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Geology and Geochemical Evidence for Structurally Controlled Hydrothermal Metallic Mineralization in the Western Oban Massif, Southeastern Nigeria

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Abstract: The Precambrian Basement Complex of southeastern Nigeria forms part of the Nigerian Basement Complex and exhibits geological characteristics comparable to Archean-Proterozoic terranes known for deformation-driven hydrothermal systems. This study investigates the geology, structural framework, and whole-rock geochemistry of basement rocks in the western Oban Massif to evaluate evidence for structurally controlled hydrothermal metal redistribution. Field mapping identifies metasedimentary, meta-igneous, and intrusive lithologies, including phyllites, schists, amphibolites, pegmatites, and quartz-feldspathic veins, commonly associated with linear and planar structures trending N–S, NE-SW, and NW-SE that acted as pathways for hydrothermal fluid circulation and localized metal redistribution. Whole-rock geochemical data show elevated SiO_2, Al_2O_3, and total Fe_2O_3 and low MnO, MgO, CaO, Na_2O, TiO_2, and P_2O_5, consistent with silica enrichment and fluid-rock interaction. Trace-element distributions display lithology-dependent enrichment patterns, with phyllites enriched in Pb, Ba, Cr, Rb, Zr, Y, and Zn; schists in Rb, Ba, Sr, Cr, Zr, and Ni; amphibolites in Ba, Sr, Rb, Y, Zr, and Zn; quartz-feldspathic veins in Zn, Sr, Cr, Pb, and Ba; and pegmatites in Rb, Sr, Ba, Cr, Zn, and Zr. Enrichment factor calculations and diagnostic geochemical ratios indicate background to moderate enrichment in host rocks and localized moderate to strong enrichment within structurally controlled veins and pegmatites. Collectively, the geological, structural, and geochemical evidence indicates that the western Oban Massif records deformation-controlled hydrothermal metal redistribution comparable to systems documented in Nigerian schist belts and other Precambrian basement terranes worldwide. Although economic mineralization is not established, the results highlight geochemical permissiveness for localized metal concentration and identify the western Oban Massif as an underexplored metallogenic system in southeastern Nigeria.

Keywords: Geochemistry, low-grade metasediments, amphibolites, pegmatites, quartz vein, metal concentration, hydrothermal system, and structural control.

1. Introduction

The Precambrian Basement Complex of Nigeria is part of the African Basement Complex (Fig. 1), constituting a major component of the Trans-Saharan mobile belt and records a prolonged history of crustal growth, deformation, metamorphism, and magmatism associated with multiple Proterozoic tectono-thermal events [1,2,3,4,5,6,7] This basement complex hosts a wide range of metalliferous mineral occurrences, including iron and ferroalloy metals (Mn, Nb, Ta, Cr, Co, V), base metals (Pb, Zn, Sn), precious metals (Au, Ag), and radioactive and rare-element mineralization involving U, Th, Y, and rare earth elements [8,9,10]. These mineral resources are spatially and genetically linked to low- and high-grade metamorphic rocks, granitoid intrusions, pegmatites, and quartz veins emplaced along ductile and brittle structural corridors during successive orogenic cycles.

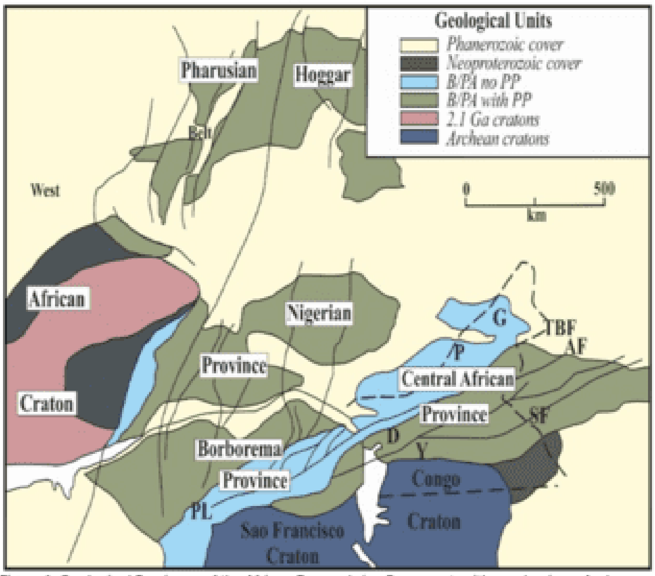

Figure 1: Geological Provinces of the African Precambrian Basement, with emphasis on Archean - Paleoproterozoic cratons and Neoproterozoic Pan-African/Brasiliano belts. Adapted from [7; 3]

Across the Nigerian Basement Complex [11] (Fig. 2), economically significant mineralization is concentrated predominantly within schist belts and associated basement terranes influenced by Paleoproterozoic Birimian crustal evolution and later Pan-African tectonism. Numerous studies have demonstrated that low-grade metasediments such as phyllites and schists, together with pegmatites and structurally controlled quartz veins, represent favorable hosts for gold, rare-metal (Nb-Ta-Sn), manganese, chromium, and base-metal mineralization [12,13,14]. These lithological assemblages are widely regarded as analogues of Archean-Proterozoic greenstone belts, which constitute some of the most productive metallogenic provinces [15,16].

Despite the well-established metallogenic framework of the Nigerian Basement Complex, the southeastern sector, particularly the Oban Massif, has received limited systematic investigation regarding mineralization. Previous studies have focused mainly on regional geology, metamorphic evolution, and petrogenesis, with only preliminary documentation of mineral occurrences such as Ta-Nb-Sn-bearing pegmatites, monazite, manganese, and ilmenite [17-20]. Reported mineralization is largely restricted to the eastern Oban Massif, leaving the western segment comparatively under-characterized. This limited dataset has fostered the perception that the western Oban Massif is metallogenically barren [21]; however, recent geological and geochemical evidence from adjacent basement terranes suggests that this view may reflect insufficient exploration rather than the true absence of mineral potential [22]. Notably, the western Oban Massif occupies a structurally strategic position within the eastern Pan-African basement and shares lithological and structural similarities with productive Nigerian schist belts, underscoring the need for systematic reassessment.

Previous reconnaissance observations indicate that the western Oban area comprises metasedimentary and meta-igneous rocks intruded by granodiorites, pegmatites, and quartz-feldspathic veins, lithologies commonly associated with hydrothermal mineralization systems worldwide [23,24]. Moreover, structural fabrics and fracture networks developed during polyphase deformation provide favorable pathways for magmatic and metamorphic fluids capable of mobilizing and concentrating metals [25]. Nevertheless, comprehensive geochemical datasets capable of constraining the mineralization potential of these rocks remain scarce.

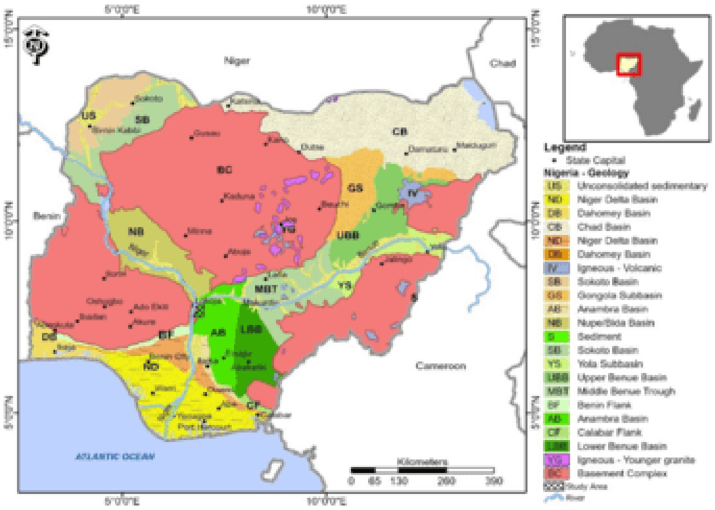

Figure 2: Geological Framework of Nigeria showing major Sedimentary Basins and Basement Terranes, Adapted from [11].

This study addresses the knowledge gap by integrating detailed field reconnaissance, structural analysis, petrographic investigation, and whole-rock geochemical data to evaluate the potential for metallic mineralization in basement rocks of the western Oban Massif. Emphasis is placed on identifying geochemical signatures, trace-element enrichment patterns, and structural controls indicative of hydrothermal mineralization. By comparing the geochemical characteristics of western Oban rocks with those of established Nigerian schist belts and global Precambrian metallogenic provinces [26,27], this study provides new insights into the metallogenic significance of the western Oban Massif and reassesses its potential as a prospective mineral province within southeastern Nigeria.

Regional Geological Setting

The western Oban Massif forms part of the southeastern Nigerian Basement Complex. It lies within the Neoproterozoic Trans-Saharan mobile belt, a major Pan-African orogenic system developed between the West African Craton to the west, the Congo Craton to the southeast, and the East Saharan Block to the northeast. This mobile belt records prolonged crustal evolution, involving continental collision, crustal thickening, regional metamorphism, and syn- to post-tectonic magmatism during the Proterozoic era.

Within Nigeria, the Trans-Saharan belt, commonly referred to as the Pan-African Orogenic Belt, is subdivided into eastern and western basement terranes. The eastern terrane, which underlies the Oban Massif, is characterized by three principal lithological components: (a) migmatite-gneiss complexes, (b) supracrustal metasedimentary and metavolcanic sequences commonly referred to as schist belts, and (c) Pan-African granitoids collectively known as the Older Granite Suite [28]. These lithological units preserve evidence of polyphase deformation and regional metamorphism associated with Pan-African tectonism.

The western Oban Massif is underlain predominantly by low- to medium-grade metamorphic rocks comprising muscovite-rich phyllites, quartz-mica schists, and localized amphibolites, which constitute the principal country rocks [29]. These supracrustal units are intruded by granodiorites, pegmatites, and quartz-feldspathic veins that occur as discordant bodies and fracture-controlled intrusions. Comparable lithological associations have been documented in other Nigerian schist belts and are considered analogous to Archean-Proterozoic greenstone belt assemblages globally [30].

The supracrustal rocks of southeastern Nigeria are interpreted as upper Proterozoic sequences that were in-folded into the migmatite-gneiss-quartzite basement during successive deformation episodes [31]. These rocks typically exhibit strong foliation and lineation trends reflecting polyphase tectonic overprinting, with dominant structural orientations aligned N-S to NE-SW. Metamorphism within the western Oban Massif is dominantly of Barrovian to Abukuma type, indicating variable pressure-temperature conditions during regional metamorphic evolution [32].

Four major thermo-tectonic episodes have been recognized within the Oban Massif and adjacent basement terranes: the Liberian (ca. 2800-2500 Ma), Eburnean (ca. 2200-1800 Ma), Kibaran (ca. 1300-900 Ma), and Pan-African (ca. 800–400 Ma) events [33]. These orogenic cycles collectively contributed to crustal reworking, deformation, metamorphism, and magmatic intrusion, ultimately shaping the present litho-structural architecture of the western Oban Massif. The Pan-African event, in particular, is considered responsible for widespread granitoid emplacement and hydrothermal fluid circulation, processes commonly associated with metal mobilization and concentration in Precambrian basement terranes [34].

Although the basement rocks of southeastern Nigeria have traditionally been regarded as relatively poor in metallic mineralization compared to schist belts elsewhere in the country, increasing geological and geochemical evidence suggests otherwise. Schist belts across Nigeria are well-established as hosts to metallic and precious-metal mineralization, including gold, base metals, and rare metals [35]. The lithological, structural, and metamorphic similarities between these productive belts and the western Oban Massif underscore the need to reassess their metallogenic potential through systematic investigation.

Field Investigation and Geological Mapping

Geological field investigations were carried out across the western Oban Massif, located within Akamkpa Local Government Area of Cross River State, southeastern Nigeria. Mapping was conducted at a scale of 1:25,000 and covered approximately 750 km² within latitudes 5°10′- 5°40′ N and longitudes 8°05′- 8°35′ E. The study area lies partly within the Uwet Sheet (Sheet 232, Oban) of the Nigerian topographic series and forms part of an undifferentiated schist belt (Fig.3) composed predominantly of metasedimentary rocks intruded by granitoids, pegmatites, and quartz veins [22,29].

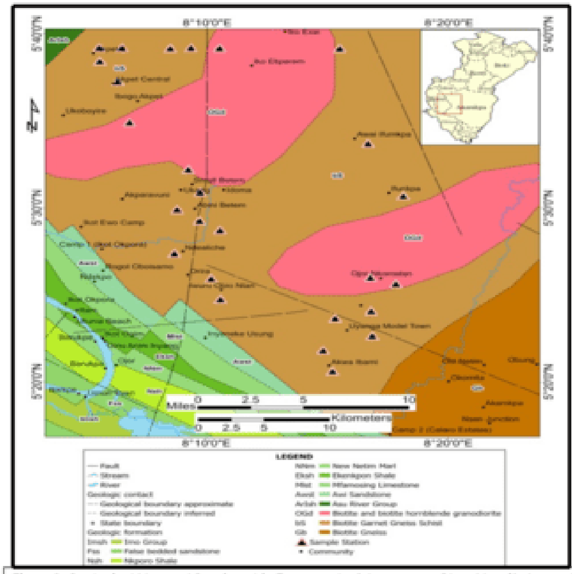

Figure 3: Geological Map and Stratigraphic Framework of the western Oban Massif, the study area. Modified after NGSA [31].

Field reconnaissance involved systematic identification of lithological units, documentation of structural features, and preliminary evaluation of mineralization indicators. Structural measurements, including orientations of foliation, fractures, shear zones, and lineations, were recorded using a compass clinometer following standard geological procedures commonly applied in Nigerian basement terrains. Attention was paid to lithological contacts and deformation zones, which are widely recognized as favorable pathways for hydrothermal fluid migration in schist belts.

In addition to conventional geological mapping, reconnaissance exploration techniques were employed, including stream sediment panning and *in-situ* elemental measurements of weathered soils and exposed bedrock using a hand-held field spectrometer (TITAN 500) to guide sampling. These methods have been successfully applied in preliminary mineral exploration studies across Nigerian schist belts to identify geochemical anomalies and guide detailed sampling [36].

Sample Collection and Preparation

Representative rock samples were collected from all major lithological units (Fig. 4) identified during field mapping, including phyllites, schists, amphibolites, pegmatites, and quartz-feldspathic veins. Sampling targeted fresh, minimally weathered outcrops to preserve primary geochemical signatures. Individual samples weighed approximately 2-3 kg and were trimmed in the field to remove altered surfaces and potential contaminants, following best practices for basement rock geochemical studies [37].

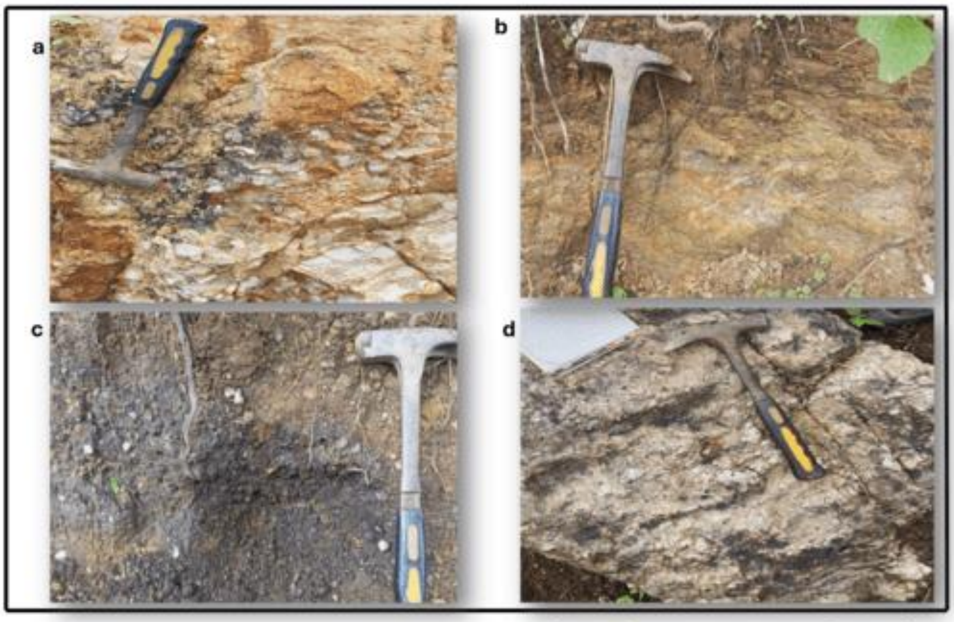

Fig. 4: Field outcrop of rocks in the western Oban area. (a) quartz-mica schist at 5° 39' N & 8° 6 'E, (b)muscovite-phyllite at 5° 39' N & 8° 5' E, (c) garnetiferous-phyllite at 5° 39' N & 8° 6' E, and k-feldspar-rich pegmatite at Betem, 5° 31' N & 8° 11' E.

All sample locations were recorded using a Global Positioning System (GPS), and the spatial distribution of samples was subsequently plotted on a sample location map (Fig. 5). Collected samples were stored in labeled polyethylene bags and transported to the Department of Geology, University of Calabar, for preliminary processing.

In the laboratory, samples were air-dried at room temperature and subsequently oven-dried at 50 °C overnight to facilitate disaggregation. Dried samples were crushed, pulverized, and sieved to obtain fine-grained powders suitable for whole-rock geochemical analysis. Care was taken throughout sample preparation to avoid cross-contamination.

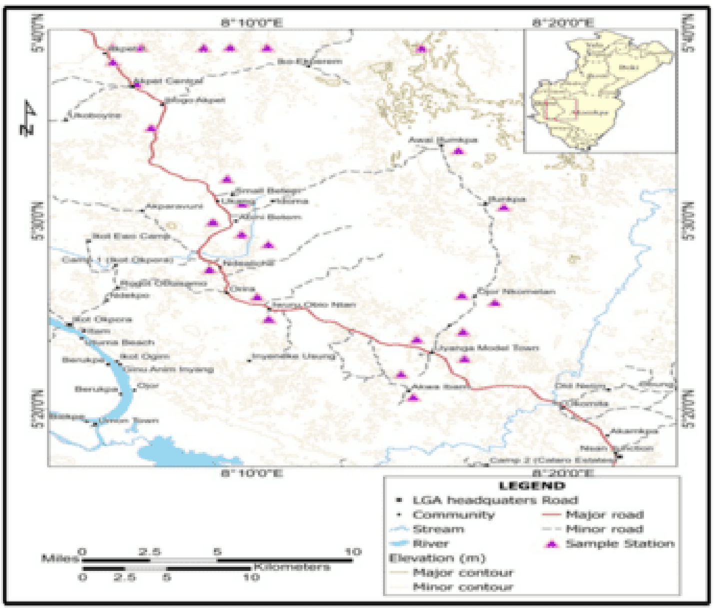

Fig. 5: Sampling Locations and Field Access Map of the study area, Southeastern Nigeria . Modified after NGSA [31].

2. Materials and Methods

Petrographic Analysis and Lithologic Description

Petrographic investigations were conducted to characterize mineralogical composition, textures, and microstructural features of representative rock samples (Table 1). Thin sections were prepared from fresh specimens and examined using a polarizing petrographic microscope at the Department of Geology, University of Calabar.

Mineral identification and textural analysis were carried out under plane-polarized light (PPL) and cross-polarized light (XPL), with emphasis on identifying metamorphic mineral assemblages, grain size, foliation, recrystallization features, and deformation fabrics. Modal mineral compositions were estimated through visual point counting and correlated with field observations, following established petrographic methods applied in Nigerian basement studies .

Low-Grade Metasediments

The dominant metasedimentary rocks exposed in the western Oban Massif are phyllites and schists (Figs. 4a-c). Phyllites are typically muscovite-rich and locally garnetiferous, exhibiting fine-to medium-grained textures and well-developed foliation. Quartz-mica schists and garnet-mica schists (Fig.6a) are medium-grained and show compositional banding defined by alternating quartz-rich and mica-rich layers. Quartz occurs as anhedral grains with undulose extinction, while garnet forms high-relief porphyroblasts containing inclusion trails, consistent with syn- to post-tectonic growth during regional metamorphism of pelitic rocks. Comparable lithological assemblages have been described from schist belts elsewhere in Nigeria and interpreted as metamorphosed pelitic to semi-pelitic protoliths.

Modal mineralogical compositions (Table 1) indicate that phyllites and schists are dominated by quartz, muscovite, feldspar, biotite, and chlorite, with garnet occurring as an accessory phase in some samples. Petrographic observations reveal aligned mica flakes, recrystallized quartz grains, and locally strained feldspar, consistent with low-grade regional metamorphism consistent with low-grade regional metamorphism under Barrovian to Abukuma conditions.

Medium-Grade Metasediments

Amphibolites occur as isolated, unmappable bodies within the western Oban Massif, particularly near Akwa Ibami and Awi. These rocks are medium-grained, dark-colored, and composed predominantly of hornblende, plagioclase, quartz, biotite, and garnet, with epidote and opaque oxides. Hornblende occurs as pleochroic prismatic crystals forming a nematoblastic texture, while plagioclase displays low relief and polysynthetic twinning. Quartz occurs as minor interstitial grains with accessory opaque minerals. These features are typical of amphibolite-facies metamorphism of mafic protoliths. Similar amphibolitic units have been reported within the Oban-Obudu basement and interpreted as metamorphosed mafic protoliths related to arc-related basaltic sources. Under the microscope, hornblende exhibits strong pleochroism, medium relief, and subhedral to euhedral crystal forms. The mineral assemblage and texture are indicative of medium-grade metamorphic conditions and suggest derivation from mafic protoliths, consistent with amphibolite-facies metamorphism reported from Pan-African basement terranes in Nigeria.

3. Results

Intrusive Rocks

Intrusive lithologies in the western Oban Massif include pegmatites (Fig. 6b) and quartz-feldspathic veins that occur as discordant bodies within the metasedimentary host rocks. Pegmatites are coarse-grained, non-foliated to weakly foliated [38] and composed primarily of quartz, plagioclase, K-feldspar, muscovite, and biotite, with accessory tourmaline, garnet, and opaque minerals. Quartz occurs as anhedral grains with uniform extinction, feldspar as subhedral twinned crystals, and muscovite as coarse flakes within the quartz-feldspar matrix, consistent with pegmatitic crystallization from evolved granitic melts [39]. Such mineral assemblages are characteristic of rare-metal pegmatites documented across Nigerian Basement Complexes [40].

Quartz-feldspathic veins are typically milky white to white in color and range in width from less than 0.3 m to approximately 0.9 m, with traceable lengths of up to 150 m in places. Their emplacement along fractures and shear zones reflects strong structural control, a feature commonly associated with hydrothermal mineralization systems in schist belts.

Table 1: Modal compositions of dominant rocks from the western Oban massif area

Sample ♯ / Rock type	**AKP2 Phl**	**AKP3 QMS**	**AKP4 GMS**	**AWIA AMP**	**AKP5 PEG**	**BET2 PEG**	**AKAB PEG**	**AKTP4 QV**
Quartz	25	27	20	10	25	23	22	70
Plagioclase	5	7	10	15	15	18	16	15
K-feldspar	-	-	-	-	10	22	30	11
Muscovite	55	24	30	-	15	15	-	-
Biotite	5	26	22	10	27	5	5	2
Garnet	-	-	10	8	1	2	1	1
Hornblende	-	2	-	50	3	5	7	-
Chlorite	7	5	4	2	-	-	-	-
Pyroxene	-	-	-	1	1	-	12	-
Epidote	-	-	2	2	-	1	1	-

Opaque oxides	2	1	2	2	2	1	2	3
Tourmaline	-	8	-	-	5	8	4	-
Rutile	-	-	-	-	1	-	-	-
Sericite	1	-	-	-	-	-	-	-
Total	100	100	100	100	100	100	100	100

<u>Legend</u>

AKP2 = Phyllite, AKP3 = Quartz mica schist, AKP4 = Garnet mica schist, AWIA = Amphibolite at Awi, AKP5 = Pegmatite at Akpet 1, BET2 = Pegmatite at Betem, AKAB = Pegmatite at Akwa Ibami, AKTP4 = Quartz vein,

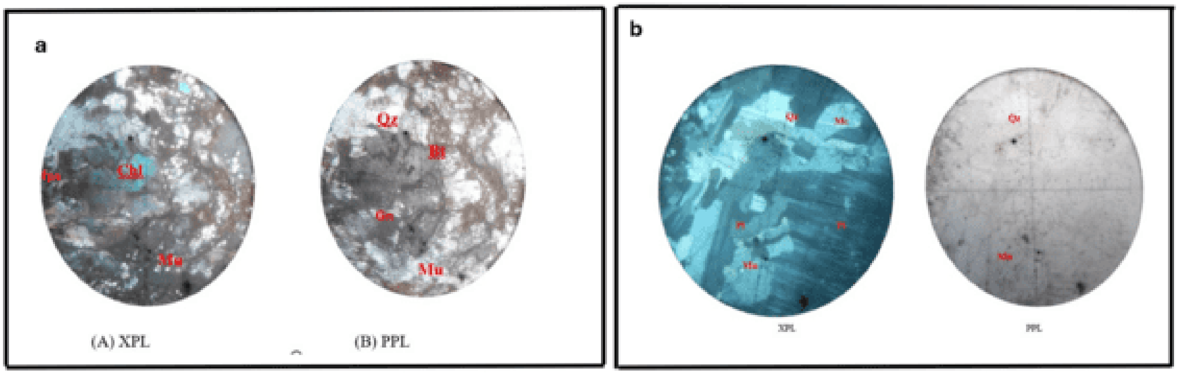

Figure 6: Photomicrographs of rocks from Akpet 1, showing mineral assemblages under cross-polarized light (XPL) and plane-polarized light (PPL). (a) garnet schist, composed of quartz (Qz), plagioclase (Pl), muscovite (Mu), biotite (Bt), chlorite (Chl), feldspar (Fsp), and garnet (Gn), and (b) pegmatite, composed predominantly of quartz (Qz), plagioclase (Pl), muscovite (Mu), and microcline (Mc).

Whole-Rock Geochemical Analysis

Analytical Method

Whole-rock geochemical analyses were performed on selected representative samples of metasediments, meta-igneous rocks, pegmatites, and quartz veins (Table 2) to determine major oxide, trace element, and rare earth element (REE) concentrations (Table 3). Analytical work was conducted at Activation Laboratories Ltd., Ancaster, Ontario, Canada, using a combination of inductively coupled plasma mass spectrometry (ICP-MS), inductively coupled plasma atomic emission spectrometry (ICP-AES), and instrumental neutron activation analysis (INAA) [41].

For ICP-MS analysis, approximately 0.5 g of powdered sample was digested using a mixed acid solution of HF, HNO_3, and $HClO_4$ in open Teflon vessels under controlled heating conditions (90–100 °C). The resulting solutions were evaporated to dryness, redissolved in HCl, and analyzed for major and trace element concentrations. Analytical accuracy and precision were monitored using blanks, duplicate samples, and certified reference materials.

INAA was employed to quantify selected trace elements, including low-field-strength elements (LFSE), high-field-strength elements (HFSE), thorium, tantalum, and selected rare-earth elements (REE), following standard procedures outlined by [42]. The combined analytical methods provide near-total elemental concentrations with precision and accuracy typically within 2-10%, consistent with international geochemical standards.

Results of Structural and Geochemical Investigations

Structural Features

Structural analysis of basement rocks in the western Oban Massif reveals the presence of both planar and linear deformation features developed within the metasedimentary and meta-igneous units, as well as locally within intrusive bodies. The dominant planar structures include foliation, fractures, shear zones, and faults, while linear structures comprise mineral lineation, folds, and pinch-and-swell features [43].

Foliation is best developed in the phyllites and schists, where it is defined by the preferred orientation of mica minerals and elongate quartz aggregates. Measured foliation orientations show dominant trends in the N-S, NE-SW, and NW-SE directions, with subordinate E-W orientations. Stereographic analysis of structural data indicates multiple maxima corresponding to these trends (Fig. 7), suggesting the superposition of polyphase deformation events, documented for the Nigerian Basement Complex [44].

Fractures and shear zones occur both parallel and oblique to foliation planes and are commonly observed in proximity to lithological contacts between metasediments and intrusive rocks. Quartz-feldspathic veins and pegmatites are frequently localized along these structures, indicating that deformation features acted as conduits for late-stage magmatic and hydrothermal fluids.

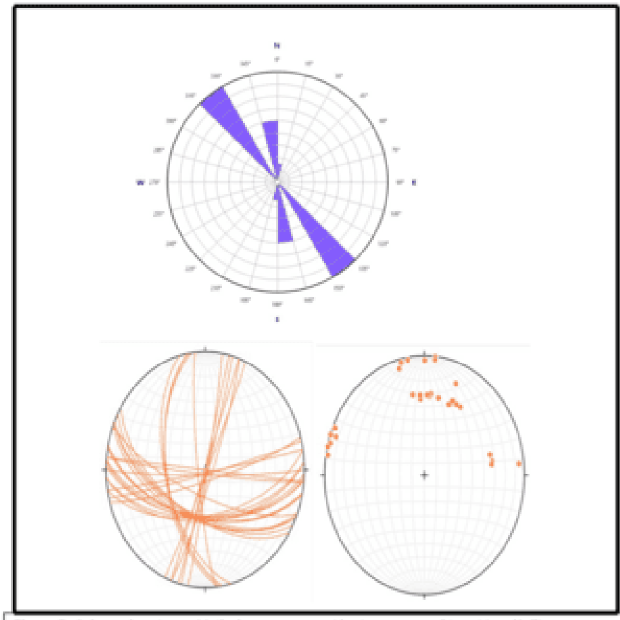

Figure 7: Orientation data of foliations measured in the western Oban Massif. The upper panel shows a rose diagram of foliation strike directions. Lower panels show lower-hemisphere, equal-area stereographic projections of foliation planes (left) and corresponding poles to foliation (right)

Major Element Geochemistry

Major-element compositions show systematic variations among lithological units in the western Oban Massif (Table 2). Metasedimentary rocks (phyllites and schists) and felsic intrusive rocks (pegmatites and quartz-feldspathic veins) are generally silica-rich, with SiO_2 contents exceeding 65 wt.%. In contrast, amphibolite samples display lower SiO_2 contents (<52 wt.%), consistent with their petrographic classification as metamorphosed mafic rocks. Comparable compositional distinctions between felsic metasedimentary units and mafic amphibolites have been reported from other Nigerian basement terranes [45].

Metasediments and pegmatites are characterized by elevated concentrations of SiO_2, Al_2O_3, and total Fe_2O_3, whereas MnO, MgO, CaO, Na_2O, TiO_2, and P_2O_5 generally occur at low levels. High silica and alumina contents in pegmatites are typical of chemically evolved granitic systems and are commonly associated with late-stage magmatic differentiation and hydrothermal modification in rare-metal pegmatite provinces. The low concentrations of CaO and MgO across most felsic lithologies further indicate limited carbonate involvement during alteration.

Quartz-feldspathic veins are distinguished by extremely high SiO_2 contents, locally approaching ~99 wt.%, and correspondingly low abundances of other major oxides. These compositions are consistent with quartz-dominated hydrothermal vein systems documented in schist belts of northwestern Nigeria and other Precambrian basement terrains. Owing to their near-monomineralic character, quartz veins primarily record silica precipitation from hydrothermal fluids rather than primary magmatic compositions.

Amphibolites in the study area exhibit hornblende-plagioclase mineral assemblages consistent with metamorphosed mafic protoliths. However, their present major-element compositions deviate from typical basaltic values, particularly in showing elevated Al_2O_3 and comparatively low CaO, Na_2O, and MgO contents. These features are interpreted to reflect element redistribution during regional metamorphism and localized fluid-rock interaction rather than primary igneous chemistry. Consequently, amphibolite samples are considered separately from felsic lithologies in major-element ratio evaluations and are not used to infer hydrothermal fluid sources.

Calculated major-element ratios (e.g., SiO_2/Al_2O_3, K_2O/SiO_2, Na_2O/CaO) are presented (Fig. 8a-c) and summarized (Table 3). These ratios are used here as comparative indicators of silica enrichment, alkali redistribution, and carbonate depletion rather than as definitive fluid-source discriminants. High SiO_2/Al_2O_3 ratios observed in metasediments, pegmatites, and especially quartz veins primarily reflect progressive silica enrichment and quartz precipitation during hydrothermal activity. Low CaO/Al_2O_3 and MgO/Al_2O_3 ratios across felsic lithologies indicate carbonate-poor alteration conditions, suggesting minimal involvement of calcite- or dolomite-rich fluids.

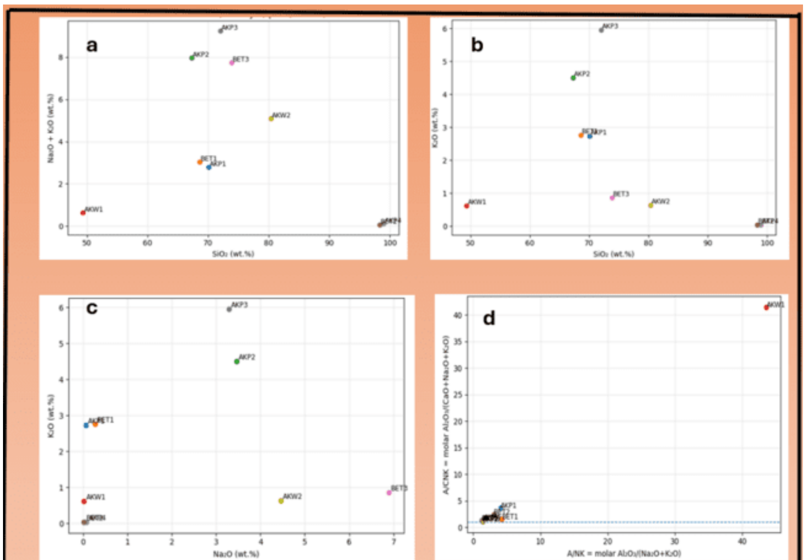

Figure 8: Major-element variation diagrams for representative rock samples from the study area. Plots show relationships between **(a)** SiO_2 and total alkalis ($Na_2O + K_2O$), **(b)** SiO_2 and K_2O, **(c)** Na_2O and K_2O, and **(d)** $Al_2O_3/(CaO+Na_2O+K_2O)$ and $Al_2O_3/(Na_2O+K_2O)$ (all in wt.%), illustrating compositional variability among analyzed samples.

Table 2: Major elements and normative compositions of Western Oban rock samples

SAMPLES	AKP1	BET1	AKP2	AKW1	AKP4	BET2	BET3	AKP3	AKW2
Oxides (wt. %)									
SiO_2	70.10	68.60	67.30	49.38	98.97	98.30	73.86	72.01	80.36
TiO_2	0.99	0.87	0.62	0.47	0.01	1.28	0.01	0.01	0.05
Al_2O_3	12.44	14.58	15.04	30.70	0.26	0.20	15.21	15.32	12.03
Fe_2O_3	6.40	5.35	2.73	6.29	1.17	1.38	1.04	0.86	1.33

MnO	0.18	0.13	0.16	0.01	X	X	0.04	0.04	X
MgO	0.92	1.41	3.18	0.14	0.03	0.01	0.05	0.04	0.27
CaO	0.21	3.35	1.85	0.02	0.01	0.01	0.18	0.03	1.21
Na_2O	0.06	0.27	3.46	0.02	0.08	0.02	6.89	3.29	4.46
K_2O	2.73	2.76	4.51	0.62	0.03	0.03	0.86	5.96	0.63
P_2O_5	0.02	0.21	0.58	0.08	0.01	0.01	0.29	0.12	X
LOI	8.15	2.30	0.32	2.68	0.01	0.17	0.87	1.02	0.63
Total	**100.0**	**99.57**	**99.75**	**100.4**	**100.6**	**99.27**	**100.5**	**98.71**	**98.95**
Niggli Values									
Si	446.66	335.617	280.359	210.344	8346.723	8054.544	427.6	428.883	445.671
Al	46.705	42.03	36.917	77.055	12.92	9.656	51.885	53.763	48.058
Fm	40.397	30.519	28.872	21.087	78.023	86.31	5.158	4.411	6.725
C	1.434	17.559	8.257	0.091	0.904	0.878	1.116	0.191	5.549
Alk	11.465	9.893	25.955	1.767	8.154	3.156	41.841	41.634	39.668
K	0.968	0.871	0.462	0.953	0.198	0.497	0.076	0.544	0.545
Mg	0.216	0.337	0.684	0.042	0.048	0.014	0.084	0.081	0.185
c/fm	4.745	3.202	1.943	1.506	0.634	78.896	0.044	0.045	0.403
Ti	0.054	0.435	1.023	0.144	0.357	0.347	0.711	0.303	0
P	0.035	0.575	0.286	0.004	0.012	0.01	0.216	0.043	0.825
Qz	300.8	196.046	76.541	103.276	8214.109	7941.918	160.238	162.347	186.998
CIPW Norms									
Q	57.545	47.786	22.852	46.688	98.356	98.065	30.426	30.011	32.812
C	9.052	5.56	2.491	29.996	0.096	0.135	2.944	3.456	0.81
Or	16.134	16.311	26.653	3.664	0.177	0.177	5.082	35.222	33.626
Ab	0.508	2.285	29.278	0.169	0.677	0.169	58.301	27.839	26.485
An	0.911	15.248	5.389	0	0	0	0	0	4.316
Di	2.292	3.512	7.922	0	0.075	0.025	0.125	0.1	0.349
Hy	0.385	0.278	0.342	0.349	0	0	0.102	0.102	0
Il	6.401	5.35	2.73	0.021	1.17	1.38	0.019	0.019	0.064
Hm	0.788	0.724	0.44	6.291	0.01	1.281	0.97	0.79	1.19
Tn	0.047	0.497	1.374	0	0.018	0.018	0	0	0.056
Ru	0	0	0	0.459	0.01	0.01	0.324	0.054	0
Sum	94.06	97.55	99.47	87.673	100.58	101.25	98.29	97.59	99.71

Legend: AKP1=Phyllite at Akpet 1, AKP2 = schist at Akpet 1, BET1 = Schist at Betem, AKW1 = Amphibolite located near Akwa Ibami, AKP4 = Quartz-vein, BET2 = Quartz-vein at Betem, BET3 = Pegmatite at Betem, AKP3 = Pegmatite at Akpet 1, AKW2 = Pegmatite at Akwa Ibami

Low K_2O/SiO_2 ratios in schists/phyllites and pegmatites are consistent with relative potassium enrichment associated with K-feldspar–bearing assemblages and potassic metasomatism. Similarly, low Na_2O/Al_2O_3 ratios across most felsic lithologies point to a dominantly crustal geochemical environment, although these ratios are not interpreted as uniquely diagnostic of fluid origin. Elevated Na_2O/CaO ratios in pegmatites and quartz veins suggest localized albite-related alteration accompanying fluid-rock interaction, whereas Na_2O/K_2O ratios below unity indicate potassium dominance over sodium in the altered systems.

Alumina saturation indices (Fig. 8d) show that most felsic samples cluster around metaluminous to weakly peraluminous compositions, consistent with evolved crustal granitic and pegmatitic contexts. In contrast, amphibolite samples yield artificially high A/CNK values owing to low alkali and CaO contents, reinforcing the interpretation that alumina saturation indices are not appropriate petrogenetic indicators for altered mafic lithologies in this study.

Overall, the major-element geochemical characteristics of the western Oban Massif indicate a silica-rich, carbonate-poor hydrothermal system operating within a dominantly crustal basement. Alkali redistribution, particularly involving potassium and locally sodium, reflects fluid-rock interaction focused along structurally controlled pathways, consistent with hydrothermal modification documented in Nigerian schist belts and comparable Precambrian basement provinces.

Table 3: Major element ratios of rocks from the western Oban massif (Interpretive implication after, applied as comparative indicators)

Major oxide ratios & sample	Values for Oban-Obudu basement area				Remarks
Rock specimen	Schists/phyllite	Amphibolite	Quartz-vein	Pegmatite	
SiO_2/Al_2O_3	5.07	1.62	380.85	5.46	Suggests quartz-rich hydrothermal veins in the selected rocks of the study area
CaO/Al_2O_3	0.11	0.12	0.04	0.07	Suggests calcite-poor hydrothermal veins
MgO/Al_2O_3	0.11	0.20	0.08	0.01	Suggests dolomite-poor hydrothermal veins
K_2O/SiO_2	0.34	0.02	0.003	0.08	Consistent with potassic alteration and K-feldspar enrichment

Na_2O/Al_2O_3	0.19	0.11	0.11	0.06	Suggests crustal ore fluid source
Na_2O/CaO	1.14	0.44	4.0	3.60	Indicate albite-rich fluid mineralization
K_2O/Al_2O_3	11	233	33	22	Suggests feldspar-controlled bulk-rock chemistry
Na_2O/K_2O	0.7	0.1	0.7	0.6	Consistent with feldspar-controlled bulk chemistry and a crustal geochemical environment.

Legend:

SiO_2/Al_2O_3 > 1 suggests quartz-rich hydrothermal mineralization potential
CaO/Al_2O_3 < 1 indicates calcite-poor hydrothermal mineralization potential
MgO/Al_2O_3 < 1 suggests dolomite-poor hydrothermal mineralization
K_2O/SiO_2 < 1 suggests k-feldspar-rich hydrothermal mineralization potential
Na_2O/Al_2O_3 < 1 is consistent with a crustal-dominated geochemical environment
Na_2O/K_2O < 1 reflects relative potassium enrichment over sodium
Na_2O/CaO > 1 suggests albite alteration-related mineralization potential
K_2O/Al_2O > 1 may reflect potassic enrichment potentially associated with metamorphic or magmatic-hydrothermal processes

Trace Element Geochemistry

Trace-element concentrations of rocks from the western Oban Massif (Table 4) display pronounced lithology-dependent variability and record the combined influence of protolith composition, magmatic differentiation, and hydrothermal redistribution. Metasedimentary rocks (phyllites and schists) are variably enriched in large-ion lithophile elements (LILE) and selected high-field-strength elements (HFSE), including Ba, Rb, Sr, Zr, Y, and Zn, whereas concentrations of Ni, Cu, Pb, and Ta are generally lower and more heterogeneous. Such patterns are consistent with derivation from crustal sedimentary protoliths subsequently modified by metamorphism and fluid-assisted element redistribution, as documented in Nigerian schist belts and other Precambrian basement terranes.

Amphibolites exhibit trace-element signatures distinct from the felsic lithologies, including relatively higher abundances of transition metals such as Cr, Co, Ni, and V, reflecting their mafic protolith affinity. Variable enrichment of Ba, Sr, and Y suggests limited but discernible fluid-rock interaction during metamorphism. Given that major elements in amphibolites may be affected by post-protolith modification, trace-element behavior provides the primary basis for evaluating their contribution to the hydrothermal system. Lithology-dependent variations in fluid-mobile and incompatible elements are further illustrated by trace-element bivariate plots (Fig. 9), which highlight systematic differences between metasediments, amphibolites, pegmatites, and quartz veins.

Pegmatites show characteristic enrichment in incompatible elements associated with evolved granitic systems, notably Rb, Ba, Sr, Ta, and Zr (Table 4). Elevated Rb and Ta contents are consistent with late-stage magmatic fractionation and/or fluid-assisted enrichment typical of rare-metal pegmatite environments in the Nigerian Basement Complex and comparable global provinces. These geochemical features indicate that pegmatites acted as chemically evolved reservoirs capable of concentrating incompatible and fluid-mobile elements.

Quartz-feldspathic veins are strongly silica-dominated and display localized enrichment in Zn, Cr, Co, Pb, and Sr relative to their metasedimentary host rocks. Such enrichment patterns are consistent with structurally controlled hydrothermal concentration within fracture- and shear-zone-hosted vein systems, where fluid flow and pressure–temperature gradients promote selective metal precipitation. Owing to their near-monomineralic composition, quartz veins primarily record hydrothermal metal redistribution rather than primary magmatic signatures.

Gold was detected only at trace levels and in a limited number of samples (Table 4). Although these concentrations are well below economic thresholds, the occurrence of trace Au within quartz veins and pegmatites indicates that hydrothermal fluids circulating within the western Oban Massif were capable of mobilizing gold at low concentrations. Similar trace-level gold signatures have been reported from structurally controlled hydrothermal systems in Nigerian schist belts, where early or weakly developed mineralization precedes economic concentration.

Overall, trace-element distributions in the western Oban Massif reflect a system dominated by crustal protolith control and late-stage hydrothermal redistribution rather than primary ore-forming magmatism. Enrichment is generally background to moderate in metasedimentary and amphibolitic units, with localized significant to extreme enrichment restricted to pegmatites and quartz veins. These characteristics are typical of reconnaissance-scale hydrothermal systems in Precambrian basement terranes and support the interpretation of structurally focused fluid activity without implying regionally pervasive or ore-grade mineralization.

Table 4: Trace element compositions of Western Oban rock samples

Sample / Elements (ppm)	AKP 1	BET1	AKP 2	AKWI	AKP4	BET2	BET3	AKP3	AKW2
Au (ppm)	0.00031	0.00012	0.0018	-	0.0001	0.0018	0.00036	0.0002	0.00016
Ag		-		-	-	-	-	-	-
As		-		2.0	-	-	2.0	-	-
Ba	910	309	775	809	2490	363	809	69	43
Be	9	18	11	2	8	-	2	112	248
Bi	-	-	-	-	-	-	-	-	3
Co	10	25	16	28	-	4	28	2	-
Cr	176	277	305	46	341	489	46	112	152
Cs	12	24	1254	3	8	2	3	45	25
Cu	43	40	3	35	35	13	35	7	6

Hf	6.7	4	6	7	6	6	7	-	2
Mo	1.3	-	0.86	-	8	8	-	-	4
Ni	6.4	35	32	28	16	17	28	7	8
Pb	6.9	16	2.7	7	24	12	7	22	-
Rb	179	170	1287	40	80	-	40	960	270
S (%)	0.9	.004	1.5	.11	0.004	0.009	.11	.002	.003
Sb	0.4	0.4	0.8	-	2.4	-	-	0.9	-
Sc	2	13.1	16	25.1	2.2	2.1	25.1	0.8	0.8
Sr	250	400	300	404	450	506	404	28	30
Ta	2	27	24	-	12	-	-	8	35
Th	14,4	7	13		7.8	14.2	2.9	-	1.2
U	2.6	6.4	2.2	2.9	13.4	1.4	-	1.5	4.6
V	67	6.0	109	-	18	16	203	-	8
Y	5.6	165	18	203	11	10	43	-	1
Zn	78	17	95	43	16	15	116	31	242
Zr	245	65	216	116	203	251	272	7	12

Legend: See Table 2

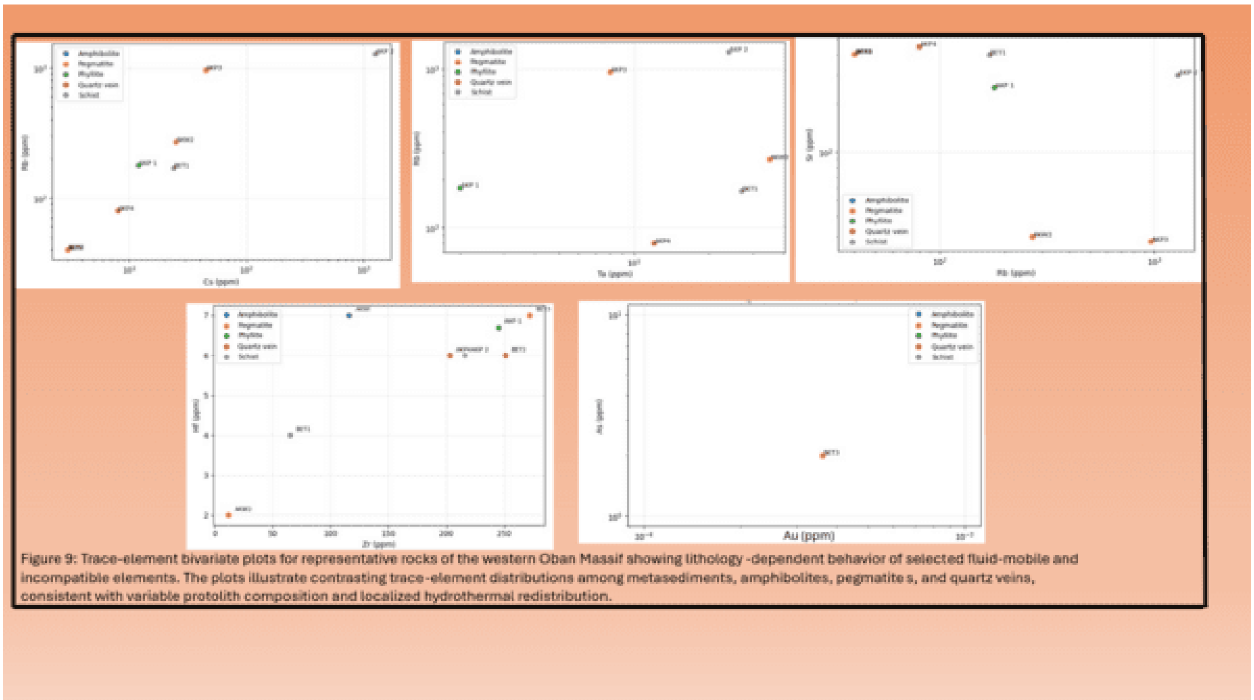

Figure 9: Trace-element bivariate plots for representative rocks of the western Oban Massif showing lithology -dependent behavior of selected fluid-mobile and incompatible elements. The plots illustrate contrasting trace-element distributions among metasediments, amphibolites, pegmatite s, and quartz veins, consistent with variable protolith composition and localized hydrothermal redistribution.

4. Discussion

Structural Framework and Control on Hydrothermal Processes

The structural architecture of the western Oban Massif exerts fundamental control on lithological emplacement, fluid migration, and hydrothermal modification. Field observations and structural analysis document a complex network of foliations, shear zones, fractures, and faults predominantly oriented N–S, NE–SW, and NW–SE (Fig. 7), reflecting polyphase deformation linked to successive Precambrian tectonothermal events culminating in Pan-

African orogenesis, consistent with regional patterns across the Nigerian Basement Complex. The spatial association between these deformation structures and intrusive bodies (Fig. 10) is particularly significant, as pegmatites and quartz-feldspathic veins preferentially occur along fractures, shear zones, and lithological contacts, indicating that these features acted as high-permeability conduits for hydrothermal fluids. Comparable structural controls have been documented in Nigerian schist belts such as Anka, Maru, and Birnin Gwari, where fluids exploited pre-existing fabrics to redistribute and locally concentrate metals. In the western Oban Massif, the absence of regionally extensive mineralized horizons and the dominance of vein-controlled occurrences further underscore the primacy of structural permeability over stratigraphic control in governing metal redistribution.

Structural corridors enhance hydrothermal circulation by promoting pressure gradients, fluid focusing, and repeated fluid-rock interaction during deformation and exhumation (Fig. 10). Quartz veins, in particular, represent sites of silica precipitation from hydrothermal fluids during episodic fluid flow, while pegmatites record late-stage magmatic and magmatic-hydrothermal processes. The intimate association of these features with deformation zones suggests syn- to post-tectonic fluid activity, a characteristic feature of hydrothermal systems in Precambrian basement terranes worldwide.

Importantly, the structural framework provides a coherent framework for interpreting the observed lithology-dependent geochemical patterns. Rather than reflecting regionally pervasive mineralization, trace-element enrichment is localized along structurally controlled pathways where fluids interacted most intensively with host rocks. This interpretation is

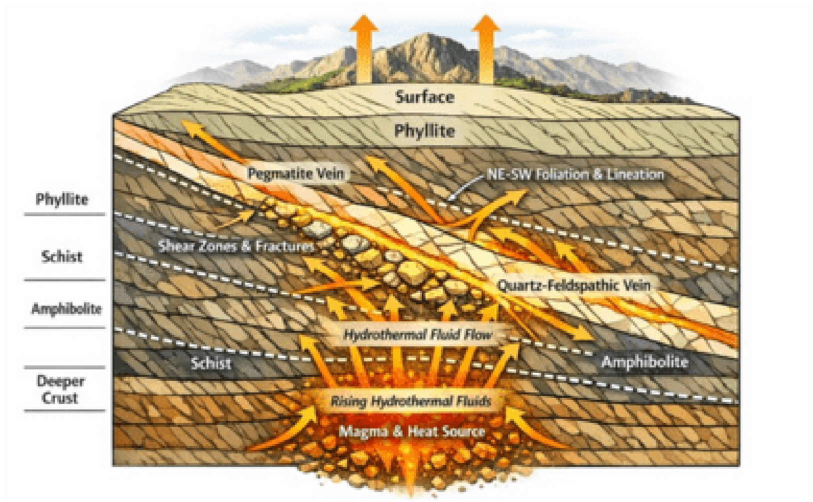

Figure 10: Conceptual tectonomagmatic-hydrothermal model for structurally controlled mineralization within the western Oban Massif, southeastern Nigeria. The model illustrates magma emplacement and associated deep crustal heat input generating buoyant, metal -bearing hydrothermal fluids that ascend through permeable structural corridors, including foliation, shear zones, and fracture networks developed during polyphase deformation. These structures act as preferential conduits for fluid migration, focusing magmatic-hydrothermal flow into the mid- to upper-crustal levels. Interaction between ascending fluids and metamorphic host rocks (amphibolite, schist, and phyllite) promotes mineral precipitation along zones of dilation and reduced pressure. Pegmatite and quartz-feldspathic veins are emplaced syn- to late-tectonically along these structural pathways, reflecting structurally localized melt and fluid transport. The model emphasizes the genetic link between deep magmatic heat sources, deformation architecture, and structurally focused mineralization within Precambrian basement terranes.

consistent with enrichment factor distributions (Table 5), which show significant to extreme enrichment restricted to quartz veins and pegmatites, while surrounding metasedimentary rocks largely retain background to moderate values. The exceptionally high Zn enrichment factor in quartz veins likely reflects localized precipitation within structurally focused conduits rather than regionally pervasive enrichment.

Overall, the structural framework of the western Oban Massif defines a deformation-driven hydrothermal system in which fractures and shear zones governed fluid migration, alteration intensity, and localized metal redistribution. This structural context forms the foundation for interpreting lithological controls, geochemical signatures, and metallogenic implications discussed in subsequent sections.

Table 5: Calculated Enrichment Factor (EF) for trace elements from basement rocks of western Oban. After

Metallic element (ppm)	Background values (ppm) of elements in basement rocks (1-7)					**E. F. (This study)** Oban-Obudu basement rock specimens				
	Phyllite	Schist	amphibolite	Pegmatite	Quartz-veins	Phyllite	Schist	Amphibolite	Pegmatite	Qtz-vein
Au	0.004	0.004	0.004	0.004	0.004	0.17	2.20	0.04	0.04	0.17
Ba	500-1500	1000-3000	500-1500	500-2000	100-500	1.29	0.45	0.59	0.59	9.21
Co	1-10	5-20	10-50	2-15	0.05-5	1.85	3.18	1.04	5.18	29.6
Cr	50-200	100-500	200-1000	2-100	5-20	2.05	0.16	0.09	6.48	36.19
Cu	10-50	20-100	50-200	20-100	5-50	1.48	0.79	0.26	0.37	2.59
Ni	10-50	20-100	50-250	50-200	2-10	1.29	2.74	0.21	0.22	3.52
Pb	5-20	10-50	20-100	10-20	10-50	3.40	0.52	0.72	0.81	10.18
Rb	50-150	100-300	50-50	50-200	10-50	1.26	4.76	2.78	7.10	2.96
Sr	100-300	200-600	100-300	100-500	50-200	1.48	0.74	1.49	1.49	4.07
Y	10-30	20-50	10-30	20-50	5-20	6.11	2.89	7.51	0.79	1.04
Zn	20-200	30-150	50-250	10-40	5-50	0.87	1.09	0.32	8.95	204.98
Zr	100-500	100-300	100-300	200-1000	50-200	0.24	0.91	0.43	0.50	1.86

Legend:

E.F. = Enrichment Factor.

EF < 1 = Depletion of the element

EF = 1 = Moderate enrichment

EF = 1- 3 = Significant enrichment

EF > 10 = Extreme enrichment.

Enrichment factor (EF) categories are applied here as relative comparative indicators rather than strict metallogenic thresholds, given the variability in background crustal reference values

Lithological Controls, Protolith Contributions, and Metal Sources

The lithological assemblage of the western Oban Massif comprises low- to medium-grade metasediments, amphibolites, and felsic intrusive rocks, each contributing distinct geochemical characteristics to the hydrothermal system. Petrographic data (Table 1) indicate that phyllites and schists are derived from pelitic to semi-pelitic sedimentary protoliths, as evidenced by quartz-mica assemblages, compositional banding, and syn- to post-tectonic garnet growth. These lithologies preserve crustal trace-element signatures characterized by enrichment in Ba, Rb, Sr, Zr, Y, and Zn, reflecting the composition of their sedimentary precursors.

Metasedimentary units serve as effective crustal reservoirs for large-ion lithophile and selected high-field-strength elements. During metamorphism and subsequent fluid circulation, these elements may be partially mobilized and redistributed into structurally favorable sites. The background-to-moderate enrichment levels observed in phyllites, and schists (Tables 4 and 5) are therefore interpreted as reflecting limited hydrothermal modification superimposed on inherited crustal compositions rather than primary ore formation.

Amphibolites are petrographically consistent with metamorphosed mafic protoliths and contribute transition metals such as Cr, Co, Ni, and V to the system. However, their major-element compositions indicate post-protolith modification during metamorphism and fluid-rock interaction, rendering major-element ratios unreliable for petrogenetic discrimination. Consequently, amphibolite contributions are evaluated primarily through trace-element behavior. Variable enrichment of Ba, Sr, and Y suggests limited fluid interaction, whereas elevated Cr and Co concentrations reflect inheritance from mafic precursors.

Pegmatites represent the most chemically evolved lithologies in the study area. Their enrichment in incompatible elements such as Rb, Ta, Zr, and Ba (Table 4) is characteristic of late-stage granitic differentiation and/or fluid-assisted enrichment in rare-metal pegmatite systems. These rocks acted as localized chemical reservoirs capable of concentrating incompatible and fluid-mobile elements, particularly where emplacement coincided with structurally prepared zones.

Quartz-feldspathic veins, by contrast, are near-monomineralic and primarily record hydrothermal precipitation rather than magmatic processes. Their localized enrichment in Zn, Cr, Co, Pb, and Sr reflects selective metal deposition during fluid flow along fractures and shear zones. Together, these lithological contrasts highlight a system in which protolith composition defines elemental availability, while structural control dictates the sites and intensity of hydrothermal redistribution.

Major and Trace Element Systematics and Hydrothermal Modification

Major-element compositions of felsic lithologies in the western Oban Massif reflect silica enrichment and limited carbonate involvement, consistent with quartz-dominated hydrothermal modification within a crustal basement environment. Elevated SiO_2 and Al_2O_3 contents coupled with low CaO and MgO concentrations indicate pervasive silicification, while variations in K_2O/SiO_2 and Na_2O/CaO (Fig. 8a-c) ratios suggest localized potassic and albite-related metasomatism. Alumina saturation indices (A/CNK) show that most felsic samples cluster within metaluminous to weakly peraluminous fields, characteristic of evolved granitic and pegmatitic systems. These major-element trends are interpreted as comparative indicators of silica enrichment and alkali redistribution rather than definitive fluid-source discriminants.

Trace-element distributions and enrichment factor calculations (Table 5) demonstrate that metasedimentary and amphibolitic units generally retain background to moderate abundances, whereas pegmatites and quartz veins exhibit localized significant to extreme enrichment in selected elements. This pattern indicates focused fluid-rock interaction along deformation zones rather than regionally pervasive alteration, consistent with structurally localized hydrothermal modification documented in Nigerian schist belts and comparable Precambrian basement terranes.

Trace-element bivariate plots (Fig. 9) illustrate lithology-dependent behavior of fluid-mobile and incompatible elements, highlighting systematic differences between host rocks and structurally controlled veins and pegmatites. These plots reinforce the interpretation that trace-element enrichment is controlled by the interplay between lithology and structural setting. Elements such as Zn, Pb, Cr, and Co show enhanced concentrations in quartz veins relative to host rocks, consistent with selective precipitation from hydrothermal fluids during fracture-controlled flow.

Gold occurs only at trace levels and in a limited number of samples. Although these concentrations are not economically significant, their presence confirms that hydrothermal fluids circulating within the western Oban Massif were capable of mobilizing gold at low concentrations. Similar trace-level Au signatures have been documented in Nigerian schist belts where hydrothermal systems are present but not necessarily ore-forming.

Trace-Element Concentration Patterns and Metallogenic Implications

Trace-element concentrations (Fig. 11a-c) further highlight contrasts among lithological units, with metasedimentary and amphibolitic rocks generally exhibiting background to moderate abundances, while pegmatites and quartz veins display localized enrichment in incompatible and fluid-mobile elements. Pegmatites are characterized by elevated Rb, Cs, Ta, Zr, and Sr, reflecting advanced magmatic differentiation and/or fluid-assisted concentration typical of evolved granitic systems. Quartz-feldspathic veins show selective enrichment in Zn, Pb, Cr, and Co relative to host rocks, consistent with precipitation during fracture-controlled fluid flow. These patterns collectively indicate localized metal redistribution within structurally prepared zones rather than system-wide mineralization.

Pegmatites exhibit markedly higher concentrations of incompatible elements, including Rb, Cs, Ta, Zr, and Sr (Fig. 11d; Table 6). These enrichments are characteristic of evolved granitic systems and reflect late-stage magmatic differentiation and/or fluid-assisted enrichment processes. The high Rb and Cs contents, in particular, indicate advanced fractionation, consistent with rare-metal pegmatite systems documented elsewhere in the Nigerian Basement Complex and comparable Precambrian terranes worldwide [23,38,39,40,44].

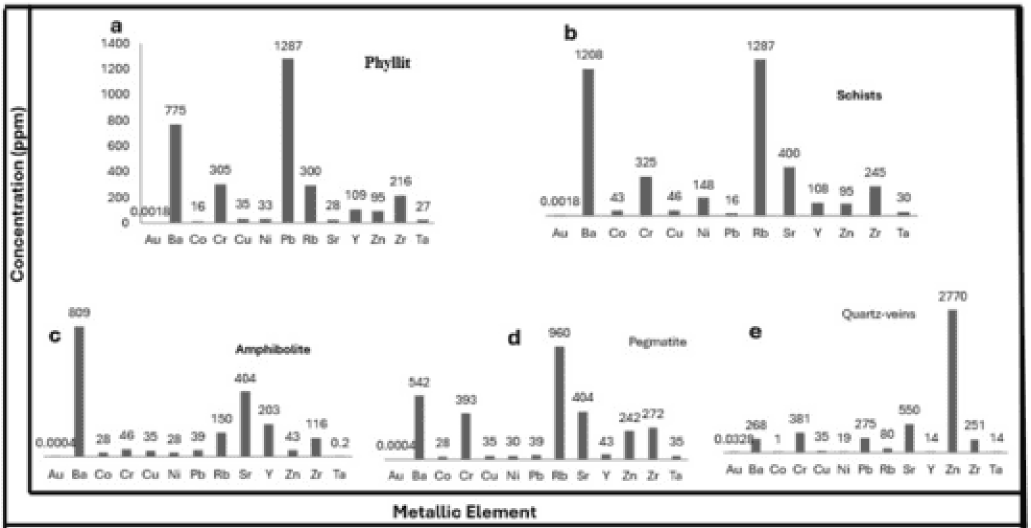

Figure 11: Trace elements concentration patterns (ppm) for the basement lithologies of the western Oban Massif, showing (a) p hyllite, (b) schist, (c) amphibolite, (d) pegmatite, and (e) quartz vein samples. Pegmatite and quartz vein display relative enrichment in selected incompatible and large-ion lithophile elements (e.gs, Rb, Sr, Y, Zr & Pb) compared to metasedimentary host rocks, whereas Au occurs at uniformly low concentration across all lithologies

Table 6: Comparative Trace-Element Concentrations for the western Oban rocks. Modified after [27].

Elements (ppm)	Phyllite	Schist	Amphibolite	Quartz-veins	Pegmatite	Max. Value	Min. value	Range	Background value (ppm)
Au	0.0018	0.0018	0.0004	0.0328	0.0004	0.0328	0.0004	0.0324	0.004
Ba	775	1208	809	268	542	1208	268	940	100-1000
Co	16	43	28	1	28	43	1	42	1-20
Cr	305	325	46	381	393	393	46	347	10-100
Cs	1254	25	35	35	45	1254	25	1229	0.5-10
Cu	35	46	35	35	35	46	35	11	10-50
Ni	33	148	28	19	30	148	19	129	10-50
Pb	1287	16	39	275	39	1287	16	1271	5-20
Rb	300	1287	150	80	960	1287	80	1207	50-150
Sr	28	400	404	550	404	550	28	522	100-300
Y	109	108	203	14	43	203	14	189	10-30
Zn	95	95	43	2770	242	2770	43	2727	20-200
Zr	216	245	116	251	272	272	116	156	100-500
Ta	27	30	20	14	35	35	14	21	5-20

Quartz-feldspathic veins show the most pronounced localized enrichment, particularly in Zn, Pb, Cr, and Co (Fig. 11e). Zinc concentrations reach values that are significantly above those observed in the surrounding host rocks, indicating selective precipitation from hydrothermal fluids within structurally controlled conduits. These patterns are further supported by enrichment factor calculations (Table 5), which demonstrate significant to extreme enrichment of selected elements in quartz veins relative to background crustal values. Importantly, these enrichments are spatially restricted and structurally controlled,

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consistent with vein-hosted hydrothermal systems rather than regionally pervasive mineralization.

Gold concentrations across all lithologies are uniformly low and near or below average crustal background values (Fig. 11a-d; Table 6). Although gold is present only at trace levels, its detection in quartz veins and pegmatites confirms that hydrothermal fluids circulating within the western Oban Massif were capable of mobilizing Au at low concentrations. This behavior is consistent with early-stage or weakly developed hydrothermal systems documented in Nigerian schist belts, where trace Au may be present without economic accumulation .

A comparative summary of trace-element ranges relative to average values in the continental crust is presented in Table 6. This table highlights that most elements occur within background to moderately enriched ranges in metasedimentary and amphibolitic units, whereas pegmatites and quartz veins display locally elevated concentrations of selected elements. The contrast underscores the role of lithology and structural focus in governing metal distribution and supports the interpretation of a hydrothermal system capable of localized metal concentration without evidence for large-scale ore formation.

Taken together, the trace-element concentration patterns illustrated in Figure 11 and summarized in Table 6 reinforce a metallogenic model characterized by crustal protolith control, evolved felsic intrusions, and structurally focused hydrothermal redistribution. While the observed enrichments indicate geochemical permissiveness for metal concentration, they do not, by themselves, imply economic mineralization. Instead, they highlight specific lithologies and structural settings that warrant further targeted investigation.

5. Conclusion

Conclusion

Whole-rock geochemical data indicate that most lithologies in the western Oban Massif are silica-rich, characterized by elevated SiO_2, Al_2O_3, and total Fe_2O_3 and comparatively low concentrations of MnO, MgO, CaO, Na_2O, TiO_2, and P_2O_5. Major-element systematics, trace-element distributions, and enrichment factor calculations collectively record significant fluid-rock interaction, silicification, and localized alkali metasomatism, particularly within structurally controlled pegmatites and quartz-feldspathic veins.

Trace-element concentrations and bar-chart distributions highlight pronounced lithology-dependent behavior, with pegmatites and quartz veins preferentially concentrating incompatible and fluid-mobile elements such as Rb, Sr, Zr, Zn, Pb, Ni, Co, and Ta relative to the surrounding metamorphic host rocks. Enrichment factor and trace-element ratio patterns indicate background to moderate enrichment in metasedimentary and amphibolitic units, with localized significant to strong enrichment restricted to veins and pegmatites, consistent with structurally focused hydrothermal redistribution rather than regionally pervasive mineralization.

Although gold occurs only at trace levels and does not indicate economic mineralization, its presence alongside rare-metal and base-metal signatures within structurally controlled veins and pegmatites confirms the operation of an active hydrothermal system capable of mobilizing ore-related elements during Pan-African tectonism. These geochemical signatures are comparable to hydrothermal systems documented in Nigerian schist belts and other Precambrian basement terranes worldwide.

Overall, the integrated geological, structural, petrographic, and geochemical evidence demonstrates that the western Oban Massif is best interpreted as an underexplored

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Precambrian basement terrane that has experienced deformation-driven hydrothermal metal redistribution. While the present dataset does not support the presence of regionally extensive or ore-grade mineralization, it clearly challenges earlier assumptions that the area is metallogenically barren. Instead, the results highlight geochemical permissiveness for localized metal concentration, particularly within structurally controlled pegmatites and quartz veins.

Future Research

Future research in the western Oban Massif should focus on refining the structural, mineralogical, and geochemical controls on hydrothermal metal redistribution identified in this study. High-resolution structural mapping integrated with geophysical methods (e.g., aeromagnetic surveys, electrical resistivity, and induced polarization) would help delineate subsurface fracture networks and shear zones that acted as conduits for hydrothermal fluids. Systematic soil and stream-sediment geochemical surveys targeting fluid-mobile and incompatible elements (e.g., Zn, Pb, Cu, Co, Ni, Rb, Sr, Ta, and Zr) are needed to assess the spatial extent of hydrothermal alteration beyond exposed outcrops. Detailed mineralogical and microanalytical studies, including SEM, EPMA, and LA-ICP-MS, coupled with fluid inclusion and stable isotope analyses, would further constrain metal hosts, alteration processes, and fluid characteristics. Establishing geochronological constraints on pegmatite emplacement, vein formation, and deformation using U-Pb and Ar-Ar methods would clarify the timing of hydrothermal activity within the Pan-African framework. Where multiple datasets converge, carefully targeted subsurface investigations may be warranted to evaluate the continuity and significance of hydrothermal alteration at depth, thereby advancing the understanding of metallogenic processes in this underexplored Precambrian basement terrane.

Declaration of Competing Interests

The authors declare that there are no financial, professional, or personal conflicts of interest that could have influenced the research presented in this study. All analyses and interpretations presented are based on the authors' independent research.

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