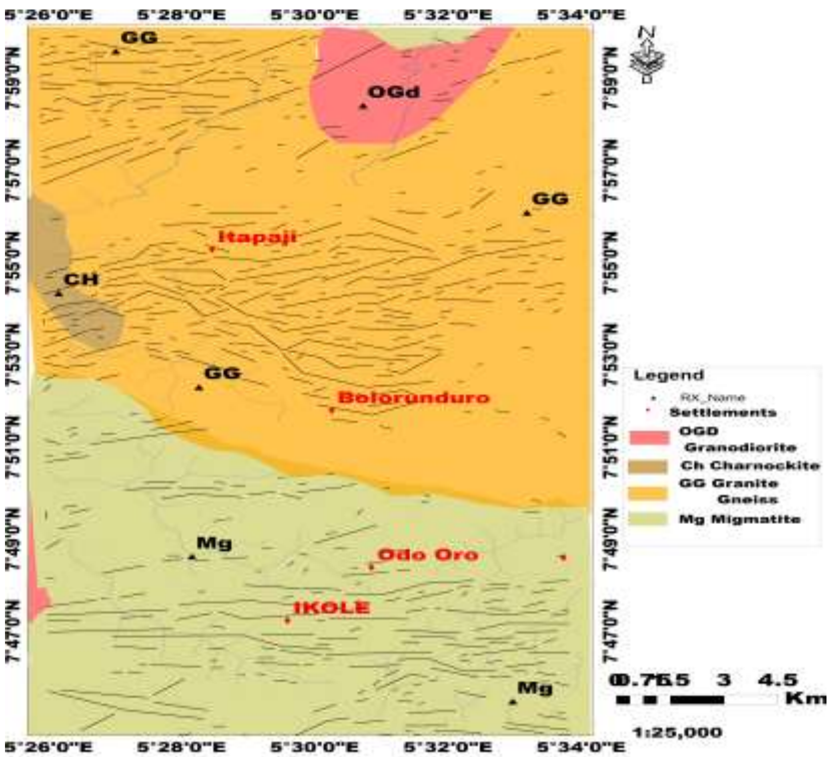


**Figure 11. The integration of lineaments with the geological map reveals the relationship between structural features and underlying lithological units. The superimposed lineaments highlight fault systems, fractures, and shear zones controlling rock boundaries and deformation patterns. This combined view enhances the understanding of structural control on geology and mineralization within the study area.**

The aeromagnetic rose diagram indicates that the lineaments within the study area are predominantly oriented in the ENE–WSW to E–W direction, reflecting a well-developed structural grain that characterizes the Ikole–Itapaji Basement Complex. This dominant orientation is consistent with the regional tectonic framework of the Nigerian Basement Complex and is attributed to the deformational events associated with the Pan-African orogeny, which controlled the development of major faults, fractures, and shear zones across southwestern Nigeria (Rahaman, 1988; Ajibade & Fitches, 1988; Anudu et al., 2014).

A subordinate ESE–WNW structural trend is also evident, although it occurs less frequently than the dominant ENE–WSW to E–W orientation. The presence of multiple lineament directions suggests that the study area experienced more than one episode of tectonic deformation, resulting in the reactivation of pre-existing basement

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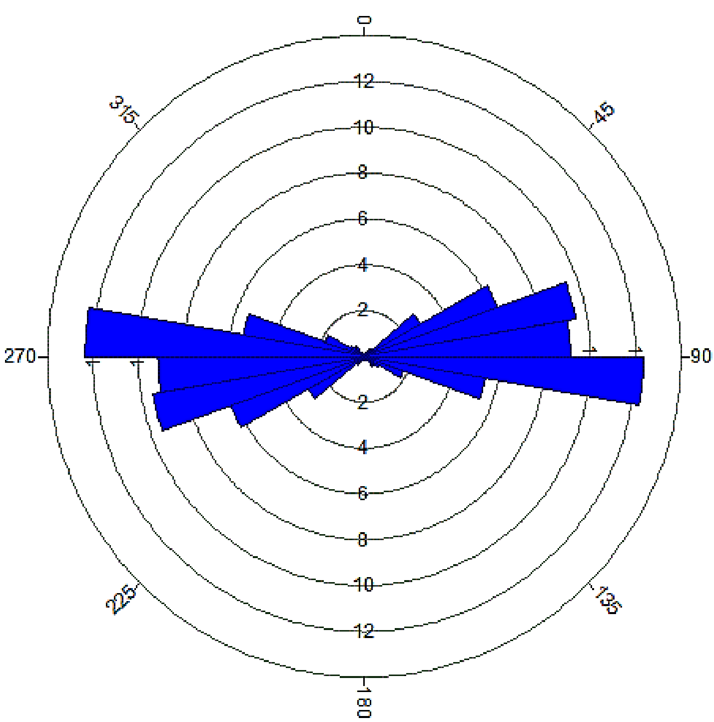
structures. Such polyphase deformation is a characteristic feature of Precambrian crystalline basement terrains and contributes significantly to the complexity of the structural architecture (Omosanya et al., 2015; Ilugbo et al., 2020).

The mapped lineaments represent zones of structural weakness that have influenced the tectonic evolution of the basement rocks and provided favourable pathways for the circulation of hydrothermal fluids. These structurally controlled corridors are important because they enhance rock permeability and play a significant role in the localization of metallic mineralization. Consequently, the aeromagnetic rose diagram provides valuable insight into the regional structural framework and serves as an important tool for identifying structurally controlled exploration targets within the study area (Ogah & Abubakar, 2024; Ige et al., 2025; Iwabi et al., 2026) (Fig. 12).




| Statistical Summary | |
|---|---|
| Calculation Method: | Frequency |
| Class Interval: | 10.0 Degrees |
| Min.Length Filtering: | Deactivated |
| Max.Length Filtering: | Deactivated |
| Azimuth Filtering: | Deactivated |
| Data Type: | Bidirectional |
| Rotation Amount: | 0.0 Degrees |
| Population: | 543 |
| Total Length of All Lineations: | 764,399.29 |
| Maximum Bin Population: | 134.0 |
| Mean Bin Population: | 36.2 |
| Standard Deviation of Bin Population: | 44.2 |
| Maximum Bin Population (%): | 12.34 |
| Mean Bin Population (%): | 3.33 |
| Standard Deviation of Bin Population (%): | 4.07 |
| Maximum Bin Length: | 98,721.35 |
| Mean Bin Length: | 25,479.98 |
| Standard Deviation of Bin Lengths: | 32,184.42 |
| Maximum Bin Length (%): | 12.91 |
| Mean Bin Length (%): | 3.33 |
| Standard Deviation of Bin Lengths (%): | 4.21 |
| Vector Mean: | 85.5 Degrees |
| | 265.49 Degrees |
| Confidence Interval: | 1.9 Degrees |
| | ( 80 Percent ) |
| R-mag: | 0.83 |

**Figure 12. Aeromagnetic Rose Diagram. The diagram illustrates the dominant orientation and frequency of magnetic lineaments within the study area. It highlights the principal structural trends controlling subsurface deformation and mineralization pathways**

The integrated lineament and Euler Deconvolution map superimposed on the geological framework provides a comprehensive representation of both surface and subsurface structural configurations within the Ikole–Itapaji Basement Complex. The integration of mapped lineaments with Euler depth solutions enhances the delineation of major structural features and provides valuable information on the geometry and depth extent of magnetic source bodies. This combined approach improves the interpretation of basement architecture by linking surface structural expressions with their corresponding subsurface continuities, thereby providing a more reliable framework for geological and mineral exploration studies (Blakely, 1995; Ogah & Abubakar, 2024).

The Euler Deconvolution solutions, represented by clustered points, define the spatial distribution and estimated depths of the causative magnetic bodies. The close alignment of these solutions with mapped lineaments, particularly around Itapaji and Bolorunduro, indicates that many of the identified faults, fractures, and shear zones extend from the near surface to considerable depths within the crystalline basement. The clustering of shallow Euler solutions along these structural corridors suggests the presence of major basement discontinuities that have experienced repeated tectonic reactivation and therefore constitute important zones of crustal weakness. In contrast,

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the relatively dispersed Euler solutions observed in some parts of the study area are interpreted to represent more complex structural geometries or deeper-seated magnetic sources (Anudu et al., 2014; Ilugbo et al., 2020; Ige et al., 2025).

Lithological variations exert a significant influence on the observed structural distribution. The granite gneiss and migmatite units exhibit relatively high concentrations of both surface lineaments and Euler solutions, reflecting their brittle response to tectonic deformation and their susceptibility to fracture development during the Pan-African orogeny. Conversely, the charnockite and granodiorite units display comparatively fewer surface lineaments; however, the occurrence of Euler solutions along their lithological contacts indicates the presence of concealed structural discontinuities that are not readily expressed at the surface. These relationships demonstrate that lithological boundaries have exerted an important control on the localization and development of basement structures within the study area (Rahaman, 1988; Ajibade & Fitches, 1988).

From a mineral exploration perspective, the coincidence of dense lineament networks with clustered Euler solutions identifies zones of enhanced structural permeability that are favourable for hydrothermal fluid circulation. The structurally complex corridors around Itapaji, Bolorunduro, and parts of the southern Ikole area are therefore interpreted as major conduits for fluid migration and represent highly prospective zones for structurally controlled metallic mineralization. Furthermore, the intersections of major structural trends with lithological contacts, particularly between the granite gneiss and migmatite units, provide favourable sites for localized strain concentration and hydrothermal fluid accumulation, thereby increasing their mineral exploration significance (Ogah & Abubakar, 2024; Adetunla et al., 2025; Ige et al., 2025; Iwabi et al., 2026) (Fig. 13).

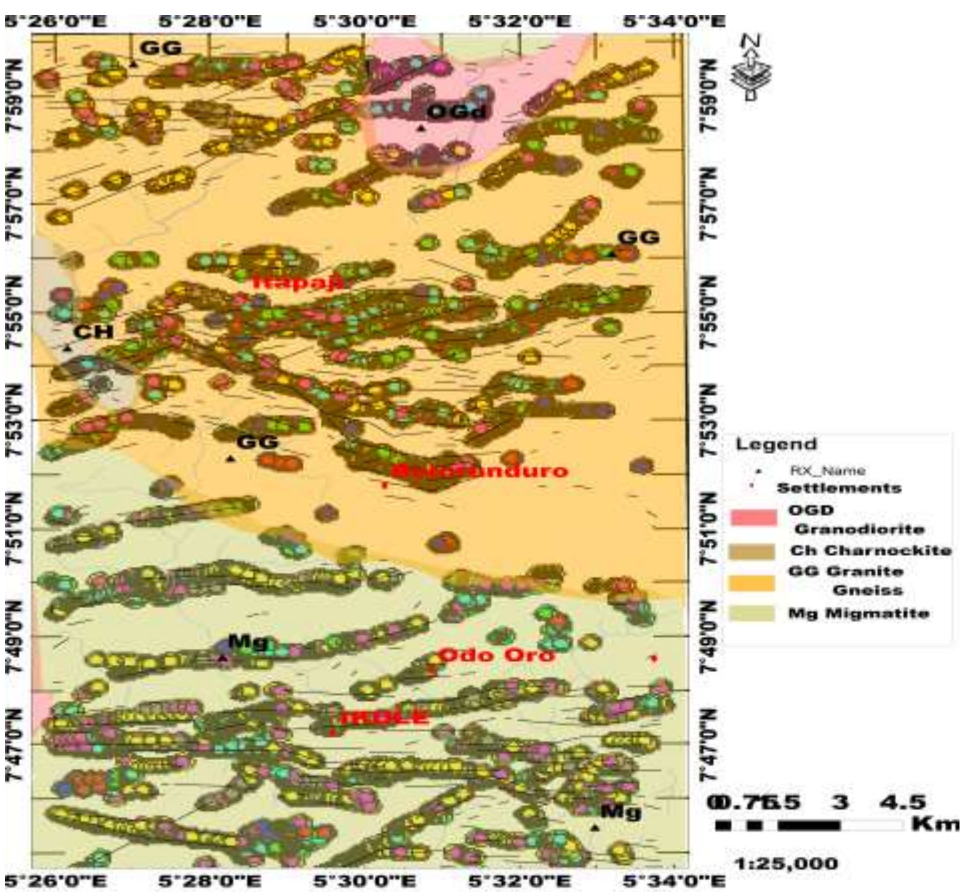


**Figure 13. Integrated lineament and Euler Deconvolution map superimposed on the geological framework of the study area. The map highlights structural trends, fracture zones, and subsurface lineaments derived from geophysical analysis. Euler solutions delineate depth estimates and structural contacts, enhancing the**

**interpretation of basement features. This integration provides insight into tectonic controls and mineralization potential within the mapped geology**

**Trace elements geochemistry**

The results of the factor analysis presented in Table 1 and Figure 14 reveal two statistically significant components that collectively explain 92.04% of the total geochemical variance within the study area. Component 1 has an eigenvalue (EV) of 8.034 and accounts for 80.34% of the total variance, whereas Component 2 has an eigenvalue of 1.171 and contributes an additional 11.71%. The cumulative variance (CVAR) of 92.04% indicates that the two extracted components adequately explain the elemental associations and geochemical variability of the study area. According to the Kaiser criterion, components with eigenvalues greater than one are considered statistically significant and represent the principal geochemical processes controlling elemental distribution. Consequently, Component 1 is interpreted as the lithological factor because it reflects the primary geochemical signature inherited from the host rocks, whereas Component 2 represents the pathfinder factor associated with hydrothermal alteration and metallic mineralization (Rollinson, 1993; Rollinson & Pease, 2021).

Table 1 shows that Component 1 is characterized by very strong positive loadings for Cu (0.966), Ni (0.983), Co (0.951), Fe (0.939), Zn (0.863), and Mn (0.849). These high factor loadings indicate strong positive relationships among the elements, suggesting a common geochemical origin and similar geochemical behaviour. Copper, nickel, cobalt, iron, zinc, and manganese commonly occur together within mafic to intermediate basement rocks and sulphide-bearing mineral assemblages. Their close association indicates that Component 1 represents the lithological factor, reflecting the primary geochemical composition inherited from magmatic differentiation and subsequent evolution of the Basement Complex. The enrichment of these elements may also reflect structurally controlled hydrothermal fluid circulation along faults, fractures, and shear zones, which promotes localized metallic mineralization within Precambrian basement terrains (Govett, 1983; Rose et al., 1979; Rahaman, 1988; Olade, 2020; Ige et al., 2026).

Component 2 is dominated by arsenic (As = 0.728), thorium (Th = 0.356), silver (Ag = 0.224), and a very weak contribution from lead (Pb = 0.008). Although the loadings of Ag, Th, and Pb are comparatively lower than those of Component 1, their association indicates a secondary geochemical process related to hydrothermal alteration and the concentration of accessory minerals. Component 2 is therefore interpreted as the pathfinder factor because arsenic is widely recognized as an effective pathfinder element for hydrothermal mineralization, while thorium is commonly concentrated in accessory minerals such as monazite, zircon, and allanite.

Silver and lead further strengthen this association, suggesting late-stage hydrothermal fluid activity and fluid–rock interaction that accompanied metallic mineralization. Similar pathfinder-element associations have been reported in geochemical investigations of basement terrains and are widely used in mineral exploration to identify concealed mineralized zones (Govett, 1983; Rose et al., 1979; Rollinson & Pease, 2021; Chen et al., 2024; Iwabi et al., 2026).

The communality values further demonstrate the robustness of the factor model. Most elements exhibit exceptionally high communalities, ranging from 0.773 for Mn to 0.998 for Cu. Copper (0.998), Co (0.997), Ni (0.967), Ag (0.963), Zn (0.958), Pb (0.956), Fe (0.921), Th (0.863), As (0.809), and Mn (0.773) all possess values exceeding 0.77, indicating that more than 77% of the variability of each element is explained by the two extracted components.

These high communalities confirm that the factor solution adequately represents the original geochemical dataset and that only a small proportion of the total variance remains unexplained. Such high communalities indicate that the extracted factors reliably summarize the dominant geochemical processes controlling trace-element distribution within the study area (Rollinson, 1993; Rollinson & Pease, 2021).

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The graphical representation in Figure 14 clearly supports the numerical results presented in Table 1. The chart illustrates the dominance of Component 1 over Component 2 through consistently high loading values for Cu, Zn, Ni, Co, Mn, and Fe. It also highlights the substantially larger eigenvalue of Component 1 (8.034) compared with Component 2 (1.171), confirming that the first component exerts the greatest influence on the geochemical dataset. Likewise, the chart demonstrates the high communality values for nearly all elements, showing that the extracted components effectively account for the observed elemental variability.

The marked difference between the percentage variance explained by Component 1 (80.34%) and Component 2 (11.71%) further emphasizes that the lithological factor constitutes the principal control on elemental distribution, whereas the pathfinder factor reflects secondary hydrothermal processes responsible for localized trace-element enrichment (Rollinson, 1993; Talapatra, 2020).

The factor analysis demonstrates that the Cu–Ni–Co–Fe–Zn–Mn association constitutes the dominant lithological factor within the study area, reflecting the primary geochemical characteristics of the basement rocks, whereas the As–Th–Ag–Pb association represents the pathfinder factor indicative of hydrothermal alteration and metallic mineralization. The cumulative variance of 92.04% indicates that the extracted components successfully summarize the geochemical behaviour of the analysed trace elements and provide a reliable basis for identifying mineralization controls.

These findings suggest that metallic mineralization within the Ikole–Itapaji Basement Complex is principally controlled by magmatic and structurally guided hydrothermal processes superimposed on favourable basement lithologies, with pathfinder elements serving as reliable indicators of prospective mineralized zones (Govett, 1983; Rose et al., 1979; Rollinson & Pease, 2021; Olade, 2020; Iwabi et al., 2026; Ige et al., 2026).

**Table 1. Results of factor analysis showing the extracted principal components, corresponding factor loadings, and the percentage of variance explained by each component. The analysis identifies the major geochemical associations and underlying processes controlling elemental distribution and mineralization patterns within the study area.**

| Variables | Comp1 | Comp2 | Communality |
|---|---|---|---|
| Cu | .966 | | .998 |
| Pb | | .008 | .956 |
| Zn | .863 | | .958 |
| Ag | | .224 | .963 |
| Ni | .983 | | .967 |
| Co | .951 | | .997 |
| Mn | .849 | | .773 |
| Fe | .939 | | .921 |
| As | | .728 | .809 |
| Th | | .356 | .863 |
| EV | 8.034 | 1.171 | |
| VAR% | 80.34% | 11.71% | |
| CVAR% | 80.34% | 92.044% | |

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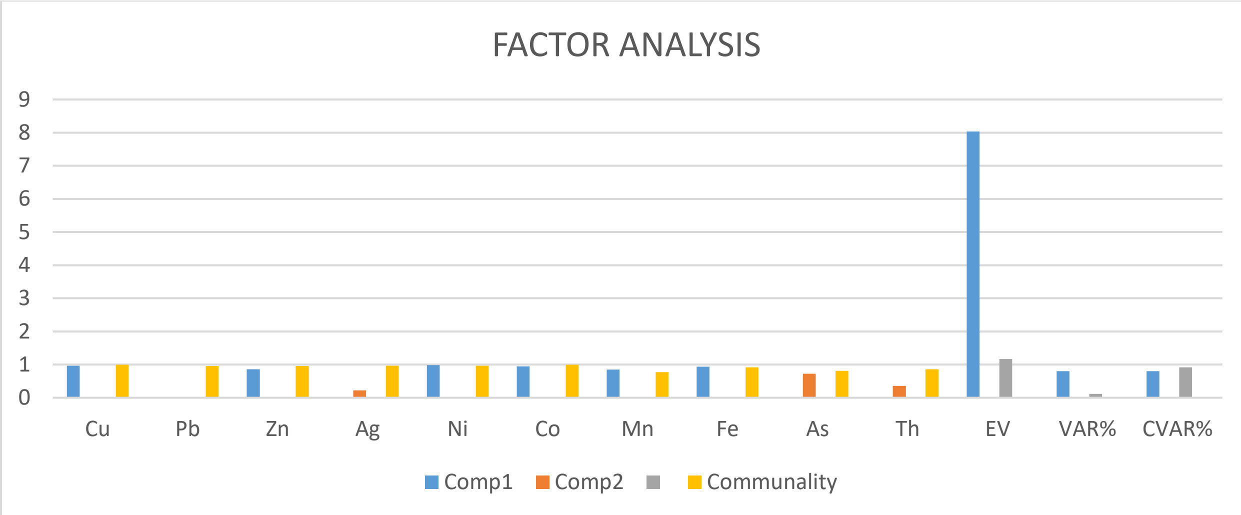


**Figure 14. Factor analysis chart showing the loadings of Components 1 and 2, communalities, eigenvalues (EV), percentage variance explained (VAR%), and cumulative variance (CVAR%) for the analysed geochemical elements. The chart illustrates the dominance of Component 1 in controlling the geochemical variability and mineralization patterns within the study area.**

The correlation coefficient matrix (Table 2) and the corresponding chart (Figure 15) reveal significant relationships among the analysed trace elements, reflecting their geochemical behaviour and possible mineralization processes. Strong positive correlations occur between Cu–Ni (r = 0.845), Cu–Co (r = 0.824), Cu–Fe (r = 0.804), Ni–Co (r = 0.935), Ni–Fe (r = 0.917), and Co–Fe (r = 0.876), indicating a common lithological source and similar geochemical affinity, most likely related to mafic mineral assemblages and structurally controlled hydrothermal enrichment. Zinc also exhibits moderate to strong positive correlations with Cu (r = 0.606), Ni (r = 0.596), Co (r = 0.683), and Fe (r = 0.529), suggesting that it belongs to the same mineralization suite. Such elemental associations are characteristic of trace-element enrichment within crystalline basement rocks and commonly reflect primary lithological composition modified by hydrothermal processes (Govett, 1983; Rose et al., 1979; Olade, 2020; Rollinson & Pease, 2021).

Conversely, Ag exhibits strong negative correlations with Cu (r = –0.858), Ni (r = –0.914), Co (r = –0.849), and Fe (r = –0.890), but shows a strong positive relationship with Pb (r = 0.913) and Th (r = 0.829), indicating that silver is controlled by a distinct geochemical process or mineral phase. Similarly, Pb displays a strong positive correlation with Th (r = 0.891) and a moderate positive correlation with As (r = 0.500), suggesting enrichment associated with hydrothermal alteration and the concentration of accessory minerals within felsic lithologies. The association of Pb, Ag, Th, and As is consistent with a secondary mineralization event superimposed upon the primary lithological framework and reflects the mobility of these elements during hydrothermal fluid–rock interaction (Govett, 1983; Rollinson, 1993; Chen et al., 2024; Iwabi et al., 2026).

Manganese and arsenic generally display weak or insignificant correlations with most of the analysed elements, indicating relatively independent geochemical behaviour and suggesting that their distribution is controlled by localized geological processes rather than the dominant mineralization system. As illustrated in Figure 15, the correlation chart clearly demonstrates the predominance of strong positive relationships among Cu, Ni, Co, Fe, and Zn, whereas Ag and Pb exhibit contrasting correlation patterns. These contrasting relationships indicate the existence of at least two distinct geochemical associations within the study area: a Cu–Ni–Co–Fe–Zn mineralization suite reflecting primary lithological control and sulphide mineralization, and a Pb–Ag–Th–As association representing hydrothermal alteration and late-stage mineralizing processes. Similar elemental associations have been widely reported in geochemical investigations of Precambrian basement terrains and constitute reliable indicators for identifying prospective zones of metallic mineralization (Rose et al., 1979; Rollinson & Pease, 2021; Talapatra, 2020; Lukman et al., 2024; Ige et al., 2026).

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**Table 2. Correlation coefficient matrix showing the degree and direction of relationships among the analyzed geochemical elements. Positive and negative correlation values indicate possible common sources, mineral associations, and geochemical processes influencing elemental distribution. The matrix provides a basis for interpreting elemental affinities and assessing mineralization potential within the study area.**

| | Cu | Pb | Zn | Ag | Ni | Co | Mn | Fe | As | |
|---|---|---|---|---|---|---|---|---|---|---|
| Cu | 1 | | | | | | | | | |
| Pb | -.543** | 1 | | | | | | | | |
| Zn | .606** | -.424* | 1 | | | | | | | |
| Ag | -.858* | .913* | -0.7598 | 1 | | | | | | |
| Ni | .845** | -.496* | .596** | -.914* | 1 | | | | | |
| Co | .824** | -.557** | .683** | -.849* | .935** | 1 | | | | |
| Mn | -0.294 | -0.1273 | 0.20883 | -.820* | -0.3365 | -0.281 | 1 | | | |
| Fe | .804** | -.710** | .529** | -.890* | .917** | .876** | -0.2066 | 1 | | |
| As | -0.176 | .500* | -0.0909 | 0.75 | -0.1921 | -0.0929 | 0.00011 | -.401* | 1 | |
| Th | -.506* | .891** | -.407* | .829* | -.493* | -.460* | -0.1191 | -.700** | .636** | 1 |

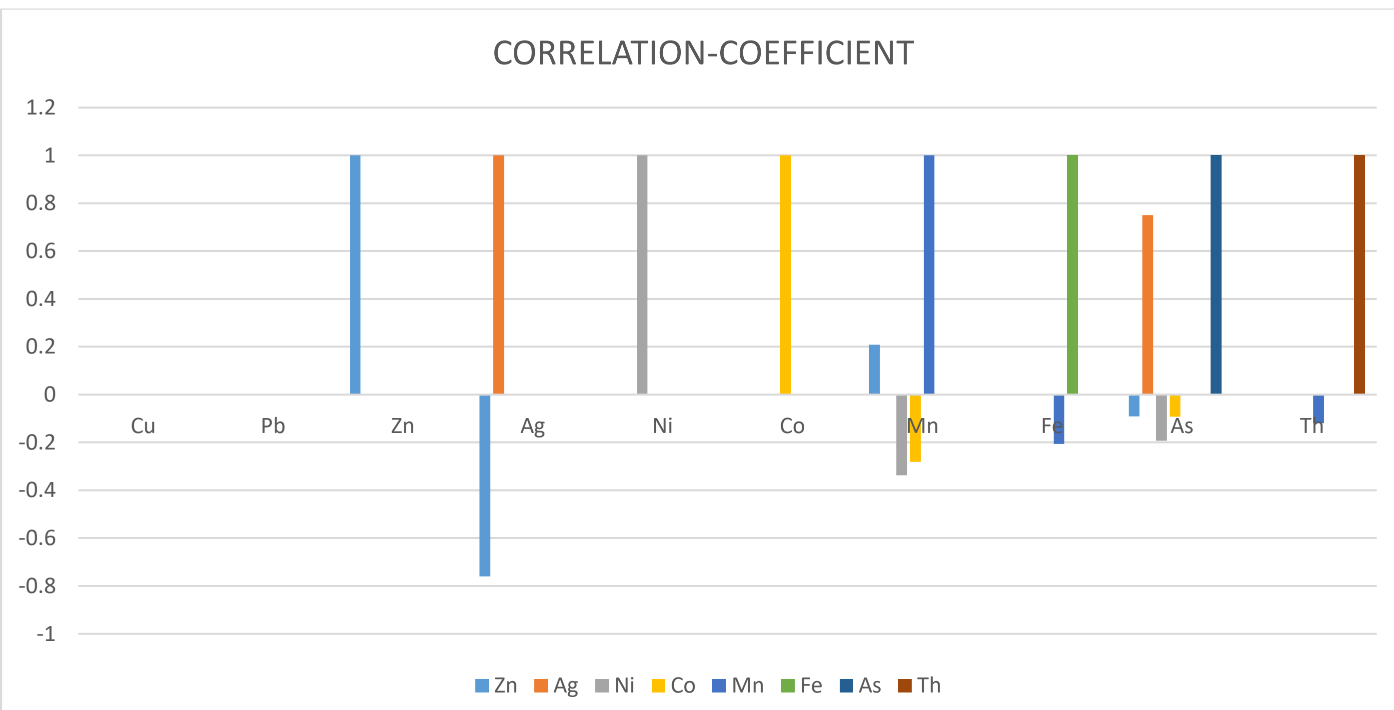


**Figure 15. Correlation coefficient chart illustrating the strength and direction of relationships among the analyzed trace elements. The chart highlights positive and negative elemental associations that reflect common geochemical sources, mineral assemblages, and mineralization processes within the study area.**

**Integration of Aeromagnetic and Trace Element Geochemical Data**

The integration of aeromagnetic and trace element geochemical data provides a robust framework for evaluating the structural controls on metallic mineralization within the Ikole–Itapaji Basement Complex. The aeromagnetic datasets delineate subsurface lithological boundaries, faults, fractures, and shear zones, whereas the trace element data identify zones of elemental enrichment related to mineralizing processes. The coincidence of these datasets enhances the reliability of delineating prospective mineralized zones (Govett, 1983; Rose et al., 1979; Rollinson & Pease, 2021).

The aeromagnetic interpretation reveals dominant NE–SW and NW–SE structural trends characterized by high magnetic anomalies, shallow Euler solutions, and dense lineament concentrations, particularly around Itapaji, Bolorunduro, and parts of Ikole. These structurally complex zones are interpreted as favourable pathways for hydrothermal fluid migration and mineral deposition within the Nigerian Basement Complex (Rahaman, 1988; Ajibade et al., 1987; Ajibade & Wright, 1989).

The trace element results complement the aeromagnetic interpretation. The strong association of Cu–Ni–Co–Fe–Zn identified by the factor and correlation analyses reflects the primary lithological and mineralization signature, whereas the As–Th–Ag–Pb association indicates hydrothermal alteration and pathfinder-element enrichment. The spatial correspondence between these geochemical anomalies and major structural features suggests that faults, fractures, and shear zones controlled the circulation of mineralizing fluids and the concentration of metallic mineralization (Govett, 1983; Rollinson, 1993; Chen et al., 2024; Ige et al., 2026).

Overall, the integrated interpretation demonstrates that the most prospective mineralized zones occur where high magnetic responses coincide with significant trace element enrichment and dense structural lineaments. These areas constitute priority targets for detailed exploration and confirm that integrating aeromagnetic and trace element geochemical datasets provides a more reliable approach to identifying structurally controlled metallic mineralization than either dataset used independently (Rollinson & Pease, 2021; Olade, 2020; Iwabi et al., 2026).

## STUDY LIMITATION

This study integrated high-resolution aeromagnetic and trace element geochemical datasets to evaluate the structural control of metallic mineralization within the Ikole–Itapaji Basement Complex. However, the interpretation is subject to certain limitations. The aeromagnetic data provide indirect information on subsurface geological structures and therefore require validation through detailed field investigations and drilling. In addition, the trace element analyses were based on a limited number of representative rock samples, which may not capture the full spatial variability of elemental distribution across the entire study area. Furthermore, tropical weathering and hydrothermal alteration may have modified the primary geochemical signatures of some rock units, potentially influencing the observed trace element concentrations. Consequently, the identified prospective mineralization zones should be regarded as exploration targets requiring further verification through detailed geological mapping, geophysical surveys, geochemical sampling, trenching, and exploratory drilling before their economic potential can be fully established.

## CONCLUSION

This study successfully integrated aeromagnetic and trace element geochemical data to investigate the structural controls on metallic mineralization within the Ikole–Itapaji Basement Complex, Southwestern Nigeria. The aeromagnetic interpretation revealed prominent NE–SW and NW–SE structural trends expressed by high magnetic anomalies, analytical signal responses, first vertical derivative, Euler deconvolution solutions, and dense lineament networks. These structures represent major faults, fractures, and shear zones that constitute favourable pathways for hydrothermal fluid migration and mineral deposition. The trace element geochemical results identified distinct elemental associations that reflect the geological evolution and mineralization processes within the study area. Factor analysis revealed a dominant Cu–Ni–Co–Fe–Zn association representing the primary lithological and mineralization signature, while the As–Th–Ag–Pb association reflects hydrothermal alteration and pathfinder-element enrichment. Correlation analysis further confirmed strong positive relationships among Cu, Ni, Co, Fe, and Zn, indicating a common geochemical source and similar mineralization processes.

The integrated interpretation demonstrates a strong spatial correspondence between structurally complex zones delineated from the aeromagnetic data and areas of trace element enrichment. This relationship confirms that basement structures exert significant control on the localization of metallic mineralization by providing conduits for hydrothermal fluid circulation. Areas around Itapaji, Bolorunduro, and parts of Ikole, where high magnetic responses coincide with favourable trace element anomalies, are therefore interpreted as the most prospective zones for future mineral exploration.

Overall, the study demonstrates that integrating aeromagnetic and trace element geochemical datasets provides a reliable and effective approach for delineating structurally controlled metallic mineralization within Precambrian basement terrains. The findings contribute to a better understanding of the mineralization framework of the Ikole–Itapaji Basement Complex and provide valuable baseline information for future detailed exploration programmes, including ground geophysical surveys, detailed geochemical investigations, trenching, and exploratory drilling to evaluate the economic potential of the identified targets.

# RECOMMENDATIONS

1. Detailed ground geophysical investigations, including magnetic, induced polarization (IP), electrical resistivity, and electromagnetic (EM) surveys, should be conducted over the delineated anomalous zones to verify the subsurface extent and continuity of the identified mineralized structures.

2. Follow-up geochemical investigations involving closer-spaced soil, trenching, channel, and rock-chip sampling are recommended within the priority target areas to better define the distribution and concentration of economically important trace elements.

3. Exploratory drilling should be undertaken across structurally controlled zones where high aeromagnetic anomalies coincide with significant trace element enrichment to validate the presence, depth, and economic potential of concealed mineralization.

4. Future studies should integrate additional exploration datasets such as petrography, mineral chemistry, fluid inclusion studies, isotopic analyses, and remote sensing data to better constrain the origin and evolution of the mineralizing system.

5. The delineated structural corridors and geochemical anomalies should be prioritized for detailed mineral exploration programmes by government agencies, exploration companies, and investors due to their favourable potential for metallic mineralization within the Ikole–Itapaji Basement Complex.

6. The integrated aeromagnetic and trace element geochemical approach adopted in this study is recommended for application in other parts of the Nigerian Basement Complex to improve mineral exploration targeting and reduce exploration uncertainty.

**Declaration of competing interests**

**Ethical Approval**

This study did not involve human participants, animals, or any form of clinical or ethical experimentation. Therefore, formal ethical approval was **not required.**

**Declaration of generative AI and AI-assisted technologies in the manuscript preparation process**

During the preparation of this work, the author used ChatGPT (GPT-5-mini) to assist with language editing and content organization. After using this tool, the author reviewed, revised, and verified all content to ensure accuracy, originality, and authenticity, and took full responsibility for the content of the published article.

### Consent to Participate

As no human participants were involved in this research, obtaining consent for participation was **not applicable.** All research activities adhered to standard field and laboratory protocols without the involvement of people.

### Consent to Publish

This study does not include any personal, sensitive, or identifiable information. Consequently, consent to publish was **not applicable**. All data presented are **scientific observations and analyses**, fully anonymized, and pose no ethical concerns.

### Availability of Data and Materials:

The datasets used and analyzed during this study are available from the corresponding author upon reasonable request.

### Author's Contribution

**Adeleke Ojo** conceived and designed the study, carried out the geological field investigations, collected rock samples, processed and interpreted the aeromagnetic and trace element geochemical data, prepared the figures and tables, performed the statistical analyses, drafted the manuscript, critically revised the manuscript for intellectual content, and approved the final version of the manuscript.

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