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REVIEW ARTICLE

INTEGRATED TRACE ELEMENT GEOCHEMISTRY AND AIRBORNE RADIOMETRIC DATA FOR DELINEATION OF MINERALIZATION ZONES IN THE IKOLE–ITAPAJI AREA, SOUTHWESTERN NIGERIA

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ABSTRACT

This study integrates airborne radiometric data and trace element geochemistry to delineate prospective mineralization zones within the Ikole–Itapaji Basement Complex, Southwestern Nigeria. Airborne radiometric datasets comprising potassium (K), thorium (Th), and uranium (U) channels were obtained from the Nigerian Geological Survey Agency (NGSA) and processed to generate K, Th, U, potassium deviation (KD), and ternary radiometric maps. Thirty-five fresh rock samples were collected during geological mapping, from which twenty representative samples were selected for trace element analysis. Trace element concentrations were determined 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. Statistical analyses involving Pearson correlation and factor analysis were used to evaluate elemental relationships and the controls on trace element distribution.The radiometric maps reveal elevated K, Th, U, and KD anomalies concentrated mainly within the Itapaji–Bolorunduro corridor, indicating felsic lithologies affected by hydrothermal alteration. Factor analysis extracted two significant components explaining 92.04% of the total variance. The first component (80.34%) is dominated by the Cu–Ni–Co–Fe–Zn association and represents the principal lithological factor, whereas the second component (11.71%) comprising As–Th–Ag–Pb reflects hydrothermal pathfinder mineralization. Correlation analysis further confirms strong positive relationships among Cu, Ni, Co, Fe, and Zn, while Ag, Pb, and Th define a distinct secondary association. The study demonstrates that integrating airborne radiometric data with trace element geochemistry provides a reliable framework for mineral prospectivity mapping and enhances metallic mineral exploration within the Nigerian Basement Complex.

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INTRODUCTION

The growing global demand for metallic mineral resources has accelerated mineral exploration in Precambrian basement terrains, which host economically important deposits of gold, iron, copper, lead, zinc, rare earth elements (REEs), lithium, tin, niobium, tantalum, and uranium. As easily accessible mineral deposits become depleted, there is an increasing need for integrated exploration techniques capable of accurately delineating concealed mineralization. Consequently, modern mineral exploration has evolved from conventional geological investigations to multidisciplinary approaches that combine geological, geochemical, geophysical, and remote sensing datasets to improve exploration efficiency and reduce uncertainty (Govett, 1983; Rose *et al*., 1979; Rollinson, 1993; Talapatra, 2020; Olade, 2020). The Nigerian Basement Complex forms part of the Pan-African Mobile Belt and comprises the Migmatite–Gneiss Complex, schist belts, Older Granites, and late-stage pegmatitic intrusions that were emplaced during the Pan-African Orogeny (Rahaman, 1988; Ajibade and Fitches, 1988; Ajibade and Wright, 1989). These lithological units have undergone multiple episodes of deformation, metamorphism, magmatism, and hydrothermal activity, resulting in the development of faults, fractures, shear zones, and other structural features that provide favourable pathways for mineralizing fluids (Olade and Elueze, 1979; Omosanya *et al*., 2015). Consequently, the Basement Complex of southwestern Nigeria has attracted considerable interest owing to its significant potential for metallic mineralization. Trace element geochemistry has become an indispensable tool in mineral exploration because ore-forming processes commonly produce anomalous concentrations of pathfinder elements such as Cu, Pb, Zn, Ni, Co, As, Mn, and Fe.

The distribution and association of these elements provide valuable information on hydrothermal alteration, elemental mobility, and mineralization processes (Govett, 1983; Rose *et al*., 1979; Rollinson, 1993). Recent advances in analytical techniques, particularly inductively coupled plasma–mass spectrometry (ICP–MS), have further improved the precision and reliability of trace element analyses used in mineral exploration (Senda *et al*., 2014; Chen *et al*., 2024). However, in tropical basement terrains, intense weathering and lateritization may modify primary geochemical signatures, making it necessary to integrate geochemical data with complementary geophysical datasets (Taylor and McLennan, 1985; Talapatra, 2020). Among geophysical methods, airborne radiometric surveying is widely recognized for its effectiveness in mapping the spatial distribution of naturally occurring radioactive elements, namely potassium (K), thorium (Th), and uranium (U). Variations in these radioelements reflect lithological changes, weathering intensity, and hydrothermal alteration, thereby providing valuable information for mineral exploration. Radiometric products such as potassium deviation, radioelement ratio maps, and ternary images have proven particularly useful in identifying alteration zones associated with metallic mineralization (NGSA, 2006; Ajakaiye *et al*., 1985; Ogah and Abubakar, 2024). Likewise, aeromagnetic investigations have successfully delineated structural features such as faults, fractures, and shear zones that influence the localization of mineral deposits within the Nigerian Basement Complex (Anudu *et al*., 2014; Akinlalu *et al*., 2018; Ilugbo *et al*., 2020; Faruwa *et al*., 2021). Several geological and geophysical investigations have been conducted within Ekiti State and other parts of southwestern Nigeria. Alagbe and Amosun (2021) and Amosun and Alagbe (2020) successfully integrated geophysical and remote sensing techniques to delineate lateritic bauxite deposits around Orin-Ekiti, while Talabi *et al*. (2018) investigated the petrography and geochemistry of basement rocks in the same area and demonstrated the influence of lithology on mineralization and weathering processes. Similarly, structural investigations have emphasized the significance of basement deformation and shear zones in controlling mineralization within southwestern Nigeria (Ajigo *et al*., 2021; Bamigboye *et al*., 2022). These studies demonstrate the effectiveness of integrated exploration techniques in evaluating mineral resource potential.

Despite these contributions, previous studies in the Ikole–Itapaji area have primarily focused on geological mapping, petrography, structural analysis, aeromagnetic interpretation, or whole-rock geochemistry. Limited attention has been given to the integration of airborne radiometric data with trace element geochemistry for the delineation of mineralization zones. Consequently, the relationships among radioelement distribution, trace element enrichment, hydrothermal alteration, and structural controls remain inadequately understood within the study area. Integrating these complementary datasets is expected to improve the discrimination of hydrothermal anomalies from lithological variations and enhance the identification of prospective mineral exploration targets. This study aims to integrate airborne radiometric data and trace element geochemistry to delineate prospective mineralization zones within the Ikole–Itapaji area, Southwestern Nigeria.

To achieve this aim, the study seeks to:

- Evaluate the spatial distribution of trace elements associated with metallic mineralization within the study area.
- Characterize the distribution patterns of potassium (K), thorium (Th), and uranium (U) using airborne radiometric data.
- Identify hydrothermal alteration zones through the interpretation of radiometric products.
- Integrate trace element geochemistry and airborne radiometric data to delineate prospective mineralization zones.
- Assess the influence of lithology and geological structures on the observed geochemical and radiometric anomalies.
- Identify priority targets for future detailed mineral exploration within the Ikole–Itapaji Basement Complex.

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 latitudes7°47′N and 8°05′Nandlongitudes 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 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.

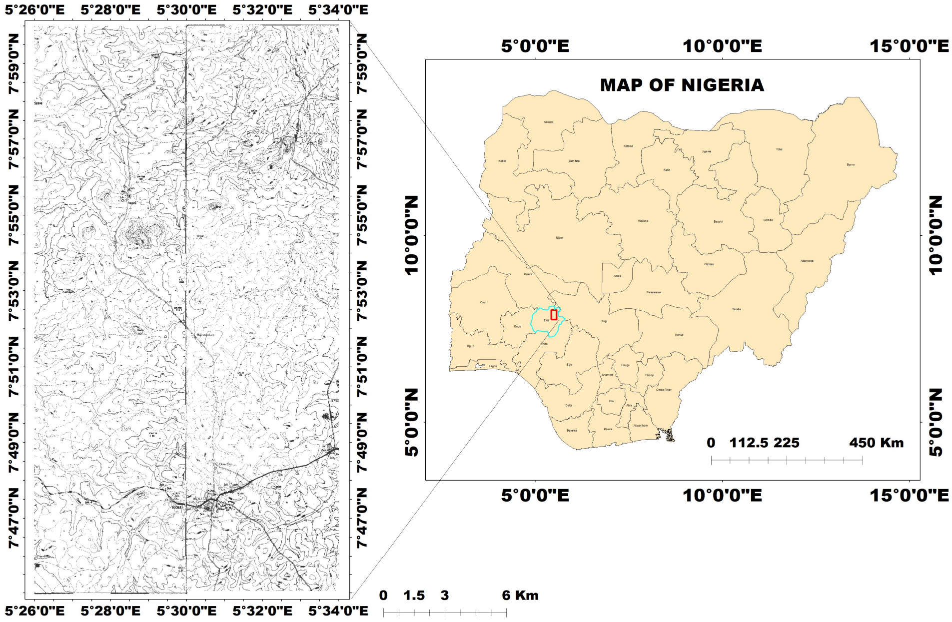

Figure 1. Location and topographic map of the Ikole–Itapaji–Ake-Ako area, Ekiti State, southwestern Nigeria, illustrating the geographical extent, drainage network, road accessibility, and topographic relief of the study area

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, 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)

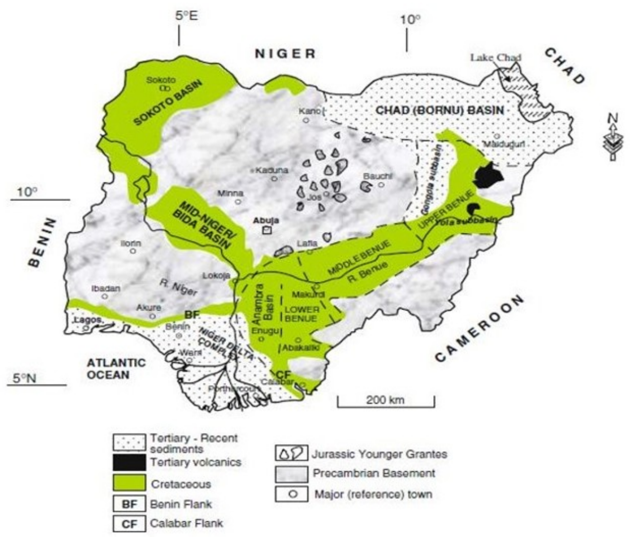

Figure 2: Geological map of Nigeria showing the distribution of major lithological units, including the Precambrian Basement Complex and surrounding sedimentary basins (Sokoto, Chad, Bida, and Benue Trough). The study area

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).

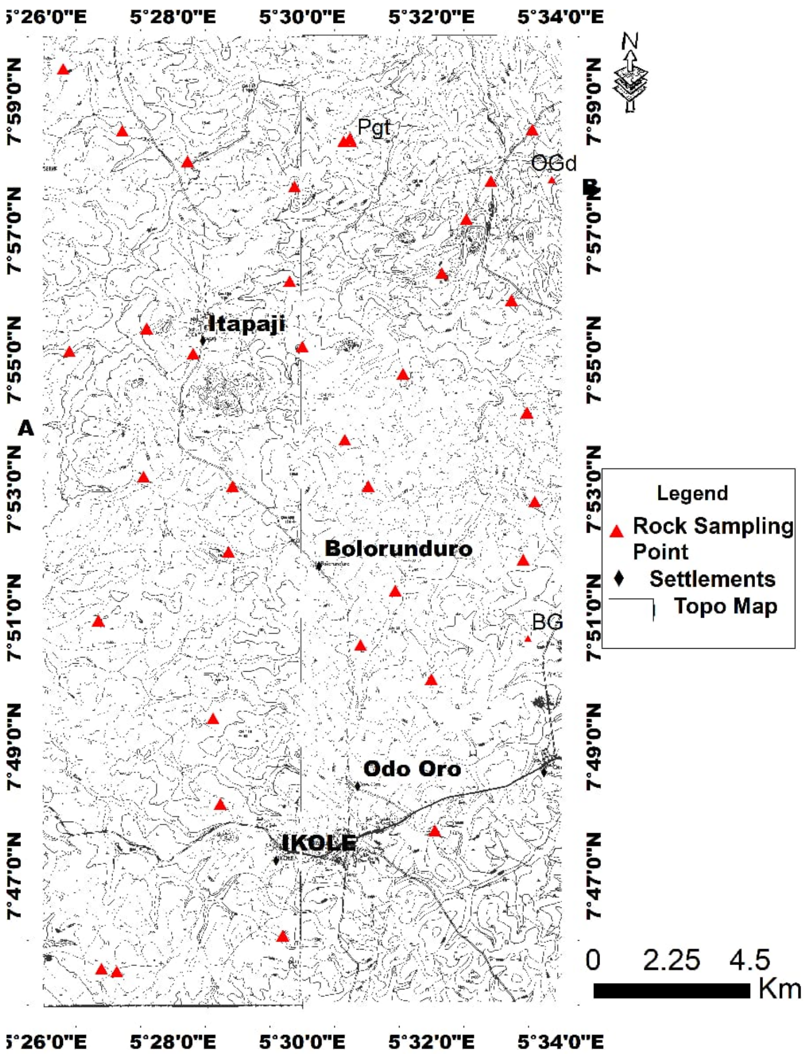

Figure 3. Topographic map of the Ikole–Itapaji–Ake-Ako area, Southwestern Nigeria, showing the distribution of geological sampling points used for geological mapping, structural measurements, and petrographic investigations. The sampling locations provide representative coverage of the major basement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

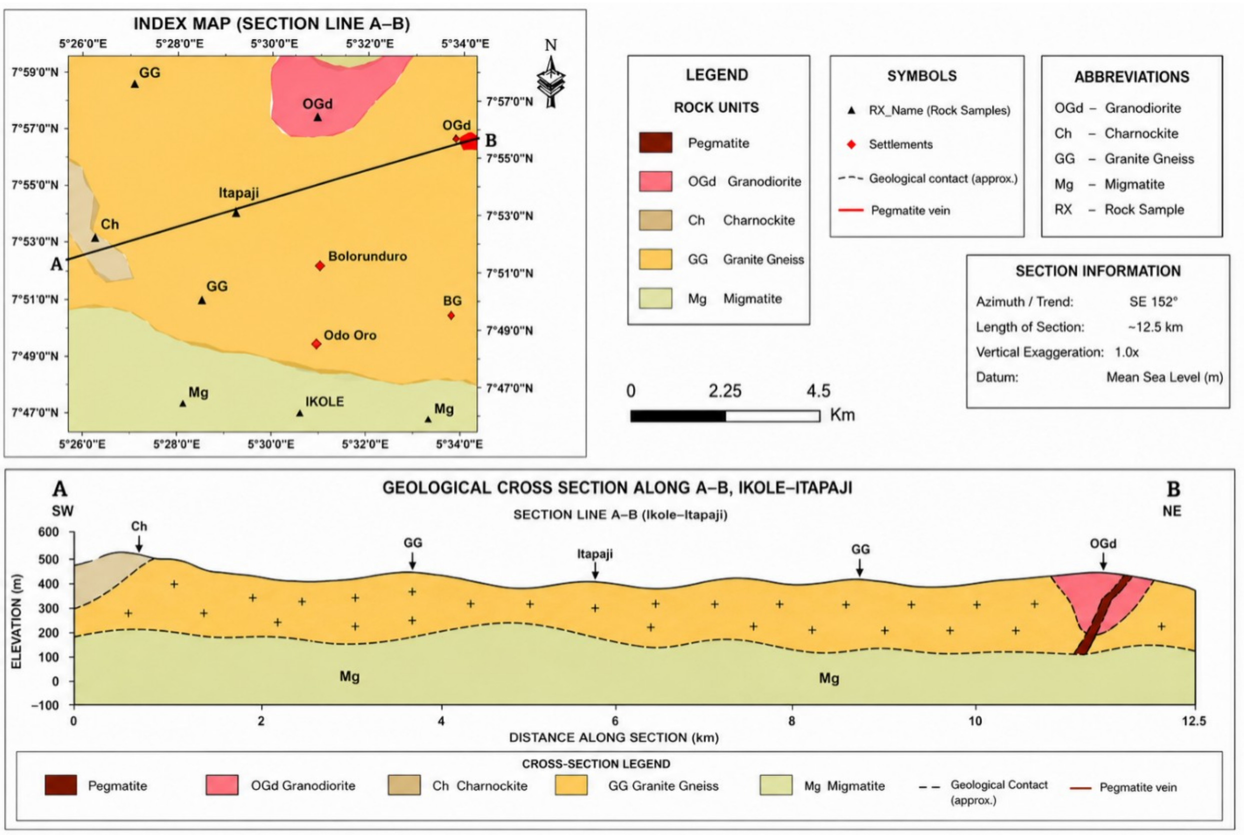

Figure 4. Geological cross-section along A–B across the Ikole-Itapaji area, showing the subsurface relationships between migmatite, granite gneiss, charnockite, granodiorite, and pegmatite units. The section reveals a migmatitic basement overlain by granite gneiss and intruded by younger granodiorite 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

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.

MATERIALS AND METHODS

Materials: The materials used for this study comprised field equipment, laboratory facilities, airborne radiometric datasets, and computer software required for geological mapping, trace element geochemical analyses, radiometric 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 consisting of safety boots, reflective jacket, hand gloves, and a safety helmet. These materials were used for geological mapping, structural measurements, sample collection, accurate positioning of outcrops, and documentation of field observations. Laboratory facilities included 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 geochemical analyses were carried out at ACME Analytical Laboratories (Bureau Veritas Commodities Canada Ltd.), Vancouver, Canada, using internationally accepted analytical procedures based on Inductively Coupled Plasma–Mass Spectrometry (ICP–MS).

Airborne radiometric datasets comprising potassium (K), thorium (Th), and uranium (U) channels 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 flown at a nominal terrain clearance of 80 m with a flight-line spacing of 150 m, tie-line spacing of 1500 m, and map scale of 1:100,000. The radiometric datasets provide measurements of the natural gamma-ray emissions of potassium, thorium, and uranium, thereby providing valuable information for lithological discrimination, hydrothermal alteration mapping, and mineral exploration. Geosoft Oasis Montaj™ 8.4HJ and ArcGIS 10.7 software packages were used for radiometric data processing, visualization, spatial analysis, and integration of the trace element and radiometric datasets.

Methods

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 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 carried out 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 such as 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 taken to document important geological features. The field observations formed the basis for geological interpretation and subsequent integration with geochemical and radiometric 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:

- Representation of all the major lithological units identified during geological mapping.
- Freshness of the rock samples, with preference given to fresh, unweathered, and minimally altered specimens.
- Lithological and mineralogical diversity to ensure adequate representation of the compositional variability of the different rock units within the study area.
- Megascopic textural variability, including differences in grain size, mineral fabric, and weathering characteristics observed during field examination.
- Structural characteristics, particularly samples exhibiting representative foliations, mineral banding, folds, quartz veins, and shear fabrics.

- Spatial distribution to ensure adequate geographical representation of the different lithological units across the study area.
- Elimination of duplicate samples exhibiting similar lithological, mineralogical, and structural characteristics from the same locality to avoid analytical redundancy while maintaining representative coverage.

This sampling strategy ensured that the analysed samples adequately represented the lithological, structural, and geochemical variability of the crystalline basement rocks within the study area. 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 geochemical 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, while 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 the accuracy, precision, and reliability of the analytical results.

Airborne Radiometric Data Processing: The airborne radiometric datasets were processed and interpreted using Geosoft Oasis Montaj™ 8.4HJ, while ArcGIS 10.7 was employed for map preparation, spatial analysis, and integration of the radiometric and geochemical datasets. Standard preprocessing procedures, including background correction, levelling, normalization, and gridding, were applied to improve data quality prior to interpretation. Individual distribution maps for potassium (K), thorium (Th), and uranium (U) were generated to evaluate lithological variations and radioelement distribution across the study area. Potassium deviation (KD), an important indicator of potassium enrichment associated with hydrothermal alteration, was calculated using:

$$KD = (K - Kmean) / Ksd$$

where K represents the measured potassium concentration, K_{mean} is the mean potassium concentration, and $K_{s}d$ is the standard deviation of potassium values. Composite ternary (K–Th–U) images were subsequently generated to enhance lithological discrimination and delineate hydrothermal alteration zones associated with potential metallic mineralization.

Statistical Analysis and Data Integration: The trace element dataset was subjected to Pearson correlation coefficient analysis to evaluate elemental relationships and identify possible geochemical associations among the analysed trace elements. Factor analysis was subsequently performed to identify the principal geochemical processes controlling elemental distribution and to distinguish lithological signatures from mineralization-related geochemical associations. The processed radiometric products and trace element geochemical data were integrated within a Geographic Information System (GIS) environment to investigate the spatial relationships between radioelement distribution and trace element enrichment. Areas exhibiting coincident anomalies in potassium, thorium, uranium, and economically important trace elements were interpreted as favourable zones for hydrothermal alteration and metallic mineralization. The integrated interpretation was used to delineate prospective mineralization zones and to evaluate the influence of lithology and geological structures on the distribution of mineralization within the Ikole–Itapaji area. This integrated workflow provided a robust framework for identifying priority targets for future mineral exploration in the study area.

RESULTS AND DISCUSSION

Radiometric maps: The Potassium (K) anomaly map reveals significant spatial variation in potassium concentration across the study area, with values ranging from low (<0.5%) to relatively high (>2.0%). Potassium distribution within crystalline basement terrains is principally controlled by lithology, mineral composition, and secondary geological processes such as hydrothermal alteration and weathering (Rahaman, 1988; Talabi *et al*., 2018). Airborne gamma-ray spectrometry has been widely recognized as an effective technique for discriminating lithological units and delineating zones of potassic alteration associated with mineralization (NGSA, 2006; Ogah & Abubakar, 2024). Higher potassium values observed in the central and northern parts of the study area are spatially associated with felsic lithologies, particularly granite gneiss and granitic rocks. These lithologies are characteristically enriched in potassium-bearing minerals such as K-feldspar, microcline, orthoclase, and biotite, resulting in relatively high radiometric potassium responses (Talabi *et al*., 2018; Frost *et al*., 2001). Elevated potassium anomalies may therefore reflect either the primary mineralogical composition of felsic rocks or secondary potassium enrichment resulting from hydrothermal alteration, which commonly accompanies mineralizing fluids in crystalline basement environments (Akinlalu *et al*., 2018; Ogah & Abubakar, 2024). Conversely, the southern and western parts of the study area exhibit comparatively low potassium concentrations, which are interpreted to reflect the occurrence of relatively mafic or intermediate lithologies and/or the effects of prolonged chemical weathering and leaching that deplete potassium-bearing minerals. Tropical weathering processes and regolith development are known to reduce near-surface potassium concentrations and consequently suppress gamma-ray responses, particularly in deeply weathered basement terrains (Alagbe & Amosun, 2021; Amosun & Alagbe, 2020). The observed spatial variation in potassium distribution therefore reflects the combined influence of lithological heterogeneity, hydrothermal alteration, and weathering processes within the Ikole–Itapaji Basement Complex (Fig. 5). The Thorium (Th) anomaly map shows concentrations ranging from <10 ppm to >40 ppm across the study area. Thorium is a relatively immobile, incompatible lithophile element that is preferentially concentrated in felsic igneous rocks and is widely regarded as one of the most reliable radioelements for lithological discrimination in airborne gamma-ray spectrometry (NGSA, 2006; Ogah & Abubakar, 2024).

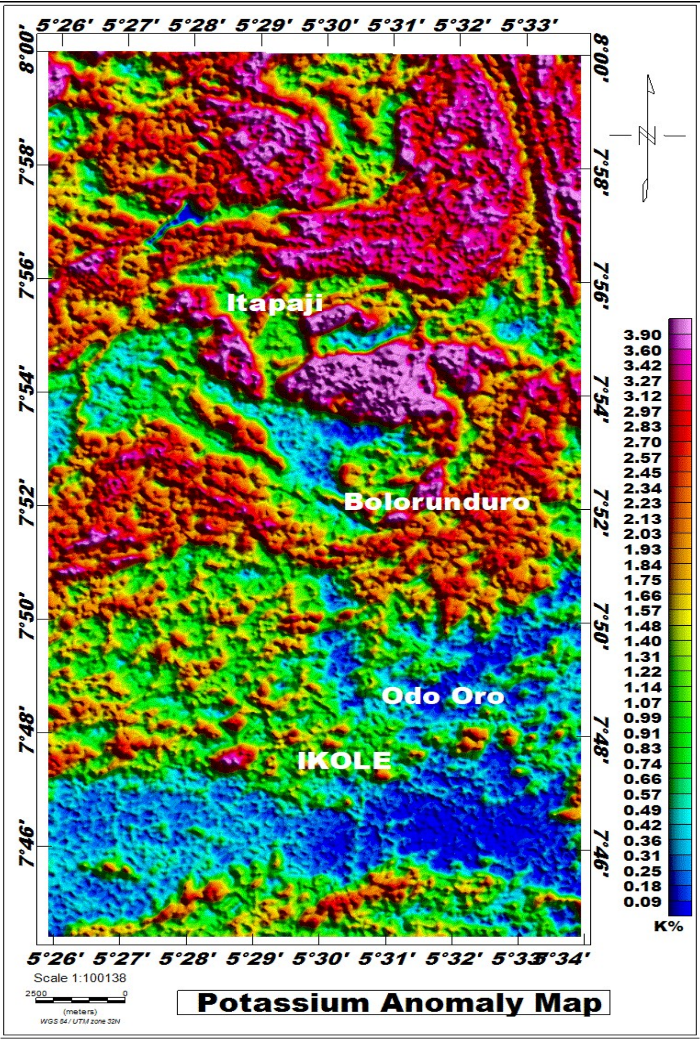

Figure 5. Potassium anomaly map of the study area highlighting the spatial distribution of K-rich radiometric signatures. The map reveals variations in potassium concentration associated with different lithologies and alteration

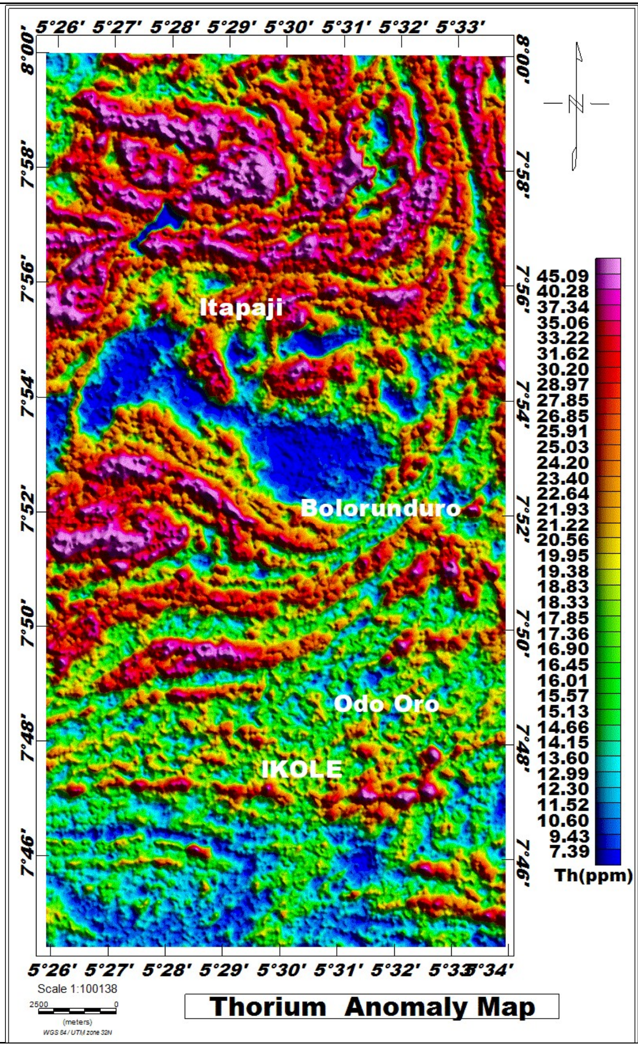

Figure 6. Thorium anomaly map of the study area showing the spatial distribution of thorium radiometric signatures. The map highlights variations in thorium concentration associated with different lithological units and structural controls. It provides useful indicators for delineating felsic rocks and potential zones of crustal enrichment

Unlike potassium, thorium is generally unaffected by most hydrothermal alteration processes and surface weathering, making its distribution a dependable indicator of primary lithological variations. High thorium values (>30 ppm) are predominantly concentrated within the northern and central parts of the study area, particularly around the Itapaji axis, where granite gneiss and granitic lithologies are extensively developed. The elevated thorium responses are attributed to the abundance of accessory minerals such as zircon, monazite, allanite, and xenotime, which preferentially incorporate thorium into their crystal structures during magmatic differentiation (Frost *et al*., 2001; Talabi *et al*., 2018). Similar associations between felsic lithologies and high thorium concentrations have been documented in basement terrains of southwestern Nigeria, where radiometric signatures effectively discriminate granitoid bodies from surrounding metamorphic rocks (Akinlalu *et al*., 2018; Alagbe & Amosun, 2021).

Conversely, the southern part of the study area, particularly around the Odo Oro–Ikole axis, is characterized by relatively low thorium concentrations (<20 ppm), corresponding largely to migmatitic rocks. These comparatively lower values may reflect the presence of more mafic or mixed metamorphic components containing fewer thorium-bearing accessory minerals, together with compositional heterogeneity inherited during migmatization (Rahaman, 1988; Olade & Elueze, 1979). The distinct contrast between high- and low-thorium zones therefore provides a clear basis for lithological differentiation across the study area. Because thorium exhibits limited mobility during weathering and hydrothermal alteration, its spatial distribution largely preserves the original geochemical characteristics of the parent rocks. Consequently, comparison of the thorium distribution with potassium anomalies provides an effective means of distinguishing primary lithological variations from secondary potassic alteration associated with hydrothermal mineralizing processes (Ogah & Abubakar, 2024; Akinlalu *et al*., 2018) (Fig. 6). The Uranium (U) anomaly map shows uranium concentrations ranging from <2 ppm to >9 ppm across the study area. Uranium is a relatively mobile radioelement under oxidizing conditions and is therefore an effective indicator of fluid migration, hydrothermal alteration, and structurally controlled mineralization in crystalline basement terrains (NGSA, 2006; Ogah & Abubakar, 2024). Unlike thorium, uranium may be redistributed by circulating hydrothermal and meteoric fluids, making its spatial distribution sensitive to both lithological and structural controls. High uranium concentrations (>6 ppm) are predominantly concentrated within the northern and central parts of the study area, particularly around the Itapaji axis, where they coincide with granite gneiss and granitic lithologies.

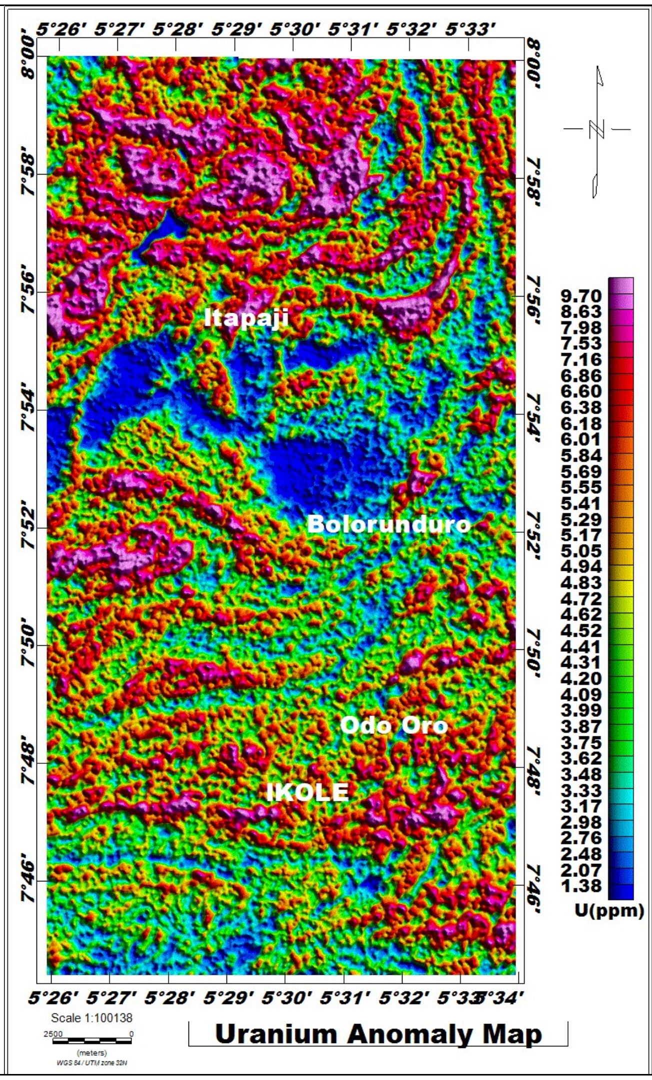

Figure 7. Uranium anomaly map of the study area depicting the spatial distribution of uranium radiometric signatures. The map highlights variations in uranium concentration linked to lithological differences and structural features. It serves as an important tool for identifying zones of radiometric enrichment and potential mineralization

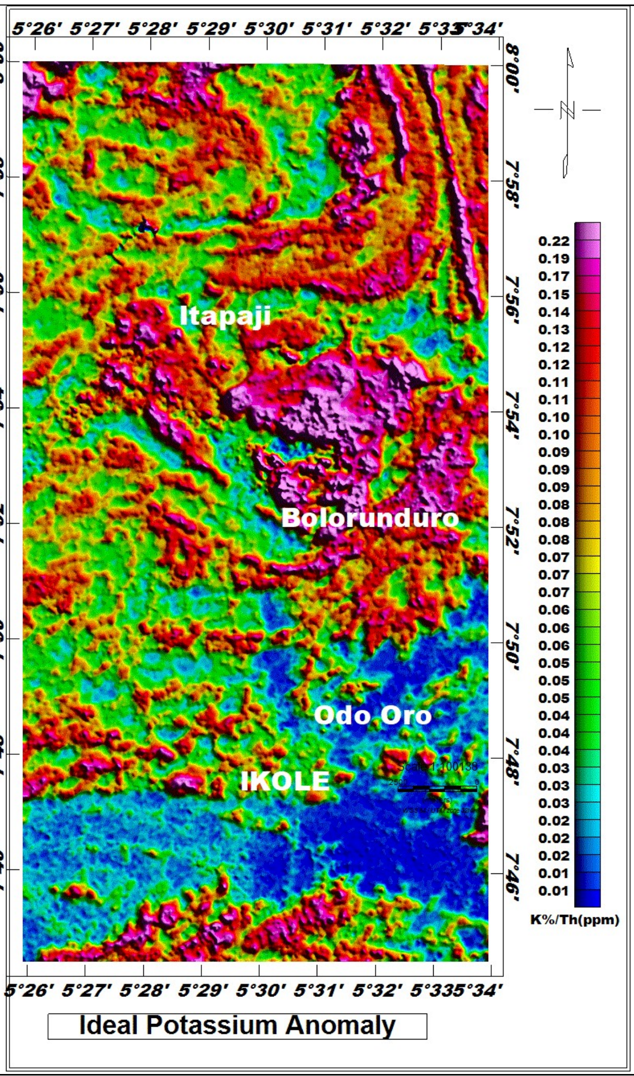

Figure 8. Potassium deviation map of the study area showing departures from background potassium radiometric values. The map highlights areas of enrichment and depletion relative to regional potassium levels. It provides insight into alteration zones and structural controls affecting potassium distribution

The enrichment is attributed to the preferential concentration of uranium during late-stage magmatic differentiation and its incorporation into accessory minerals such as zircon, apatite, monazite, and allanite, which are characteristic of evolved felsic rocks (Frost *et al*., 2001; Talabi *et al*., 2018). Comparable uranium enrichment associated with granitoid bodies has been reported in other crystalline basement terrains of southwestern Nigeria, where airborne radiometric data have successfully delineated lithological variations and mineralization zones (Akinlalu *et al*., 2018; Alagbe & Amosun, 2021).

In contrast, the southern part of the study area, particularly around the Odo Oro–Ikole axis, is characterized by relatively low uranium concentrations (<3 ppm), corresponding largely to migmatitic rocks. These lower values are consistent with lithologies containing fewer uranium-bearing accessory minerals and may also reflect uranium depletion through prolonged chemical weathering and leaching under oxidizing near-surface conditions (Rahaman, 1988; Talabi *et al*., 2018). Such weathering processes are common within tropical basement terrains and may significantly influence the surface distribution of uranium. Structurally, several zones of elevated uranium concentration exhibit spatial correspondence with the dominant E–W and ENE–WSW structural trends recognized within the study area. These structures likely acted as permeable pathways for uranium-bearing hydrothermal fluids, promoting localized uranium enrichment along fractures, joints, and shear zones. Similar relationships between radiometric uranium anomalies and structurally controlled mineralization have been documented in basement complexes of southwestern Nigeria (Ilugbo *et al*., 2020; Faruwa *et al*., 2021). Comparison of the uranium distribution with the potassium and thorium anomaly maps therefore provides valuable insight into distinguishing primary lithological signatures from secondary hydrothermal alteration and structurally controlled mineralization, thereby enhancing the delineation of prospective mineralization zones within the study area (Ogah & Abubakar, 2024) (Fig. 7). The Potassium Deviation (KD) map, expressed as the normalized relationship between potassium concentration and its statistical distribution relative to the lithological background, highlights zones of potassium enrichment by minimizing the influence of primary lithological variations. Because potassium is relatively mobile during hydrothermal alteration whereas thorium remains comparatively immobile, potassium deviation is widely employed to identify areas affected by potassic metasomatism and hydrothermal fluid activity (NGSA, 2006; Ogah & Abubakar, 2024).

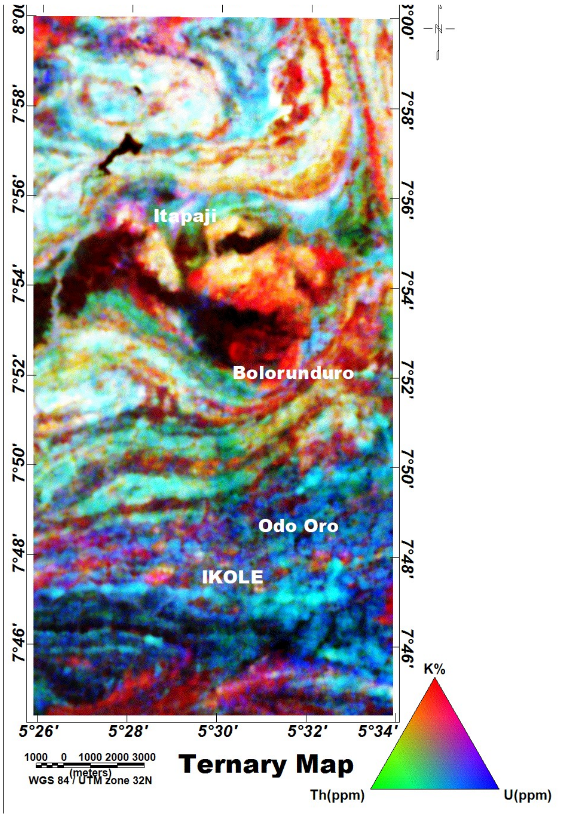

Figure 9. Ternary radiometric diagram illustrating the relative proportions of potassium, thorium, and uranium in the study area The diagram aids in lithological discrimination and identification of radiometric anomalies associated with mineralization

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%	

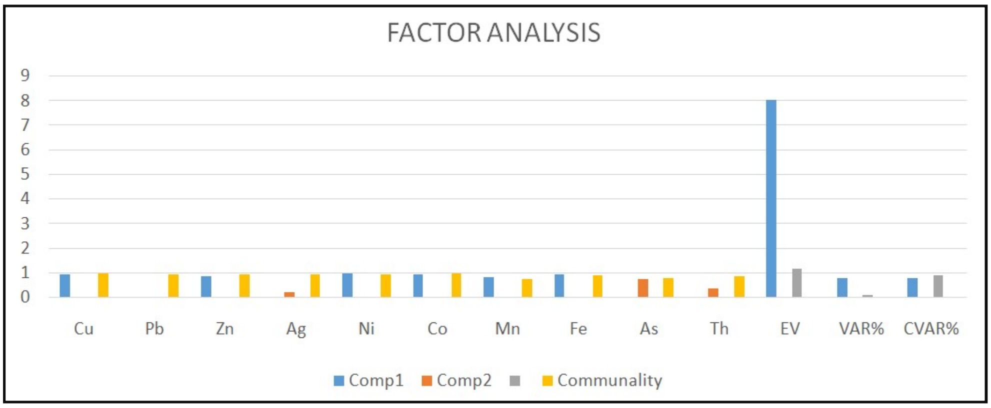

Figure 10. Factor analysis chart showing the loadings of Components 1 and 2, communalities, eigenvalues (EV), percentage variance explained (VAR%), and cumulative variance (CVAR%) for the analysed geochemical elements. The chart illustrates the dominance of Component 1 in controlling the geochemical variability and mineralization patterns within the study area

The KD map shows values ranging from <0.03 to >0.15, indicating considerable spatial variation in potassium enrichment across the study area. High KD anomalies (>0.15), represented by red to magenta colours, are concentrated mainly within the central and northern parts of the study area, particularly around the Itapaji axis extending toward Bolorunduro. These anomalies indicate zones of significant potassium enrichment resulting from hydrothermal alteration, where circulating mineralizing fluids have introduced or redistributed potassium through alteration processes such as sericitization, biotitization, and secondary K-feldspar development. Such alteration is commonly associated with structurally controlled hydrothermal systems and has been recognized as an important indicator of metallic mineralization in crystalline basement terrains (Akinlalu *et al*., 2018; Ogah & Abubakar, 2024). Conversely, the southern part of the study area, particularly around the Odo Oro–Ikole axis, is characterized by consistently low KD values (<0.03), suggesting little or no potassium enrichment beyond the primary lithological background. These low values are interpreted to reflect the relatively stable geochemical characteristics of the migmatitic rocks together with limited hydrothermal overprinting. In addition, prolonged tropical weathering may have contributed to potassium depletion through the alteration and leaching of potassium-bearing minerals, thereby suppressing the potassium deviation response (Rahaman, 1988; Alagbe & Amosun, 2021). The spatial distribution of the high potassium deviation anomalies exhibits a marked alignment along the dominant E–W and ENE–WSW structural trends within the study area, suggesting that fractures, faults, and shear zones served as preferential conduits for potassium-rich hydrothermal fluids. Similar relationships between structurally controlled potassium enrichment and mineralization have been documented in basement terrains of southwestern Nigeria using integrated airborne geophysical techniques (Ilugbo *et al*., 2020; Faruwa *et al*., 2021). The coincidence of these potassium deviation anomalies with favourable lithological units and structural features therefore identifies the Itapaji–Bolorunduro corridor as a highly prospective target for hydrothermal mineralization and future mineral exploration (Fig. 8).

The ternary radiometric map integrates potassium (K), thorium (Th), and uranium (U) into a composite RGB image, providing a comprehensive representation of the spatial distribution of radioelements and facilitating lithological discrimination, hydrothermal alteration mapping, and structural interpretation. In the composite image, potassium is displayed in red, thorium in green, and uranium in blue, allowing variations in radioelement abundance and geological units to be readily distinguished (NGSA, 2006; Ogah & Abubakar, 2024). Bright white to pinkish-yellow zones occurring predominantly within the northern and central parts of the study area, particularly around the Itapaji axis, indicate relatively high concentrations of all three radioelements. These radiometric signatures correspond mainly to granite gneiss and granitic lithologies, which are characteristically enriched in potassium-bearing feldspars and radioactive accessory minerals such as zircon, monazite, allanite, and apatite. Such felsic rocks commonly exhibit elevated K, Th, and U responses because of their evolved magmatic compositions and the concentration of incompatible elements during fractional crystallization (Frost *et al*., 2001; Talabi *et al*., 2018). Similar radiometric signatures have been reported from crystalline basement terrains in southwestern Nigeria, where integrated airborne radiometric data successfully delineated granitoid bodies and associated mineralization zones (Akinlalu *et al*., 2018; Alagbe & Amosun, 2021). In contrast, the southern part of the study area, particularly around the Odo Oro–Ikole axis, is characterized by darker cyan to bluish colours, reflecting comparatively lower potassium and thorium concentrations with relatively subdued uranium responses. These radiometric characteristics are consistent with the migmatitic rocks that dominate this part of the study area and suggest lower concentrations of radioactive minerals relative to the felsic granitoids. The reduced radiometric intensity may also reflect the combined effects of lithological composition and prolonged tropical weathering, which can modify the near-surface distribution of radioelements (Rahaman, 1988; Olade & Elueze, 1979). Distinct colour transitions and linear radiometric contrasts observed throughout the ternary image, particularly along the dominant E–W and ENE–WSW structural trends, define major lithological contacts and structurally controlled discontinuities within the basement complex. These structural features are interpreted as faults, fractures, and shear zones that have influenced fluid circulation and localized hydrothermal alteration. The pronounced pink to reddish colouration observed along the Itapaji–Bolorunduro corridor indicates potassium enrichment associated with hydrothermal metasomatism and coincides with the high potassium deviation anomalies identified earlier. The spatial coincidence of elevated K, Th, and U responses with favourable lithologies and major structural corridors suggests that this zone represents a highly prospective target for hydrothermal mineralization and future mineral exploration within the study area (Ilugbo *et al*., 2020; Faruwa *et al*., 2021; Ogah & Abubakar, 2024) (Fig. 9).

Trace elements geochemistry: The results of the factor analysis presented in Table 1 and Figure 10 reveal two statistically significant components that collectively explain 92.04% of the total geochemical variance within the study area. Component 1 has an eigenvalue 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 of 92.04% indicates that the two extracted components adequately explain the elemental associations and overall geochemical variability of the study area. According to the Kaiser criterion, only components with eigenvalues greater than one are considered statistically significant; therefore, both extracted components represent the principal geochemical processes controlling elemental distribution and mineralization within the basement terrain (Rollinson, 1993). Component 1 is interpreted as the lithological (geogenic) factor because it reflects the primary geochemical signature inherited from the crystalline basement rocks, whereas Component 2 represents the pathfinder factor, highlighting trace elements associated with hydrothermal alteration and metallic mineralization. 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 that these elements exhibit strong positive correlations and most likely originated from a common geochemical source. Their close association reflects the primary mineralogical composition of the crystalline basement rocks and the geochemical evolution of the host lithologies through magmatic differentiation and subsequent metamorphic processes (Taylor & McLennan, 1985; Rollinson, 1993). The enrichment of these elements may have been further enhanced by structurally controlled hydrothermal fluid circulation along fractures, shear zones, and lithological contacts, resulting in localized concentration of metallic elements within favourable structural zones. Similar trace element associations have been recognized as important indicators of geogenic controls and hydrothermal mineralization in crystalline basement environments (Govett, 1983; Talapatra, 2020). 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 observed for Component 1, their association suggests a secondary geochemical process related to hydrothermal alteration, accessory mineral concentration, and late-stage fluid–rock interaction. Component 2 is therefore interpreted as the pathfinder factor because arsenic is widely recognized as one of the most effective pathfinder elements in hydrothermal mineral exploration, while thorium commonly occurs within resistant accessory minerals such as monazite, zircon, and allanite. The presence of silver and lead further supports the influence of hydrothermal processes and localized metallic enrichment that may accompany structurally controlled mineralization (Rose *et al*., 1979; Govett, 1983; Chen *et al*., 2024). 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 communalities greater than 0.77, indicating that more than 77% of the variability of each element is explained by the two extracted components. These high values confirm that the factor solution adequately represents the original geochemical dataset and that only a small proportion of the elemental variability remains unexplained, demonstrating the reliability of the statistical model for interpreting trace element associations and mineralization controls (Rollinson, 1993). The graphical representation in Figure 10 strongly supports the numerical results presented in Table 1. The factor loading plot illustrates the clear dominance of Component 1 through consistently high positive loadings for Cu, Ni, Co, Fe, Zn, and Mn, while Component 2 is principally defined by As, Th, Ag, and Pb. The pronounced difference between the eigenvalues of Component 1 (8.034) and Component 2 (1.171) confirms that the lithological factor exerts the greatest influence on the geochemical dataset. Similarly, the uniformly high communality values demonstrate that the extracted components effectively account for the observed elemental variability. The substantial difference between the percentage variance explained by Component 1 (80.34%) and Component 2 (11.71%) further indicates that primary lithological composition constitutes the dominant control on trace element distribution, whereas the second component reflects subordinate hydrothermal processes responsible for localized elemental enrichment. Overall, the factor analysis demonstrates that the Cu–Ni–Co–Fe–Zn–Mn association is the dominant lithological factor controlling trace-element distribution within the Ikole–Itapaji Basement Complex. These elements primarily reflect the inherent geochemical characteristics of the crystalline basement rocks, with localized enrichment enhanced by structurally controlled hydrothermal fluid circulation. In contrast, the As–Th–Ag–Pb association represents a secondary pathfinder factor related to hydrothermal alteration, accessory mineral concentration, and mineralizing fluid activity. The cumulative variance of 92.04% confirms that the two-component model adequately explains the geochemical variability of the study area and provides a reliable framework for delineating prospective mineralization zones. When integrated with airborne radiometric anomalies, these geochemical associations provide compelling evidence that metallic mineralization within the study area is primarily controlled by the interaction among favourable lithologies, structural features, and hydrothermal processes. Consequently, the combined geochemical and radiometric datasets provide an effective exploration tool for identifying prospective targets for future mineral exploration within the Ikole–Itapaji Basement Complex (Rose *et al*., 1979; Govett, 1983; Rollinson, 1993; Talapatra, 2020). The correlation coefficient matrix (Table 2) and the corresponding chart (Figure 11) reveal significant relationships among the analysed trace elements, reflecting their geochemical behaviour and the processes controlling elemental distribution within the study area. 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 that these elements are closely associated and most likely originated from a common geogenic source. Their strong correlations suggest that they were controlled primarily by the mineralogical composition of the crystalline basement rocks and were subsequently influenced by structurally controlled hydrothermal remobilization. Such elemental associations are commonly regarded as indicators of favourable lithological environments and hydrothermal mineralization within Precambrian basement terrains (Govett, 1983; Rollinson, 1993; Talapatra, 2020).

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), indicating that it forms part of the same geochemical association. The affinity of Zn with these transition metals suggests that they were controlled by similar geological processes and may have been concentrated during the same mineralizing events. Such relationships commonly characterize hydrothermal systems in which structurally controlled fluid circulation promotes the redistribution and concentration of metallic elements within favourable host rocks (Rose *et al*., 1979; Govett, 1983). 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 correlation with Pb (r = 0.913) and Th (r = 0.829). This contrasting behaviour suggests that silver is controlled by a different geochemical process or mineral phase from the Cu–Ni–Co–Fe association. Similarly, Pb displays a strong positive correlation with Th (r = 0.891) and a moderate positive correlation with As (r = 0.500), indicating an association with felsic lithologies, accessory minerals, and late-stage hydrothermal fluid activity. Thorium commonly occurs within resistant accessory minerals such as zircon and monazite, whereas arsenic and lead are widely recognized as important pathfinder elements associated with hydrothermal mineralization (Rose *et al*., 1979; Odewumi & Olarewaju, 2013; Chen *et al*., 2024). Manganese and arsenic generally display weak to moderate correlations with most of the analysed elements, suggesting relatively independent geochemical behaviour and indicating that their distribution was influenced by localized geological conditions, secondary alteration, or separate hydrothermal episodes rather than by the dominant lithological controls. The relatively weak correlations further imply that these elements may have experienced differential mobility during weathering and hydrothermal alteration (Rollinson, 1993). The correlation chart presented in Figure 11 clearly illustrates the dominance of the strong positive relationships among Cu, Ni, Co, Fe, and Zn, while simultaneously highlighting the contrasting behaviour of Ag, Pb, and Th. These contrasting elemental relationships indicate the presence of at least two distinct geochemical associations within the study area. The first association, comprising Cu–Ni–Co–Fe–Zn, represents the principal lithological and mineralization suite inherited from the crystalline basement rocks and enhanced by structurally controlled hydrothermal processes. The second association, consisting primarily of Pb–Ag–Th with contributions from As, represents a secondary pathfinder suite related to hydrothermal alteration, accessory mineral enrichment, and late-stage mineralizing fluids. These geochemical associations provide valuable evidence for multiple stages of geochemical evolution and mineralization within the Ikole–Itapaji Basement Complex and, when integrated with the airborne radiometric anomalies, provide a robust framework for delineating prospective zones of metallic mineralization (Govett, 1983; Rollinson, 1993; Talapatra, 2020; Chen *et al*., 2024).

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	Th
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

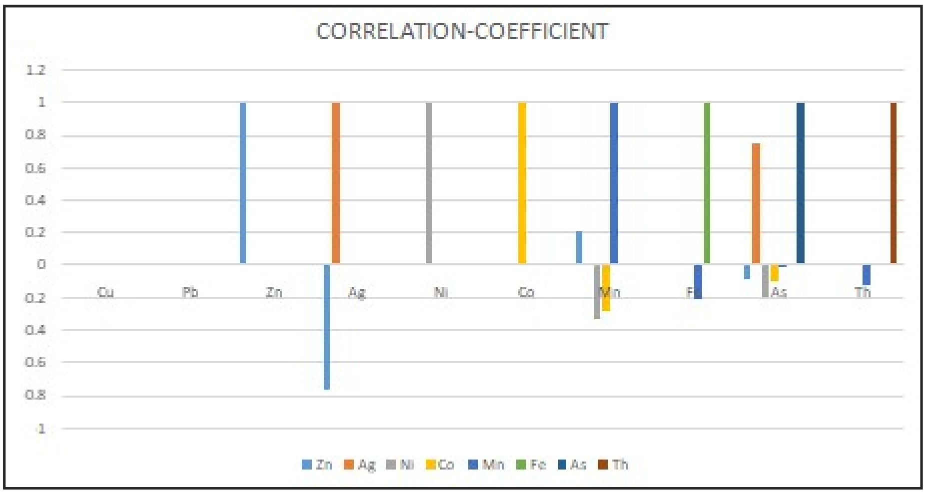

Figure 11.Correlation coefficient chart illustrating the strength and direction of relationships among the analyzed trace elements. The chart highlights positive and negative elemental associations that reflect common geochemical sources, mineral assemblages, and mineralization processes within the study area.

Integrated Interpretation of Trace Element Geochemistry and Airborne Radiometric Data: The integration of airborne radiometric data with trace element geochemistry provides a comprehensive framework for identifying favourable lithological units, hydrothermal alteration zones, and structurally controlled mineralization within the Ikole–Itapaji Basement Complex. While the radiometric data define the spatial distribution of radioelements and alteration patterns at the regional scale, the trace element geochemical data provide direct evidence of elemental enrichment and the geochemical processes associated with mineralization. The combined interpretation therefore reduces the uncertainty associated with using either dataset independently and significantly improves the delineation of prospective mineralized zones (Rose *et al*., 1979; Govett, 1983; Ogah & Abubakar, 2024). The potassium, thorium, uranium, potassium deviation, and ternary radiometric maps consistently identify the central and northern parts of the study area, particularly the Itapaji–Bolorunduro corridor, as zones characterized by elevated radioelement concentrations. The coincidence of high potassium and potassium deviation anomalies with elevated thorium and uranium responses indicates the presence of felsic lithologies that have experienced varying degrees of hydrothermal alteration. Potassium enrichment within these areas is interpreted to result from hydrothermal metasomatism associated with structurally controlled fluid circulation, whereas the relatively immobile behaviour of thorium preserves the primary lithological signature of the host rocks. The uranium anomalies further suggest the influence of late-stage hydrothermal fluids migrating through fractures and shear zones, thereby identifying favourable pathways for metallic mineralization (NGSA, 2006; Akinlalu *et al*., 2018; Ogah & Abubakar, 2024). The trace element geochemical data complement these radiometric observations by identifying coherent elemental associations related to mineralization. Factor analysis demonstrates that the Cu–Ni–Co–Fe–Zn association constitutes the dominant lithological factor, reflecting the primary geochemical characteristics of the crystalline basement rocks with localized enrichment through hydrothermal remobilization. In contrast, the As–Th–Ag–Pb association represents a secondary pathfinder suite indicative of hydrothermal alteration and mineralizing fluid activity. Similarly, the correlation coefficient matrix reveals strong positive relationships among Cu, Ni, Co, Fe, and Zn, confirming that these elements were controlled by similar geological processes and may have been concentrated during the same mineralizing events. The contrasting behaviour of Ag, Pb, As, and Th further supports the existence of secondary hydrothermal processes superimposed upon the primary lithological framework

(Rollinson, 1993; Talapatra, 2020; Chen *et al*., 2024). Based on the integrated interpretation, the Itapaji–Bolorunduro corridor constitutes the most prospective mineralization zone within the study area. This corridor is characterized by the coincidence of high potassium deviation values, elevated potassium, thorium, and uranium concentrations, strong ternary radiometric responses, favourable lithological units dominated by granite gneiss and granitic rocks, major structural lineaments, and significant enrichment of economically important trace elements including Cu, Ni, Co, Zn, Fe, As, and Pb. The convergence of these independent geological, geochemical, and radiometric indicators provides compelling evidence that the area has undergone prolonged magmatic evolution followed by structurally controlled hydrothermal alteration capable of concentrating metallic minerals.

Overall, the integrated interpretation demonstrates that airborne radiometric data and trace element geochemistry are highly complementary exploration techniques for crystalline basement terrains. Radiometric data effectively delineate lithological variations, structural features, and hydrothermal alteration patterns, whereas trace element geochemistry confirms elemental enrichment and identifies pathfinder associations directly related to mineralization. Their integration significantly enhances exploration confidence and provides a reliable basis for prioritizing exploration targets. Consequently, the Itapaji–Bolorunduro structural corridor is interpreted as the principal exploration target within the Ikole–Itapaji Basement Complex and warrants detailed follow-up investigations involving detailed geological mapping, ground geophysical surveys, trenching, and drilling to evaluate its economic mineral potential (Rose *et al*., 1979; Govett, 1983; Rollinson, 1993; Talapatra, 2020; Ogah & Abubakar, 2024).

Study limitations: Although the integration of airborne radiometric data and trace element geochemistry provided valuable insights into the delineation of mineralization zones within the Ikole–Itapaji Basement Complex, several limitations should be acknowledged. The airborne radiometric data represent surface and near-surface radioelement distributions and are therefore influenced by factors such as weathering, regolith thickness, vegetation cover, and soil moisture, which may attenuate or modify the measured gamma-ray responses (NGSA, 2006; Ogah & Abubakar, 2024). Consequently, radiometric anomalies may not always directly reflect the composition of the underlying bedrock. The trace element interpretation was based on twenty representative whole-rock samples selected to adequately cover the major lithological units within the study area. Although these samples captured the principal lithological and geochemical variability, a higher sampling density could provide improved spatial resolution and enhance the delineation of localized mineralized zones, particularly within structurally complex areas. Furthermore, the mineralization zones identified in this study were interpreted from integrated geochemical and airborne radiometric datasets without direct subsurface verification through trenching, drilling, or detailed mineralogical investigations. As a result, the delineated targets should be regarded as prospective zones requiring further validation through detailed geological mapping, ground geophysical surveys, petrographic and mineralogical analyses, and exploratory drilling. Despite these limitations, the integration of trace element geochemistry with airborne radiometric data provides a robust and reliable approach for regional mineral exploration. The consistency between the geochemical signatures, radiometric anomalies, lithological distribution, and structural framework increases confidence in the identified prospective mineralization zones and provides a sound basis for future exploration within the Ikole–Itapaji area.

CONCLUSION

This study integrated trace element geochemistry and airborne radiometric data to delineate prospective mineralization zones within the crystalline basement rocks of the Ikole–Itapaji area, Southwestern Nigeria. The integrated approach proved effective in characterizing lithological variations, identifying hydrothermal alteration zones, and establishing the structural controls on metallic mineralization. The radiometric datasets comprising potassium (K), thorium (Th), uranium (U), potassium deviation (KD), and ternary RGB images successfully discriminated the major lithological units and highlighted zones of radioelement enrichment associated with felsic rocks and hydrothermal alteration. High potassium deviation values, together with elevated K, Th, and U concentrations, were concentrated predominantly within the central and northern parts of the study area, particularly along the Itapaji–Bolorunduro corridor, indicating favourable conditions for hydrothermal mineralization. Trace element geochemistry further complemented the radiometric interpretation by revealing significant elemental associations related to mineralization. Factor analysis extracted two statistically significant components that explained 92.04% of the total geochemical variance. The first component, represented by the Cu–Ni–Co–Fe–Zn association, reflects the dominant lithological (geogenic) control inherited from the crystalline basement rocks and locally enhanced by hydrothermal remobilization. The second component, characterized by As–Th–Ag–Pb, represents a pathfinder association indicative of hydrothermal alteration and late-stage mineralizing fluid activity. Correlation analysis supported these interpretations by demonstrating strong positive relationships among Cu, Ni, Co, Fe, and Zn, while Ag, Pb, and Th formed a distinct secondary association related to hydrothermal processes. The integration of trace element geochemistry with airborne radiometric data demonstrated a strong spatial correspondence between radioelement anomalies, favourable lithological units, and trace element enrichment. The coincidence of elevated potassium deviation anomalies, strong ternary radiometric responses, favourable trace element associations zone identifies the Itapaji–Bolorunduro axis as the most prospective mineralization zone within the study area. Overall, the study demonstrates that the integration of airborne radiometric data and trace element geochemistry provides a robust and reliable exploration strategy for crystalline basement terrains. The complementary nature of both datasets significantly improves confidence in delineating hydrothermal alteration zones and identifying prospective targets for metallic mineralization. The results provide an important geoscientific framework for future mineral exploration within the Ikole–Itapaji Basement Complex and recommend detailed follow-up investigations involving ground geophysical surveys, detailed geochemical sampling, mineralogical studies, trenching, and exploratory drilling to evaluate the economic potential of the identified targets

Recommendations

Based on the findings of this study, the following recommendations are proposed

- The Itapaji–Bolorunduro corridor, identified by the coincidence of elevated potassium deviation anomalies, high K–Th–U concentrations, favourable trace element associations, and major structural lineaments, should be prioritized for detailed mineral exploration due to its high metallic mineralization potential.
- Detailed ground geophysical investigations, including induced polarization (IP), electrical resistivity tomography (ERT), electromagnetic (EM), and high-resolution ground magnetic surveys, should be conducted to validate the airborne radiometric anomalies and improve the delineation of subsurface mineralized structures.
- A denser geochemical sampling programme involving rocks, soils, stream sediments, and trench samples should be undertaken to refine the spatial distribution of economically important trace elements and better define geochemical dispersion patterns within the identified prospective zones.
- Detailed petrographic, mineralogical, and ore microscopic investigations, complemented by scanning electron microscopy (SEM), electron probe microanalysis (EPMA), or laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), are recommended to determine the mineral hosts of the trace elements and to better understand the mineralization processes and paragenetic relationships.
- Exploratory trenching and diamond drilling should be carried out across the identified mineralization corridors to verify the continuity, thickness, depth extent, and economic significance of the interpreted hydrothermal mineralized zones.
- Future investigations should integrate additional exploration datasets, including airborne magnetic, gravity, remote sensing, and structural geological data, with trace element geochemistry and radiometric information to develop a more comprehensive mineral prospectivity model for the Ikole–Itapaji Basement Complex.
- The integrated exploration approach adopted in this study should be extended to adjacent parts of the Nigerian Basement Complex with similar geological settings to improve regional mineral resource assessment and support sustainable mineral exploration programmes within Southwestern Nigeria.
- The implementation of these recommendations will improve the understanding of the mineralization system within the study area, reduce exploration uncertainty, and facilitate the identification and evaluation of economically viable metallic mineral deposits.

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 authors used ChatGPT (GPT-5-mini) to assist with language editing and content organization. After using this tool, the authors reviewed, revised, and verified all content to ensure accuracy, originality, and authenticity, and take 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.

Authors' Contributions

Adeleke Ojo conceived and designed the study, carried out the geological field investigations and rock sample collection, processed and interpreted the airborne radiometric datasets, conducted the trace element geochemical analyses and statistical interpretation, prepared the figures and tables, and drafted the manuscript. Akinola Oluwatoyin supervised the research, provided methodological guidance, contributed to the interpretation of the radiometric and trace element geochemical results, critically reviewed the manuscript for important intellectual content, and approved the final version of the manuscript. Both authors read and approved the final manuscript.

REFERENCES

Adetunla, F. R., Ayodele, O. S., Asowata, I. T., & Olususi, J. (2025). Integrated geological, aeromagnetic, and remote sensing datasets in litho-structural mapping of basement rocks in southwestern Nigeria. *Asian Journal of Geological Research, 8*(3), 523–553. https://doi.org/10.9734/ajoger/2025/v8i3213

Ajakaiye, D. E., Hall, D. H., & Millar, T. W. (1985). Interpretation of aeromagnetic data across the central crystalline shield area of Nigeria. *Geophysical Journal International, 83*(2), 503–517. https://doi.org/10.1111/j.1365-246X.1985.tb06500.x

Ajibade, A. C., & Fitches, W. R. (1988). The Nigerian Precambrian and the Pan-African Orogeny. In *Precambrian Geology of Nigeria* (pp. 45–53). Geological Survey of Nigeria.

Ajibade, A. C., & Wright, J. B. (1989). The Togo-Benin-Nigeria Shield: Evidence of crustal aggregation in the Pan-African Belt. *Tectonophysics, 165*, 125–129. https://doi.org/10.1016/0040-1951(89)90041-3

Ajibade, A. C., Woakes, M., & Rahaman, M. A. (1987). Proterozoic crustal development in the Pan-African regime of Nigeria. In A. Kröner (Ed.), *Proterozoic Lithospheric Evolution* (Geodynamics Series, Vol. 17, pp. 259–271). Washington, DC: American Geophysical Union. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/GD017p0259

Ajigo, I. O., Odeyemi, I. B., & Ademeso, O. A. (2021). Field geology and structures of migmatitic gneisses around Ibillo–Okene Area, Southwestern Nigeria. *Journal of Environment and Earth Science*. https://www.iiste.org/Journals/index.php/JEES/article/view/46465

Akinlalu, A. A., Adelusi, A. O., Olayanju, G. M., Adiat, K. A. N., Omosuyi, G. O., Anifowose, A. Y. B., & Akeredolu, B. E. (2018). Aeromagnetic mapping of basement structures and mineralization characterisation of Ilesa Schist Belt, Southwestern Nigeria. *Journal of African Earth Sciences, 138*, 383–391. https://doi.org/10.1016/j.jafrearsci.2017.11.033

Alagbe, O. A., & Amosun, J. O. (2021). Application of geophysical and remote sensing techniques to delineate lateritic bauxite deposit zone in Orin Ekiti, Nigeria. *International Journal of Geology and Mining, 7*(1), 337–357. https://www.scribd.com/document/497698402/

Amosun, J. O., & Alagbe, O. A. (2020). Imaging lateritic bauxite-bearing zones in Ekiti, Southwestern Nigeria using magnetic and electrical resistivity tomography techniques. *SN Applied Sciences*. https://www.researchgate.net/publication/346089898

Anudu, G. K., Stephenson, R. A., & Macdonald, D. I. M. (2014). Using high-resolution aeromagnetic data to identify intra-sedimentary structures in the Middle Benue Trough, Nigeria. *Journal of African Earth Sciences, 99*, 625–636. https://doi.org/10.1016/j.jafrearsci.2014.02.017

Bamigboye, O. S., Bamidele, T. E., Adedoyin, A. D., Issa, T. A., & Omorinoye, O. A. (2022). Shear sense analyses of basement rocks in parts of Southwestern Nigeria. *International Journal of Earth Sciences Knowledge and Applications*. https://www.ijeska.com/index.php/ijeska/article/view/151

Blakely, R. J. (1995). *Potential theory in gravity and magnetic applications*. Cambridge University Press. https://www.cambridge.org/core/books/potential-theory-in-gravity-and-magnetic-applications/348880F23008E16E663D6AD14A41D8DE

Chen, Y., Li, H., Halassane, N., Ghaderi, M., Gu, S., Wang, Y., & Li, D. D. (2024). Pyrite geochemistry controlling large gold deposit formation in the Jiaodong Peninsula. *Ore Geology Reviews, 165*, Article 105934. https://doi.org/10.1016/j.oregeorev.2024.105934

Faruwa, A. R., Qian, W., Akinsunmade, A., Akingboye, S. A., & Dusabemariya, C. (2021). Aeromagnetic and remote sensing characterization of structural elements influencing iron ore deposits in Kabba, Southwestern Nigeria. *Advances in Space Research, 68*(8), 3302–3313. https://doi.org/10.1016/j.asr.2021.06.024

Frost, B. R., Barnes, C. G., Collins, W. J., Arculus, R. J., Ellis, D. J., & Frost, C. D. (2001). A geochemical classification for granitic rocks. *Journal of Petrology, 42*(11), 2033–2048. https://openresearch-repository.anu.edu.au/handle/1885/93167

Govett, G. J. S. (1983). Rock geochemistry in mineral exploration. In *Handbook of Exploration Geochemistry* (Vol. 3). Elsevier Scientific Publishing. https://api.pageplace.de/preview/DT0400.9781483289700_A23884968

Ilugbo, S. O., Edunjobi, H. O., Adewoye, O. E., Alabi, T. O., Aladeboyeje, A. I., Olutomilola, O. O., & Owolabi, D. T. (2020). Structural analysis using integrated aeromagnetic data and Landsat imagery in a basement complex terrain, Southwestern Nigeria. *Asian Journal of Geological Research, 3*(2), 78–94. https://journalajoger.com/index.php/AJOGER/article/view/105

Lukman, L. M., Najime, T., Ogunleye, P. O., Magaji, S., & Caleb, N. K. (2024). Geology and geochemical characterization of basement rocks around Burumburum Area, Nigeria. *Earth Sciences, 13*(1), 14–38. https://doi.org/10.11648/j.earth.20241301.13

Macmillan, S., & Maus, S. (2005). International Geomagnetic Reference Field—the tenth generation. *Earth, Planets and Space, 57*(12), 1135–1140. https://doi.org/10.1186/BF03351896

Nigerian Geological Survey Agency. (2006). *Geophysical mapping of Nigeria: Airborne radiometric and magnetic survey data*. Nigerian Geological Survey Agency. https://ngsa.gov.ng

Odewumi, S. C., & Olarewaju, V. O. (2013). Petrogenesis and geotectonic setting of granitic rocks in the Idofin–Osi–Eruku area, Southwestern Nigeria. *Journal of Geology & Geosciences, 2*(1), 1–9. https://doi.org/10.4172/2329-6755.1000109

Ogah, A. J., & Abubakar, F. (2024). Solid mineral potential evaluation using integrated aeromagnetic and aeroradiometric datasets. *Scientific Reports, 14*, Article 1637. https://doi.org/10.1038/s41598-024-52270-6

Ojo, O. F., Osazuwa, B. I., Chiemeke, C. C., Osumeje, O. J., Oyedele, A. A., Adagunodo, T. A., Oyeyemi, K. D., & Ejiga, E. G. (2024). Classification of the basement complex using aeromagnetic and remote sensing data analyses: Case study of Ekiti State, southwestern Nigeria. *Earth Sciences Malaysia, 8*(2), 158–162. https://doi.org/10.26480/esmy.02.2024.158.162

Olade, M. A. (2020). *Mineral deposits and exploration potential of Nigeria*. Elsevier. https://books.google.com/books?id=vjj1DwAAQBA

Olade, M. A., & Elueze, A. A. (1979). Petrochemistry of the Ilesha amphibolites and Precambrian crustal evolution in the Pan-African domain of southwestern Nigeria. *Precambrian Research, 8*(3–4), 303–318. https://doi.org/10.1016/0301-9268(79)90033-0

Omosanya, K. O., Ariyo, S. O., Kaigama, U., Mosuro, G. O., & Laniyan, T. A. (2015). Polycyclic orogenies in the Basement Complex of Southwestern Nigeria: Outcrop evidence. *Journal of Geography and Geology, 7*(3), 24–34. https://doi.org/10.5539/jgg.v7n3p24

Oyinloye, A. O. (2011).*Geology and geotectonic setting of the basement complex rocks in Southwestern Nigeria: Implications on provenance and evolution.*https://doi.org/10.5772/26990

Rahaman, M. A. (1988). Recent advances in the study of the Basement Complex of Nigeria. In *Precambrian Geology of Nigeria* (pp. 11–43). Geological Survey of Nigeria. https://www.sciepub.com/reference/318092

Rollinson, H. R. (1993). *Using geochemical data: Evaluation, presentation, interpretation*. Longman Scientific & Technical. https://books.google.com/books?id=L44sY6RX8_cC

Rollinson, H. R., & Pease, V. (2021). *Using Geochemical Data: To Understand Geological Processes* (2nd ed.). Cambridge: Cambridge University Press. https://doi.org/10.1017/9781108777834

Official Publisher: https://www.cambridge.org/core/books/using-geochemical-data/426537667EEB68205371A28DF9B2FFD5

Rose, A. W., Hawkes, H. E., & Webb, J. S. (1979). *Geochemistry in mineral exploration* (2nd ed.). Academic Press. https://openlibrary.org/books/OL33090211M

Salako, K. A., Adetona, A. A., Rafiu, A. A., Augie, A. I., Jimoh, M. O., Alkali, A., Muriana, R. A., & Lawrence, J. O. (2024). Integrated geophysical investigation for gold mineralization potential over the southern parts of Kebbi State, northwestern Nigeria. *Heliyon, 10*(14), e34093. https://doi.org/10.1016/j.heliyon.2024.e34093

Senda, R., Kimura, J.-I., & Chang, Q. (2014). Rapid sample digestion for trace element analysis of granitoids with acid-resistant minerals. *Geochemical Journal, 48*(1), 99–103. https://www.jstage.jst.go.jp/article/geochemj/48/1/48_2.0280

Talabi, A. O., Oyinloye, A. O., Olaolorun, O. A., Obasi, R. A., Eluwole, A. B., Adebayo, O. F., & Ademilua, O. L. (2018). Petrography and geochemistry of Orin-Ekiti basement rocks, Southwestern Nigeria: Implications on bauxitization. *American Journal of Applied Sciences, 15*(4), 230–239. https://doi.org/10.3844/ajassp.2018.230.239

Talapatra, A. K. (2020). *Geochemical exploration and modelling of concealed mineral deposits*. Springer. https://link.springer.com/book/10.1007/978-3-030-48756-0

Taylor, S. R., & McLennan, S. M. (1985). *The continental crust: Its composition and evolution*. Blackwell Scientific Publications. https://commons.library.stonybrook.edu/geo-articles/12/

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