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Integrated bedrock and stream sediment geochemistry with multivariate analysis for mineral exploration in the Okemesi–Ijero Basement Complex, southwestern Nigeria

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Abstract

Integrated geological mapping, bedrock and stream sediment geochemistry, and multivariate statistical analysis were applied to evaluate the mineralization potential of the Okemesi–Ijero area within the Precambrian Basement Complex of southwestern Nigeria. Detailed field mapping identified a polydeformed assemblage comprising quartzites of the Effon Psammite Formation, schists, migmatite–gneiss complexes, granitoids, pegmatites, calc-gneiss, and charnockites, reflecting a complex tectono-magmatic history. A total of 85 bedrock samples and 70 stream sediment samples were collected and analyzed for major and trace elements using inductively coupled plasma techniques following four-acid digestion and lithium borate fusion. Geochemical results show marked spatial variation in elemental concentrations across different lithologies and drainage systems. Granitic and pegmatitic rocks are enriched in lithophile and rare-metal-related elements, whereas polymetallic associations involving Cu, Pb, Zn, Mn, and Sn characterize granitoid and structurally disturbed zones. Stream sediment geochemistry effectively integrates upstream bedrock signatures, highlighting drainages influenced by granitic and pegmatitic sources and areas of elevated base-metal concentrations. Multivariate statistical analyses, including factor analysis, principal component analysis, and hierarchical cluster analysis, successfully discriminate background geochemical signatures from anomalous elemental populations and elucidate elemental associations related to lithology, magmatism, and secondary dispersion processes. The combined geological, geochemical, and statistical evidence indicates that the Okemesi–Ijero area is prospective for base-metal and rare-metal mineralization, particularly within granitic and pegmatitic domains and structurally favorable zones. This study demonstrates the effectiveness of integrating multivariate statistical techniques with conventional geological and geochemical methods for mineral exploration in complex basement terrains and provides a transferable framework for regional exploration targeting.

1. Introduction

Bedrock and stream sediment geochemistry constitute fundamental tools in mineral exploration, as they represent primary and secondary repositories of elemental signatures derived from source rocks (Doherty et al., 2023; Balaram, & Sawant, 2022). Unweathered bedrocks provide direct information on primary mineralization processes, while stream sediments integrate geochemical

signals from upstream lithologies and weathering products, making them particularly effective for regional exploration targeting metallic, industrial, and gemstone resources. In tropical environments, stream sediments often inherit their geochemical characteristics from intensely weathered bedrocks and soils, which may contain both residual primary minerals and newly formed secondary phases (Ngatcha et al., 2025).

The interpretation of large, multivariate geochemical datasets requires robust statistical approaches to distinguish meaningful geochemical patterns from background variability. Multivariate statistical techniques have therefore become indispensable in modern mineral exploration, enabling the identification of elemental associations, lithological controls, and geochemical anomalies linked to mineralization (Mikšová, 2020). Applications of multivariate statistics in geochemical exploration have been widely reported, including the delineation of ore-related elemental populations, discrimination of lithological units, and optimization of exploration strategies. For example, geostatistical and multivariate analyses have been successfully applied to gold exploration in the Ashanti Belt, Ghana, and to trace-element discrimination of native gold from orogenic deposits (Nude et al., 2012; Umar et al., 2017), where elemental signatures reflect fluid–rock interaction along hydrothermal pathways. Similar approaches have also proven effective in complex geological environments, including arid and deeply weathered terrains (Sun et al., 2021).

In southwestern Nigeria, the Precambrian Basement Complex hosts numerous schist belts and granitoid intrusions that are known to be prospective for base metals, rare metals, and precious mineralization. However, many areas within this basement terrain remain underexplored using integrated geochemical and statistical methods. The Okemesi–Ijero area, located within the Dahomeyide Fold Belt and adjacent to the Ifewara shear zone, is characterized by diverse lithologies including quartzites, schists, gneisses, granites, pegmatites, and charnockites (Ayodele et al., 2019). These rocks have undergone multiple deformation and metamorphic events, creating favorable structural and lithological conditions for mineral concentration and redistribution (Bamisaiye & Ajala, 2021**)**.

Despite this geological complexity and prospectivity, systematic multivariate evaluation of bedrock and stream sediment geochemical data in the Okemesi–Ijero area has been limited. This study therefore applies multivariate statistical techniques to trace-element geochemical data obtained from bedrocks and stream sediments in the area, with the aim of identifying elemental associations, lithological controls, and potential mineralization signatures. By integrating geological mapping with advanced statistical analysis, this work seeks to assess the metallic and base-metal potential of the Okemesi–Ijero area and to demonstrate the effectiveness of computer-based multivariate methods in mineral exploration within crystalline basement terrains.

2. Geological setting

The Okemesi–Ijero area is located in southwestern Nigeria, between latitudes 7°45′–8°00′N and longitudes 4°52′–5°08′E, spanning parts of Ekiti and Osun States. The area includes the towns of Okemesi and Ijero-Ekiti and is accessible through a network of seasonal roads and motorable tracks that connect it to surrounding settlements. The region lies within the Precambrian Basement Complex of Nigeria and forms part of the eastern segment of the Dahomeyide Fold Belt (Bamisaiye, & Ajala, 2021**)**.

2.1 Physiography and Drainage

The terrain of the Okemesi–Ijero area is characterized by a combination of rugged highlands, low-lying plains, and isolated hills, reflecting strong lithological and structural controls. Elevations locally exceed 250 m above sea level, with prominent ridges and undulating topography developed over resistant lithologies such as quartzites, gneisses, and pegmatitic intrusions. Schist-dominated areas generally form low-relief plains as a result of enhanced weathering (Fig.1).

A prominent northwest–southeast-trending ridge associated with the Effon Psammite Formation dominates the eastern part of the area and represents a major structural and geomorphic feature that delineates the Okemesi fold belt (Oyinloye, 2011**)**. This ridge system extends through several localities and includes deeply incised gorges and steep slopes, reflecting differential erosion along structurally controlled zones.

Drainage in the area is largely dendritic, although trellis patterns occur locally where stream courses are structurally guided by foliation, fractures, and joints. Major rivers include the Osun, Oyi, Isa, and several tributaries that drain southward. The distribution and orientation of streams are influenced by topographic gradients, lithology, climatic conditions, and structural elements such as shear zones, joints, and foliations.

2.2 Regional and local geology

Geologically, the study area is underlain by crystalline basement rocks that have experienced multiple episodes of deformation, metamorphism, and magmatic intrusion (Fig. 2). These rocks form part of the Nigerian Basement Complex and represent an extension of the Dahomeyide orogenic system. Earlier primary structures have largely been obliterated by polyphase deformation, although relict features are locally preserved (Adetunji et al., 2020).

The Ifewara fracture zone, a major transcurrent shear system in southwestern Nigeria, plays a significant tectonic role in the region. This structure separates lithologically distinct units within the Ilesha schist belt and has been interpreted as a major crustal discontinuity associated with Pan-African tectonism. Previous studies have linked this zone to large-scale tectonic transport, back-arc basin development, and nappe emplacement, highlighting its importance in crustal evolution and mineralization.

The dominant lithology in the Okemesi–Ijero area is the Effon Psammite Formation, which consists mainly of massive and schistose quartzites and quartz schists. This formation extends over a length of approximately 180 km in a general NNE–SSW direction and represents one of the most extensive quartzite belts in southwestern Nigeria. The quartzites are interbanded with schists and migmatite–gneiss complexes, reflecting intense deformation and metamorphism.

Other rock units in the area include banded gneiss, biotite gneiss, granite gneiss, calc-gneiss, porphyritic granites, pegmatites, charnockites, mica schists, and minor quartzites. Granitic and pegmatitic bodies occur as plutons and dykes intruding the metasedimentary units, while calc-gneisses occur as localized intrusions within the migmatite and quartzite assemblages. These lithological units display well-defined contacts and variable structural orientations, including folding, shearing, and foliation.

Geological mapping reveals that the metasedimentary and migmatitic units are commonly interbanded, whereas granitoids, pegmatites, and charnockites occupy discrete domains. Structural analysis indicates the presence of folding, particularly within schistose quartzites, with antiform structures being locally developed. The complex interplay between lithology, structure, and magmatism provides favorable conditions for elemental redistribution and mineral concentration within the area.

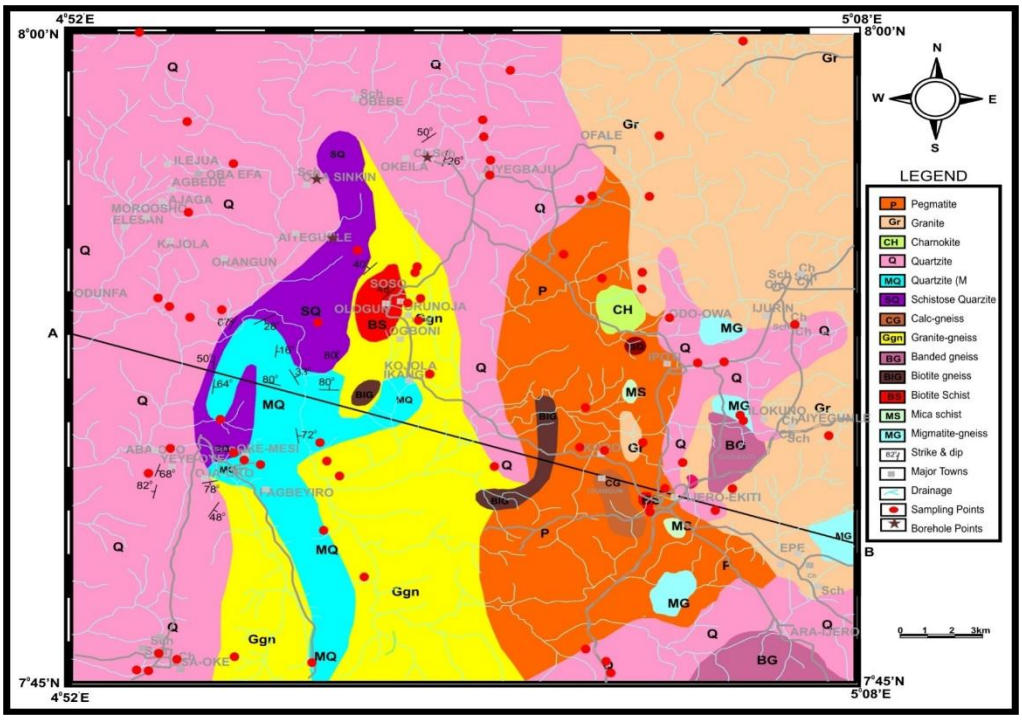


Figure 1: Geologic map of study area showing drainage system and stream sediment sampling points (After Ayodele, 2015)

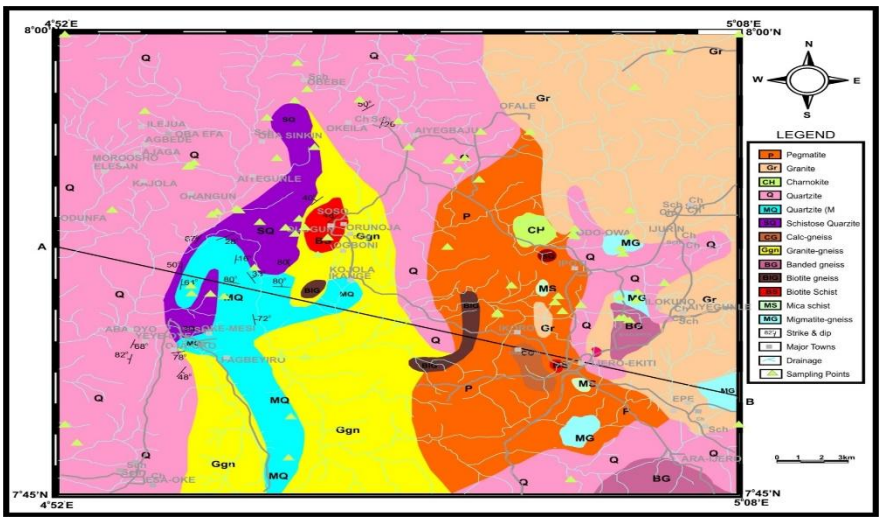


Figure 2: Geologic map showing lithologic units and bed rock sampling points (After Ayodele, 2015)

3. Materials and Methods

3.1 Geological mapping and sampling

Geological mapping of the Okemesi–Ijero area was carried out at a scale of 1:50,000 to delineate lithological units, structural features, and sample locations. Field observations focused on lithology, outcrop relationships, and structural elements including foliation, folds, joints, and fractures. Geographic coordinates of all sampling sites were recorded using a handheld GPS.

A total of 85 bedrock samples were collected from fresh or minimally weathered outcrops to represent the major lithological units. In addition, 70 stream sediment samples were collected from active stream channels at depths of 20–25 cm, targeting sites downstream of tributary confluences to ensure representative upstream geochemical signatures.

3.2 Sample preparation and geochemical analysis

Rock samples were crushed and pulverized using agate equipment to minimize contamination. Stream sediment samples were air-dried, sieved to obtain the <150 μm fraction, and pulverized prior to analysis. All samples were prepared following standard geochemical protocols.

Geochemical analyses were performed using inductively coupled plasma–mass spectrometry (ICP-MS) and inductively coupled plasma–atomic emission spectrometry (ICP-AES). A four-acid digestion (HCl–HNO_3–$HClO_4$–HF) was applied to both rock and sediment samples to achieve near-total dissolution suitable for exploration-scale studies. Selected rock samples were additionally analyzed using lithium borate fusion to ensure complete digestion of refractory phases. Analytical quality control followed laboratory standard procedures.

3.3 Statistical and multivariate analysis

Geochemical datasets were subjected to multivariate statistical analysis using IBM SPSS software. Prior to analysis, data were standardized to eliminate scale effects. Descriptive statistics were computed to characterize elemental distributions.

Factor analysis with varimax rotation was applied to correlation matrices to identify elemental associations, retaining factors with eigenvalues greater than one. Elements with factor loadings ≥0.40 were considered significant. Hierarchical cluster analysis was performed using Ward's linkage method and squared Euclidean distance to classify geochemical populations. Threshold and anomalous concentrations were defined using box plot statistics based on interquartile ranges.

Geochemical distribution maps and visualizations were generated using Surfer and RockWorks software following conversion of geographic coordinates to the Universal Transverse Mercator (UTM) system.

4. Results

4.1 Geological Mapping Results

Geological mapping of the Okemesi–Ijero area identified ten major lithological units (Table 1). These include massive and schistose quartzites of the Effon Psammite Formation, mica schists, migmatite–gneiss complexes, banded gneiss, biotite gneiss, granite gneiss, porphyritic granites, pegmatites, calc-gneiss, and charnockites. Quartzites constitute the dominant lithology and form extensive north–south to NNE–SSW-trending ridges across the study area. Schistose and migmatitic units occur as interbands within the quartzite sequence, while granitoid and charnockitic bodies occur as discrete intrusive units with well-defined contacts.

Structural measurements indicate the widespread presence of foliation, folding, joints, and fractures. Foliation is most prominent within schistose quartzites and schists, while folding is locally developed, including antiform structures. Granitic and pegmatitic intrusions truncate pre-existing structural fabrics in several locations.

4.2 Statistical characteristics of geochemical data

Descriptive statistical analysis (Tables 2 and 3) shows that elemental concentrations vary widely across both bedrock and stream sediment datasets. Tests of equality (Fig. 3) of group means indicate no statistically significant differences among sampling locations, whereas statistically significant differences exist among elemental concentrations. Q–Q plots (Figs. 4-7) indicate that most elemental datasets approximate normal distributions, while sample distributions display localized heterogeneity.

Discriminant analysis produced high classification accuracy for elemental datasets, indicating consistent grouping based on elemental concentration patterns. These statistical characteristics formed the basis for subsequent multivariate analyses.

Table 1. Summary of lithological units and field characteristics of the Okemesi–Ijero area

Lithological unit	Dominant mineralogy	Texture / fabric	Field characteristics	Structural features / occurrence
Effon Psammite (Quartzite)	Quartz ± muscovite ± biotite	Massive to schistose; medium- to coarse-grained	Forms prominent ridges and steep escarpments; resistant to weathering; locally interbanded with schist	Well-developed foliation; locally folded; antiform structures common
Mica schist	Quartz, muscovite, biotite ± garnet	Fine- to medium-grained; strongly schistose	Occurs as low-lying plains and interbands within quartzite; highly weathered	Strong foliation; crenulation cleavage locally developed
Migmatite–gneiss complex	Quartz, feldspar, biotite ± hornblende	Banded to nebulitic; medium- to coarse-grained	Widely distributed basement unit; alternating leucocratic and melanocratic bands	Gneissic banding; folded and locally sheared
Banded gneiss	Quartz, plagioclase, biotite ± hornblende	Well-banded; medium-grained	Distinct compositional layering; moderately resistant outcrops	Gneissic foliation; tight to open folds
Biotite gneiss	Quartz, feldspar, biotite	Medium- to coarse-grained; weakly banded	Occurs as discrete bodies within migmatite and quartzite terrains	Weak foliation; locally fractured
Granite gneiss	Quartz, K-feldspar, plagioclase, biotite	Medium- to coarse-grained; foliated	Transitional between gneiss and granite; exposed as low ridges	Foliation defined by biotite alignment
Porphyritic granite	K-feldspar phenocrysts, quartz, plagioclase, biotite	Porphyritic; coarse-grained	Occurs as intrusive plutons; sharp contacts with country rocks	Cuts foliation; joints and fractures common
Pegmatite	Quartz, K-feldspar, muscovite ± lepidolite	Very coarse-grained	Occurs as dykes and veins; locally mineralized	Discordant to foliation; structurally controlled emplacement

Calc-gneiss	Calcite, quartz, plagioclase ± diopside	Medium-grained; weakly foliated	Localized bodies within migmatite and quartzite units	Weak foliation; conformable contacts
Charnockite	Quartz, feldspar, orthopyroxene ± biotite	Medium- to coarse-grained; massive	Occurs as isolated intrusive bodies; dark greenish appearance	Massive to weakly foliated; sharp intrusive contacts

Table 2. Descriptive statistics of trace-element concentrations in bedrock samples (ppm)

Element	Minimum	Maximum	Mean	Median	Standard deviation
Mo	0.05	1.95	0.52	0.45	0.32
Cu	0.02	14.73	2.25	0.94	3.49
Pb	0.02	69.38	16.47	6.43	18.71
Zn	0.20	142.30	26.51	15.05	32.22
Ag	20.00	203.00	48.60	34.00	46.52
Ni	0.10	55.70	5.44	1.30	10.61
Co	0.20	125.60	39.68	33.30	22.11
Mn	2.00	651.00	174.77	84.00	205.78
Fe	0.02	3.29	0.93	0.48	1.10
As	0.20	4.20	1.01	0.95	0.86
U	0.10	15.20	2.17	0.90	2.98
Au	0.10	0.10	0.10	0.10	—
Th	0.10	30.80	7.47	3.40	9.04
Sr	1.00	793.00	121.11	25.00	187.01
Cd	0.02	0.24	0.06	0.05	0.05
Sb	0.02	5.90	0.29	0.05	0.98
Bi	0.04	1.30	0.17	0.11	0.26

V	1.00	63.00	14.87	5.00	18.34
Cr	1.00	54.00	12.68	9.00	15.02
Ba	1.00	1783.00	426.46	90.00	539.45
Ti	0.001	0.385	0.10	0.03	0.12
W	0.10	198.40	138.54	155.70	59.40
Zr	0.20	97.60	21.94	11.20	24.29
Sn	0.10	130.60	5.72	1.00	21.85
Be	1.00	6.00	2.89	2.50	1.60
Sc	0.10	10.10	2.68	0.90	3.03
S	0.04	0.04	0.04	0.04	—

Table 3. Descriptive statistics of selected trace elements in stream sediments from the study area. Values are in ppm except Fe (wt.%). Concentrations below detection limit were replaced by half the detection limit for statistical treatment.

Element	**Min**	**Max**	**Mean**	**Median**	**Std. Dev.**
Mo	0.00	2.51	0.45	0.29	0.53
Cu	2.04	39.12	11.1	9.9	7.8
Pb	2.73	78.75	23.9	15.9	21.4
Zn	2.20	84.40	25.6	21.7	18.9
Ag	0.00	188	16.9	0.0	40.3
Ni	1.0	39.3	8.6	5.8	9.2
Co	0.6	41.6	8.4	5.9	9.8
Mn	51	1591	512	365	403
Fe (%)	0.51	9.05	2.12	1.79	1.74
As	0.10	5.40	1.39	1.1	1.21
U	0.4	114.4	6.1	3.4	17.6
Th	1.1	165.6	31.7	20.1	34.9
Sr	6	672	48.9	22	106
Cd	0.00	0.60	0.05	0.03	0.10

Sb	0.03	6.14	0.32	0.14	0.92
Bi	0.04	2.42	0.23	0.11	0.41
V	7	106	40.8	36	24.6
La	7.1	364.9	82.3	57.9	78.4
Cr	4	140	33.2	26	32.1
Ba	27	2729	405	138	658
Ti	0.1	3.1	0.72	0.6	0.64
Zr	13.5	270.4	86.1	69.4	59.8
Sn	0.5	20.3	2.7	1.3	4.6
Sc	0	260	7.8	2.1	40.6
Y	2.0	52.4	15.2	10.5	14.1
Ce	17.3	832.2	191	128	187
Rb	4.2	228.4	70.6	47.9	59.9

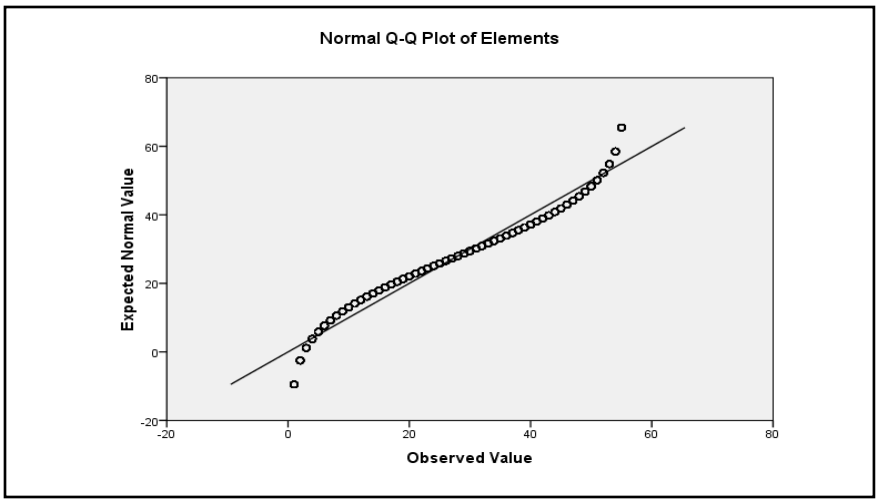


Figure 3: Graph of Test of Equality between elements (Major and trace elements)

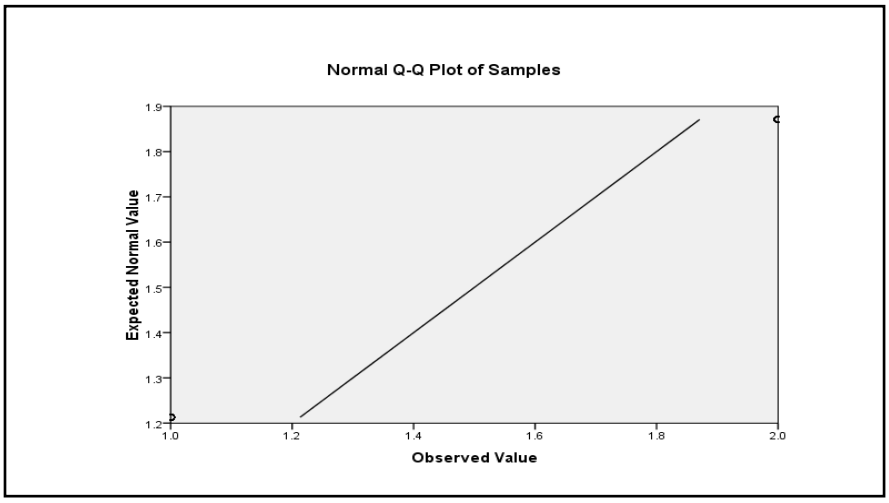


Figure 4: Q-Q plots for samples in the study area.

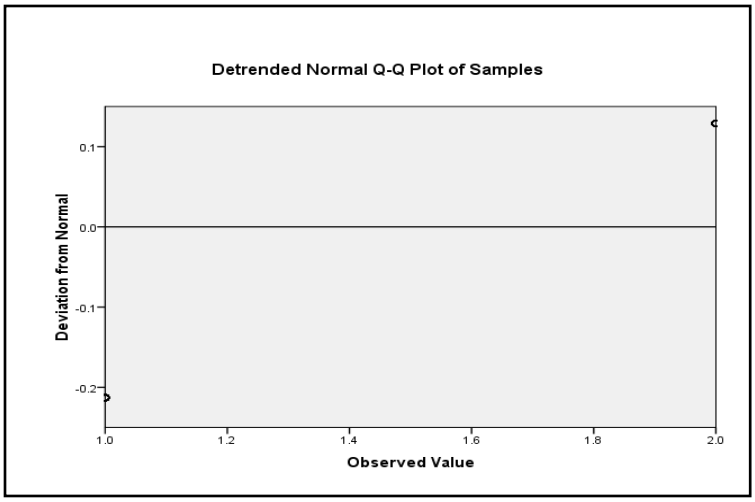


Figure 5: Detrended normal Q-Q plots for samples showing their inhomogeneity after Tunkey's Test

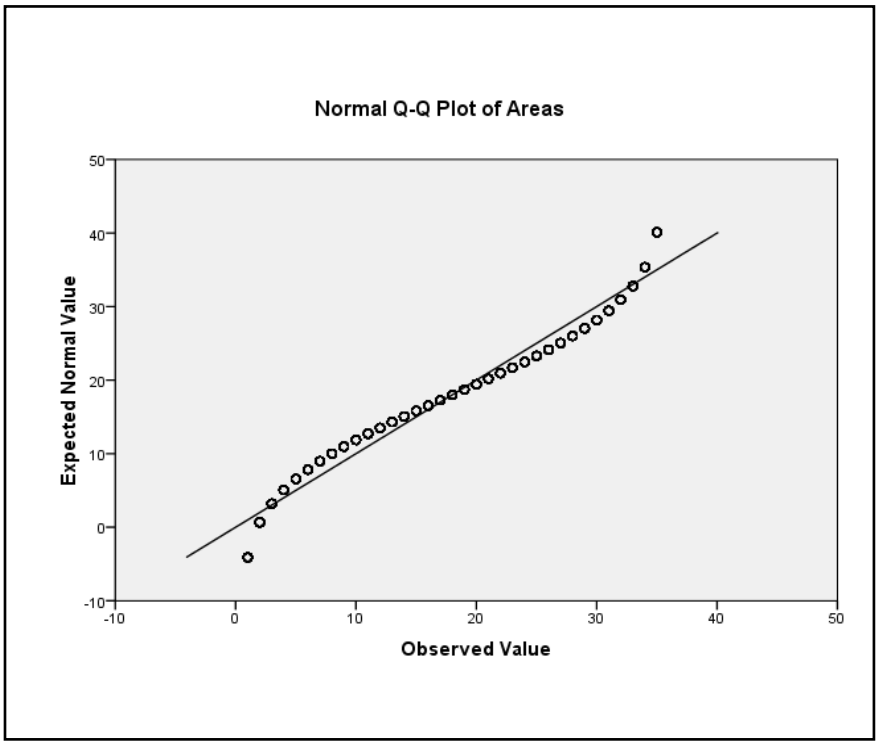


Figure 6: Normal Q-Q plots for the geochemical sampling sites (Areas)

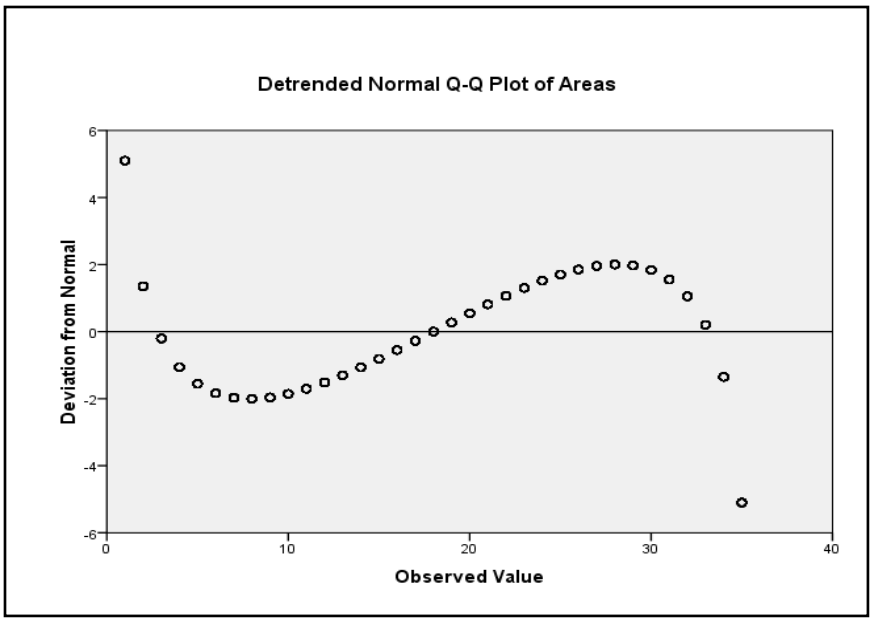


Figure 7: Detrended Q-Q plots for geochemical sampling sites (Areas)

4.3 Trace element concentrations in bedrock samples

Trace element analysis of bedrock samples reveals variable elemental abundances across different lithologies and sampling locations (Figs. 8-13). Elevated concentrations of Ba are recorded in granitic and pegmatitic rocks from Baba Ori Oke, Idao, Oke-Ila, Iroko, Osun, and Epe Ekiti. Bedrock samples from the Odo-Owa area show elevated concentrations of Ba, Cr, Cu, Mn, and Zn.

Granites, banded gneisses, and schistose quartzites exhibit elevated concentrations of Pb, Zn, Mn, and Sn. Bedrock samples from the Ijero area show elevated concentrations of Li, Sn, Zn, and Rb, particularly within pegmatitic lithologies. Copper and zinc concentrations are higher in biotite-rich lithologies and granitoid rocks. Elevated Cu concentrations are also recorded in the Ajindo (Aworo) area.

4.4 Trace element concentrations in stream sediment samples

Stream sediment samples display elevated concentrations of Cu, Zn, Ni, Mn, Th, Zr, Ce, and Rb, with spatial variation across the drainage network (Table 3). High Cu concentrations are recorded in sediments from the Odo-Owa Abidogun River. Elevated Zn and Pb concentrations occur in selected drainage channels.

Manganese concentrations are elevated in sediments derived from areas underlain by quartzitic lithologies. Stream sediments from the Ijero–Ipoti drainage system show elevated concentrations

of Th, Zr, Ce, Rb, W, Be, U, Li, Nb, Ta, Cs, and Ga. Chromium and arsenic concentrations are generally low across the study area.

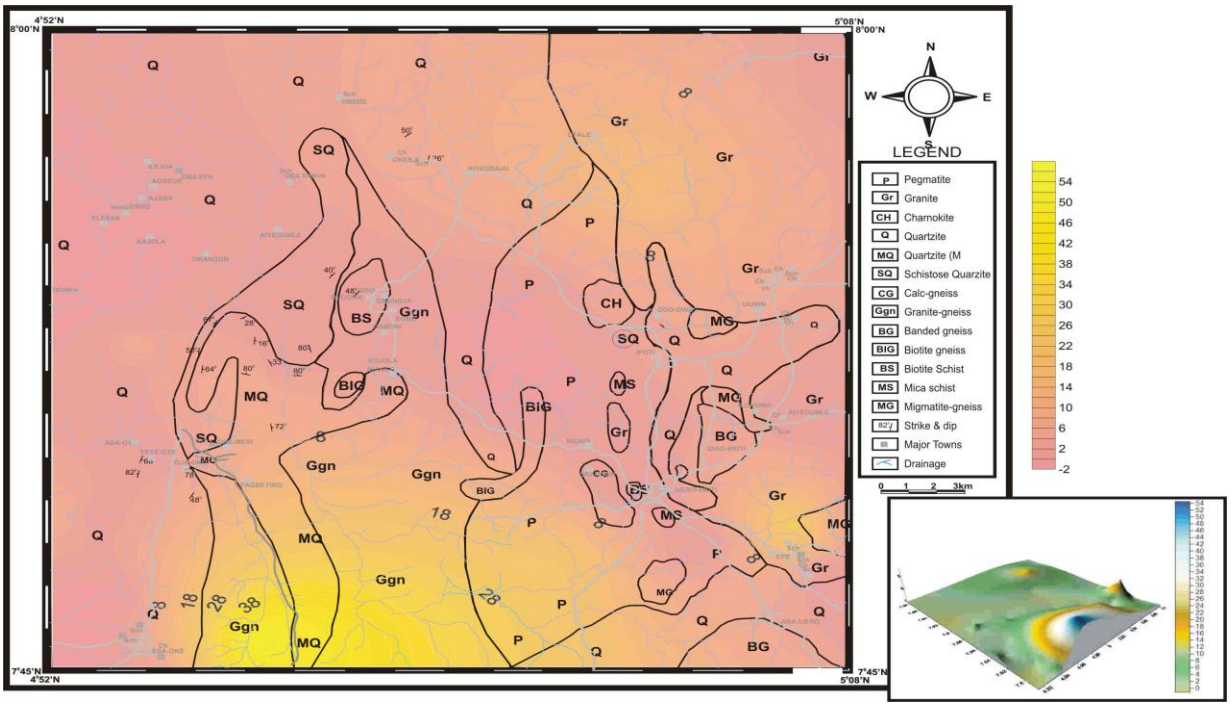


Figure.8: Rock Geochemical Map of Ni

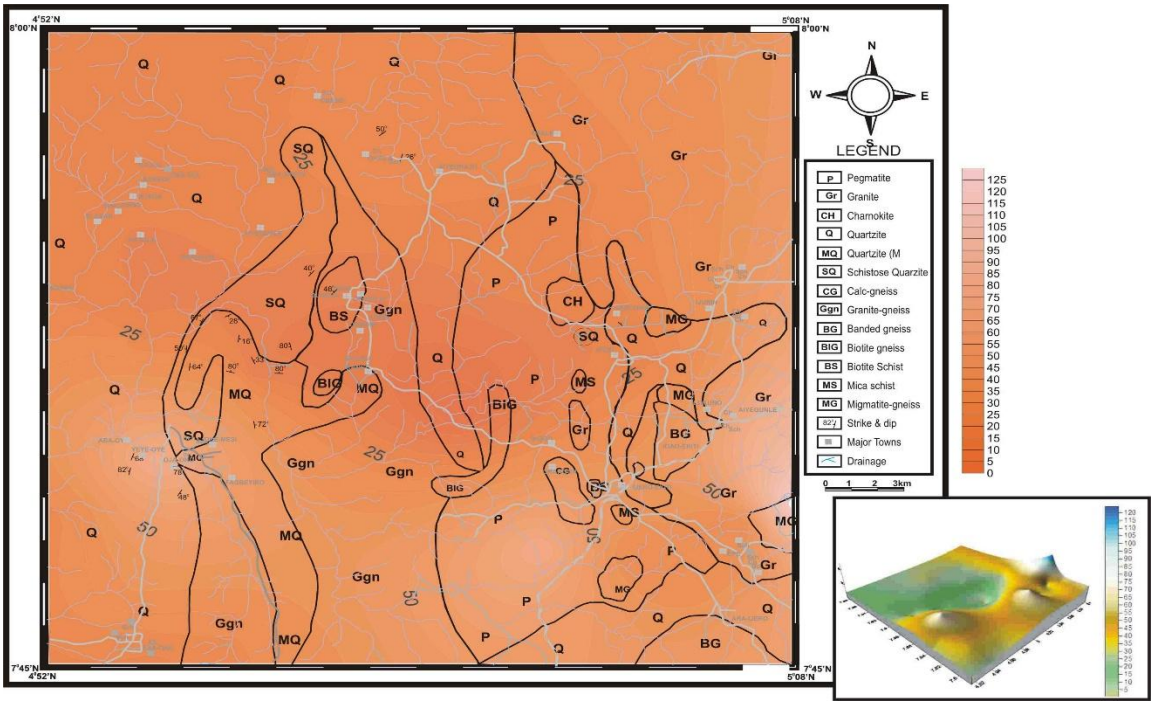


Figure 9: Rock Geochemical Map of Copper (Cu)

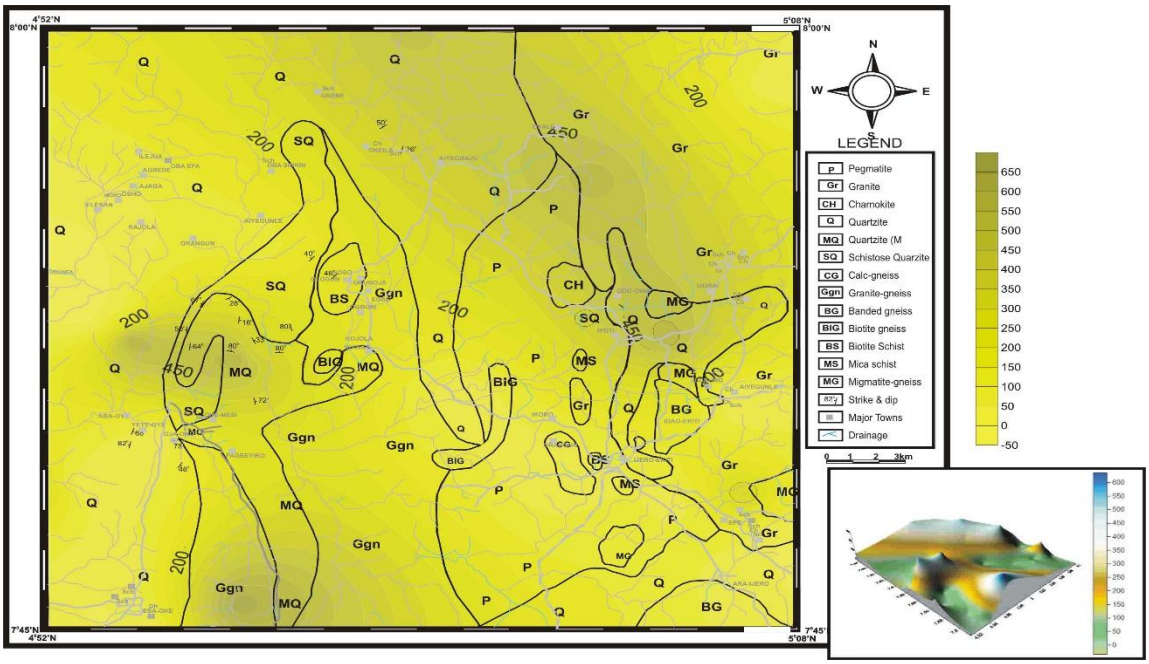


Figure 10: Rock Geochemical Map of Mn

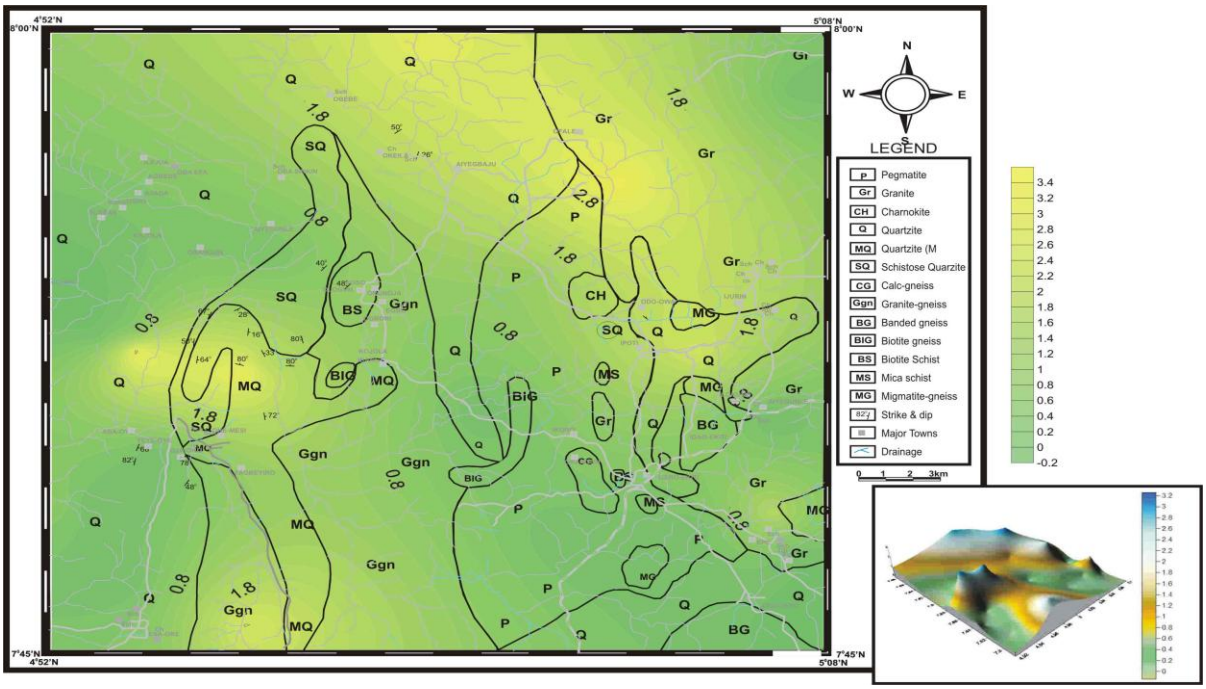


Figure 11: Rock Geochemical Map of Fe

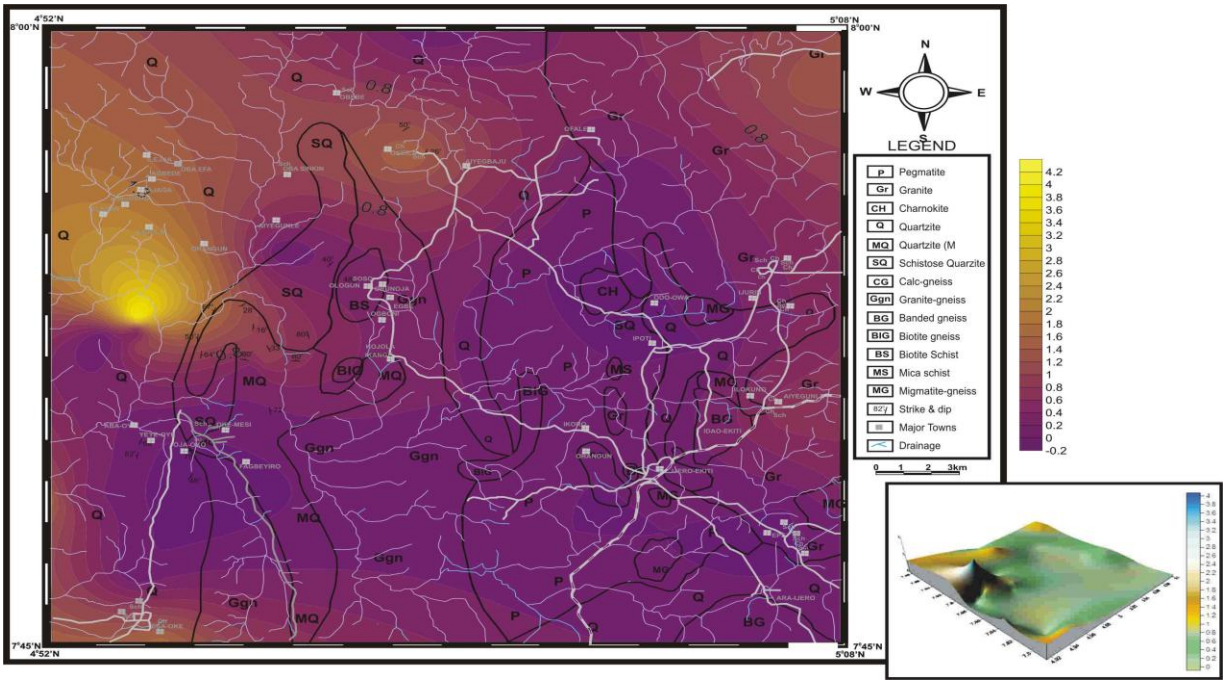


Figure 12: Rock Geochemical Map of As

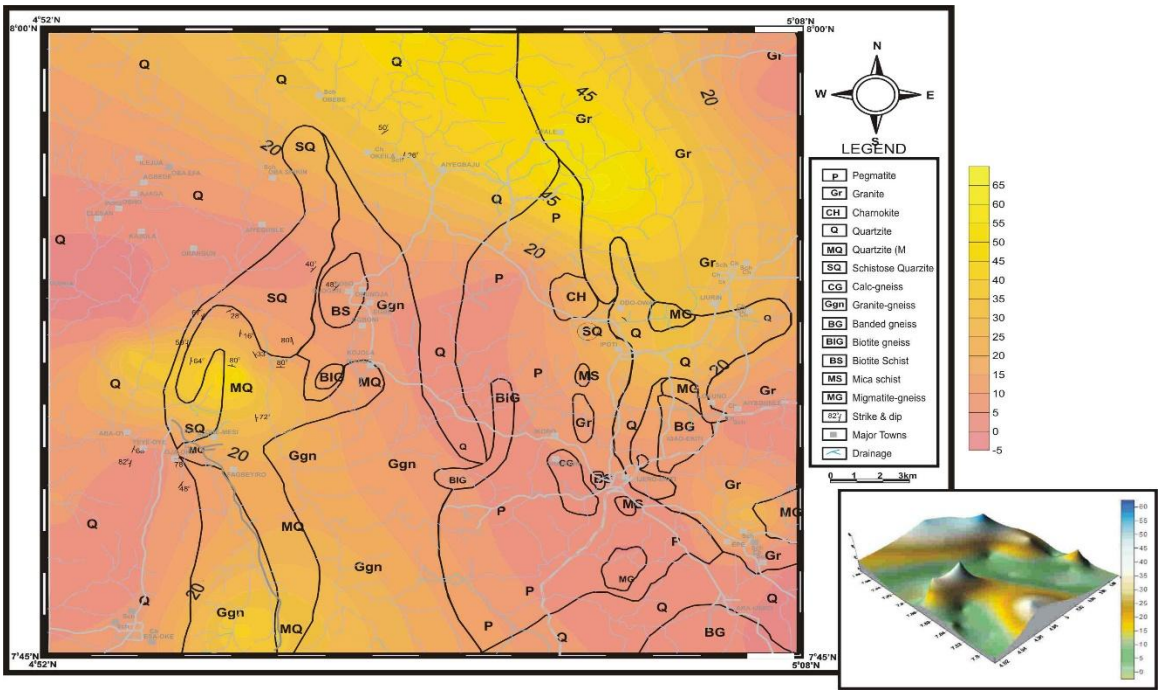


Figure 13: Rock Geochemical Map of Va

4.5 Multivariate statistical results

Hierarchical cluster analysis of standardized bedrock trace-element data using Ward's linkage method and squared Euclidean distance reveals well-defined elemental groupings (Table 4; fig.14). The resulting dendrogram delineates four principal clusters, indicating systematic geochemical associations within the dataset. A first cluster is dominated by base-metal elements, including Cu, Pb, Zn, Ni, and Co, reflecting their coherent behavior across the sampled lithologies. A second cluster groups rare-metal–related elements such as Sn, W, Li, Be, Nb, and Ta, which display strong internal similarity and separation from base-metal associations.

A third cluster comprises lithogenic and felsic-related elements, notably Ba, Rb, Th, Zr, and Ce, while a fourth cluster is characterized by Mn, Fe, V, and Cr. The latter group shows relatively high linkage distances compared to the other clusters, suggesting greater variability in their distribution. Overall, the cluster patterns are consistent across the dataset and demonstrate clear separation between base-metal, rare-metal, and lithogenic element associations.

Factor analysis (Table 5) identifies multiple factors with eigenvalues greater than one. Factors are defined by elemental loadings exceeding 0.40, with strong loadings (>0.75), moderate loadings (0.50–0.75), and weak loadings (0.40–0.50) recorded across different elemental groups. Principal component analysis yields similar elemental groupings and variance distributions.

The box-and-whisker plots of trace-element concentrations in stream sediment samples (Fig.15) display marked variability in elemental distributions across the study area. For most elements, the median values (50th percentile) lie closer to the lower quartile, indicating positively skewed distributions characterized by a limited number of high-concentration samples. This skewness is particularly evident for Cu, Pb, Zn, Mn, Ce, and Zr, where elongated upper whiskers and discrete high-end values suggest localized enrichment relative to background levels. Elements such as Ba, Th, and Rb exhibit comparatively narrower interquartile ranges, reflecting more uniform background distributions across the drainage system. In contrast, Ag, Be, and S show compressed boxes and frequent zero or near-zero values, indicating concentrations close to or below analytical detection limits in most samples. Following the approach of Turkey (1977), concentrations between the median (50th percentile) and the upper quartile (75th percentile) are interpreted as threshold values, while values exceeding the 75th percentile are classified as anomalous.

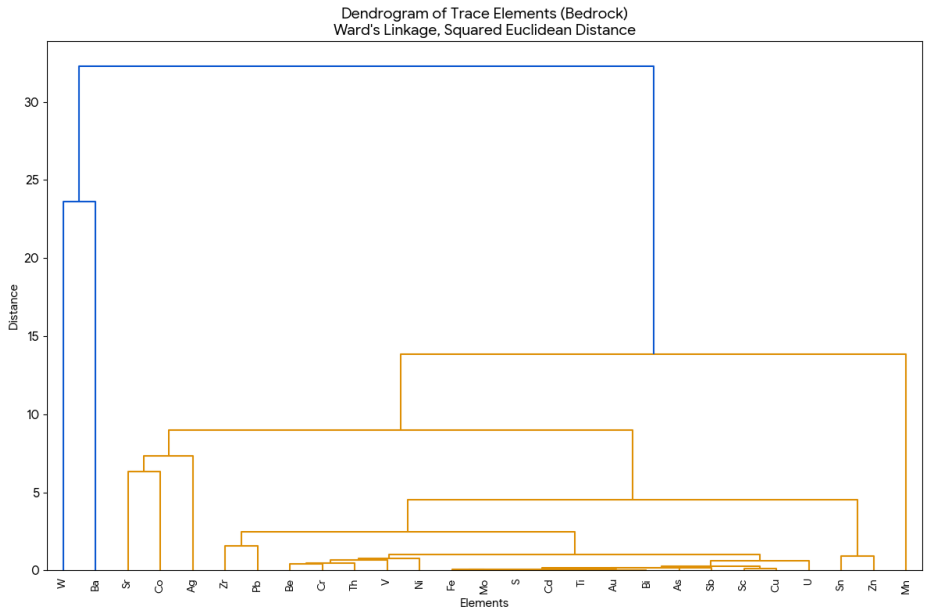


Figure 14. Hierarchical cluster analysis dendrogram of bedrock trace elements from the Okemesi–Ijero area using Ward's linkage method and squared Euclidean distance on standardized data. The dendrogram reveals distinct elemental clusters corresponding to base-metal associations, rare-metal–enriched systems, felsic magmatic signatures, and secondary dispersion processes.

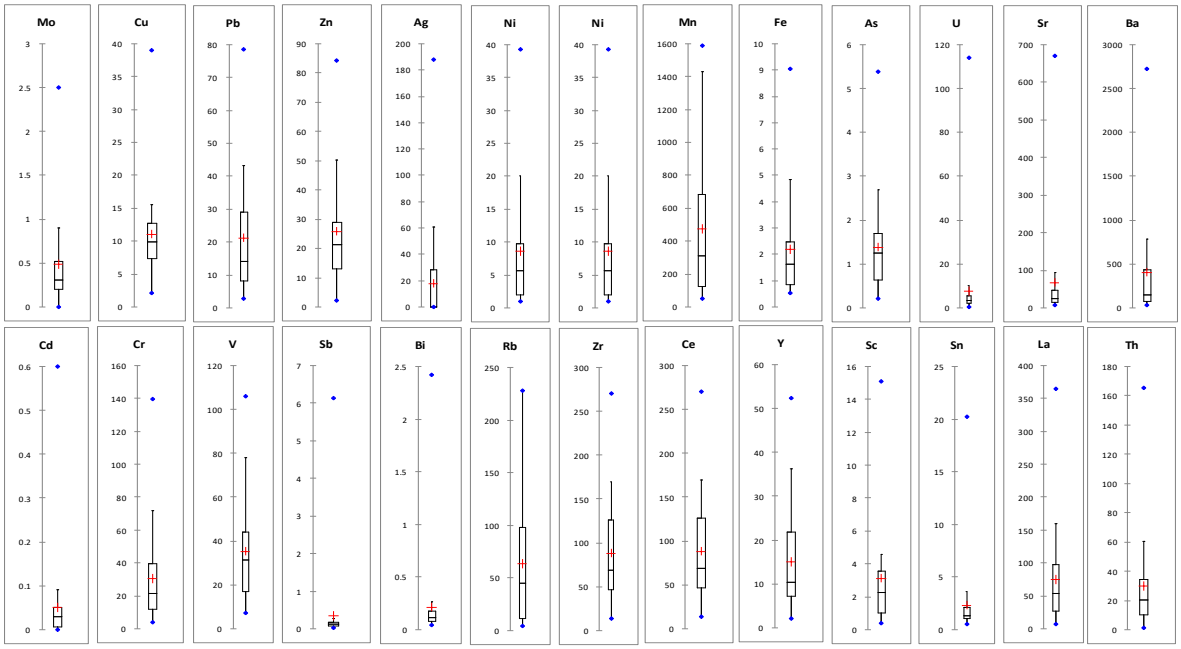


Fig. 15: Box and whisker plots showing element distribution in the analysed stream sediments. The middle line corresponds to the background value (median); lower and upper bounds of the box indicate 25th and 75th percentiles respectively. Values above the 75th percentile are

considered. Element contents between the 50th and 75th percentiles are regarded as the threshold. (Turkey, 1977)

Table 4. Element clusters derived from hierarchical cluster analysis

Cluster	Elements	Interpretation
Cluster 1	Cu, Pb, Zn, Ni, Co	Base-metal association
Cluster 2	Sn, W, Li, Be, Nb, Ta	Rare-metal / pegmatitic affinity
Cluster 3	Ba, Rb, Th, Zr, Ce	Felsic magmatic signature
Cluster 4	Mn, Fe	Secondary enrichment / weathering

Table 5. Summary of factor loadings from multivariate statistical analysis of stream sediment geochemical data

Factor	Eigenvalue	Variance explained (%)	Elements with loadings ≥ 0.40	Remark
Factor 1	>1.0	—	Ba, Rb, Li, Sn, Th, Zr, Ce, Nb, Ta	felsic magmatic / pegmatitic affinity
Factor 2	>1.0	—	Cu, Pb, Zn, Ni, Co, Mn	base-metal association
Factor 3	>1.0	—	Fe, Mn, V	secondary dispersion / weathering processes
Factor 4	>1.0	—	Cr, Ni	mafic or lithological control
Factor 5	>1.0	—	W, Be, U, Cs, Ga	rare-metal enrichment

Notes: Only elements with factor loadings ≥ 0.40 are listed, following standard practice. Eigenvalues are reported as >1.0 to reflect the Kaiser criterion used in factor retention.

5. Discussion

5.1 Geological controls on elemental distribution

The distribution of lithological units and structural features in the Okemesi–Ijero area exerts a strong control on the observed geochemical patterns. The dominance of quartzites of the Effon Psammite Formation, interbanded with schists and migmatite–gneiss complexes, reflects a polydeformed metasedimentary sequence that has been repeatedly reworked during Pan-African tectonism (Akanmu et al., 2019). The emplacement of granitoids, pegmatites, and charnockites into this framework introduced additional geochemical heterogeneity and created favorable structural traps for fluid migration and elemental redistribution.

The spatial coincidence of elevated elemental concentrations with zones of intense deformation, folding, and intrusive contacts highlights the importance of structural permeability in concentrating metals. Antiform structures and intrusive margins likely acted as conduits for magmatic and hydrothermal fluids, enhancing the redistribution of metals within both bedrock and surficial environments (Ilevbare, & Orisamika, 2021).

5.2 Lithological affinity of trace elements in bedrocks

Trace element enrichment patterns observed in bedrock samples reflect strong lithological control. The concentration of Ba within granitic and pegmatitic lithologies is consistent with the involvement of evolved felsic magmas and late-stage magmatic differentiation. Similarly, the association of Li, Sn, Zn, and Rb with pegmatitic rocks in the Ijero area is indicative of rare-metal-enriched granitic systems, particularly those containing lepidolite and related lithium-bearing phases (Zhang et al., 2025).

The Pb–Zn–Mn–Sn association identified in granites, banded gneisses, and schistose quartzites suggests a polymetallic signature that may be related to hydrothermal overprinting of pre-existing lithologies. Elevated Cu and Zn concentrations within biotite-rich rocks and granitoids further emphasize the role of mafic mineral phases and magmatic sources in hosting chalcophile elements (Hao et al., 2025). These patterns collectively point to a mixed magmatic–hydrothermal control on bedrock geochemistry within the study area.

5.3 Stream sediment signatures and provenance

Stream sediment geochemistry effectively integrates upstream lithological and geochemical signatures and provides insight into sediment provenance and metal dispersion pathways. Elevated concentrations of Cu, Zn, Pb, and Mn in selected drainage systems reflect proximity to mineralized bedrock sources and structurally favorable zones (Hansani et al., 2025). The enrichment of Th, Zr, Ce, and other high-field-strength elements in sediments derived from granitic and pegmatitic terrains underscores the contribution of felsic intrusions and resistant accessory minerals to sediment composition (Kankuzi, 2019).

The pronounced enrichment of W, Be, U, Li, Nb, Ta, Cs, and Ga in the Ijero–Ipoti drainage system is particularly significant, as it reflects the erosion and dispersion of rare-metal-bearing pegmatites. These elements are relatively immobile during weathering and transport, allowing their sedimentary concentrations to preserve primary source signatures (Lipp et al., 2020). Conversely, the generally low concentrations of Cr and As suggest limited development of gold-associated mineralization in the area, reinforcing the dominance of base metal and rare metal systems (Anand et al., 2025).

5.4 Interpretation of multivariate statistical associations

Multivariate statistical analyses provide a robust framework for disentangling the complex geochemical relationships within the dataset. Cluster analysis effectively separates background geochemical signatures from anomalous populations, distinguishing quartzite- and schist-dominated terrains from areas influenced by granitoid and pegmatitic sources. The clustering of Cu, Pb, Zn, Ni, Mn, Ba, Th, Zr, and rare earth elements within high-concentration groups highlights areas of enhanced mineralization potential.

Factor and principal component analyses further clarify the geochemical processes responsible for these associations. Factors dominated by Ba, Rb, Li, Sn, Th, Zr, and rare earth elements are interpreted as reflecting felsic magmatic and pegmatitic sources, whereas associations involving Cu, Zn, Pb, Ni, and Co are indicative of base metal enrichment linked to granitoid intrusion and structural control. Secondary elements such as Mn, Fe, and V reflect weathering, oxidation, and sedimentary dispersion processes (Jiang et al., 2020).

The consistency between factor, cluster, and spatial analyses confirms the effectiveness of multivariate techniques in reducing data complexity and enhancing exploration targeting in crystalline basement terrains.

5.5 Implications for mineral exploration

The integrated geological, geochemical, and statistical evidence indicates that the Okemesi–Ijero area is prospective for both base metal and rare metal mineralization. Granitic and pegmatitic domains, particularly in the Ijero and Ijero–Ipoti areas, represent high-priority targets for lithium, tin, tantalum, niobium, and associated rare metals. Polymetallic Pb–Zn–Cu–Mn–Sn signatures associated with granitoid intrusions and structurally complex zones further enhance the exploration potential of the area.

The results demonstrate that combining bedrock and stream sediment geochemistry with multivariate statistical analysis provides an effective exploration strategy in complex basement terrains. This integrated approach allows for the delineation of geochemical anomalies, discrimination of lithological controls, and prioritization of exploration targets with reduced uncertainty.

6. Conclusion

This study demonstrates the effectiveness of integrating geological mapping, bedrock and stream sediment geochemistry, and multivariate statistical analysis in evaluating mineralization potential within a complex crystalline basement terrain. Detailed field mapping of the Okemesi–Ijero area identified a polydeformed assemblage of quartzites, schists, migmatite–gneiss complexes, granitoids, pegmatites, and charnockites, providing a structurally and lithologically diverse framework for geochemical investigation.

Geochemical results reveal systematic spatial variation in trace element distributions across both bedrock and stream sediment media. Granitic and pegmatitic lithologies are characterized by enrichment in lithophile and rare-metal-related elements, whereas polymetallic associations involving base metals occur within granitoid intrusions and structurally disturbed zones. Stream sediment geochemistry effectively captures these upstream signatures and highlights drainage systems influenced by mineralized source rocks.

Multivariate statistical analyses successfully discriminate background geochemical signatures from anomalous elemental populations and clarify elemental associations related to lithology, magmatism, and secondary dispersion processes. The consistency between factor, cluster, and spatial analyses confirms the robustness of the applied statistical framework and its suitability for reducing data complexity in regional exploration datasets.

Overall, the results indicate that the Okemesi–Ijero area is prospective for base metal and rare metal mineralization, particularly within granitic and pegmatitic domains and structurally favorable zones. The methodological approach adopted in this study provides a reliable and transferable exploration model for basement terranes and underscores the value of combining traditional geological methods with advanced statistical techniques in mineral exploration.

Author contribution

E. E. IGONOR: Conceptualization, methodology, field investigation, data curation, formal analysis, visualization, and writing—original; O. S. Ayodele: Conceptualization, methodology, supervision, validation, interpretation of geochemical results, and writing—review and edit; S. O. Daramola: Data analysis, statistical analysis, interpretation of results, visualization, and writing—review and editing.

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Data availability

All relevant data are included in the paper.

Declarations

Ethics approval and consent for participate

Not applicable

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests

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