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Geochemical and Mineralogical Evidence for Contrasting Gold Mineralisation Systems in the Oban Massif and Obudu Plateau, Southeastern Nigeria

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Abstract

Artisanal gold occurrences are widely distributed in the Oban Massif and Obudu Plateau, south-eastern Nigeria. This study presents the first integrated metallogenic investigation of these basement terranes using stream-sediment geochemistry, gold-grain microchemistry and mineral inclusion analysis. A total of 120 stream-sediment samples from eight drainage systems were analysed by ICP–MS, while recovered gold grains were characterised using SEM–BSE/EDS imaging and CAMECA SX Five EPMA–WDS analyses. Hierarchical Cluster Analysis and Au–Ag–Cu ternary discrimination were applied to constrain mineralisation affinity and ore-forming processes. Results identify two compositionally and metallogenically distinct gold systems. Gold from the Oban Massif exhibits angular to sub-angular morphologies, heterogeneous internal textures and moderate fineness values (781–1000; mean ~905). Associated sericite/illite, muscovite and cassiterite inclusions, together with coherent Au–As–Sb–Cu–Pb–Zn–S–Mo stream-sediment signatures, indicate predominantly shear-controlled orogenic-hydrothermal mineralisation with a minor intrusion-related Sn-bearing overprint. In contrast, gold from the Obudu Plateau displays rounded morphologies, homogeneous compositions and consistently high fineness values (987–1000; mean ≈996). Stream sediments contain monazite, zircon and ilmenite, with diffuse Au–K_2O–Ba–U lithophile associations, indicating derivation from a high-temperature magmatic-hydrothermal system spatially associated with Late Pan-African granitoid intrusions. Collectively, the data support a two-stage metallogenic evolution involving Late Pan-African hydrothermal emplacement (~600–550 Ma), followed by Cenozoic weathering, mechanical dispersion and placer concentration. The study demonstrates significant metallogenic heterogeneity across a single transect of the Pan-African basement and proposes a new exploration model for these basement terranes.

Keywords: gold metallogeny, stream-sediment geochemistry, Pan-African basement.

1.0 Introduction

Gold mineralisation in Precambrian mobile belts is commonly associated with large-scale crustal deformation, fluid migration, granitoid magmatism and lithospheric reworking during episodes of continental assembly and tectonic accretion [1–3]. The Neoproterozoic orogenic systems associated with the Pan-African cycle constitute one of the most important but relatively poorly studied metallogenic provinces in the world, spanning the Arabian–Nubian Shield, Central Africa, and portions of West Gondwana [4]. These basements exhibit different styles of gold mineralisation, ranging from structurally controlled orogenic systems to intrusion-related and porphyry-associated deposits formed during late- to post-collisional tectono-magmatic evolution [5–7]. Therefore, understanding the genesis and spatial distribution of these systems is critical, not only for mineral exploration, but also for reconstructing crustal evolution during Neoproterozoic continental amalgamation.

Recent advances in ore microchemistry and sediment-based exploration geochemistry have greatly enhanced the characterisation of gold-bearing hydrothermal systems, particularly in deeply weathered Precambrian terrains where primary mineralisation is seldom exposed [8]. Gold-grain morphology, internal textures, alloy composition and mineral inclusion assemblages are useful constraints on transport history, depositional environment, physicochemical conditions of ore formation and possible source lithologies [9, 10]. Similarly, integrated stream-sediment geochemistry continues to be one of the most powerful reconnaissance tools for the recognition of regional hydrothermal footprints and metallogenic zonation in tropical crystalline basement provinces [11]. SEM imaging and EPMA-WDS microanalysis further improved the ability to discriminate between orogenic, intrusion-related and magmatic-hydrothermal gold systems through variations in fineness, trace-element substitution and associated mineral inclusions [12, 13].

The Nigerian Basement Complex is part of the large Pan-African mobile belt between the West African and Congo cratons and is characterised by polyphase deformation, granitoid emplacement, regional metamorphism and shear-zone development associated with the Pan-African orogeny (~750–500 Ma) [14, 15]. The schist belt-hosted gold mineralisation in north-western Nigeria has attracted significant scientific interest but the south-eastern basement regions have remained relatively poorly studied despite increasing artisanal exploitation of alluvial gold occurrences. The Oban Massif and Obudu Plateau in particular are characterised by large exposures of high-grade gneisses, migmatites, granitoids and structurally deformed supracrustal assemblages which may be favourable hosts for different types of hydrothermal mineralisation [16–18]. Yet, the metallogenic affinity, hydrothermal evolution, and source characteristics of the gold occurrences in these basements are still unresolved.

Previous studies in southeastern Nigeria have largely focused on regional lithostratigraphy, structural evolution and reconnaissance mapping of mineral occurrences, with relatively less attention to integrated metallogenic analysis of the gold systems themselves. Basic questions remain as to the genetic classification of the mineralisation, the role of Pan-African deformation and granitoid magmatism in ore formation, and the extent to which the gold systems record a single or multiple hydrothermal events. Additionally, no detailed study has hitherto integrated stream-sediment geochemistry with microchemistry of gold grains and analysis of mineral inclusions in both the Oban Massif and Obudu Plateau.

This study addresses these deficiencies through a combined study of ICP–MS multi-element stream-sediment geochemistry, SEM–BSE/EDS gold-grain characterisation, and CAMECA SX Five EPMA–WDS microchemical analysis of placer gold recovered from eight drainage systems across south-eastern Nigeria. Hierarchical Cluster Analysis and Au–Ag–Cu compositional discrimination were also used to constrain elemental associations and metallogenic affinity. The study aims at: (i) characterising the geochemical signatures of gold-bearing drainages in the Oban Massif and Obudu Plateau; (ii) determining the compositional and microtextural characteristics of the recovered gold grains; (iii) assessing the genetic significance of mineral inclusion assemblages and alloy chemistry; and (iv) establishing a metallogenic model for gold mineralisation in this segment of the Pan-African mobile belt. The results provide new constraints on the diversity of Neoproterozoic gold systems in West Africa, and contribute to the broader understanding of metallogenesis in deeply weathered Precambrian basements.

1.1. Geological setting

The basement regions of south-eastern Nigeria belong to the vast Neoproterozoic Pan-African mobile belt created during the assembly of Gondwana between the West African and Congo cratons (Fig. 1) [19, 20]. This orogenic belt is spread over large areas of West and Central Africa and documents complex interactions of continental collision, crustal thickening, transcurrent shearing, granitoid magmatism and widespread hydrothermal activity related to the Pan-African tectonothermal event (~700–500 Ma) [21–23]. In many parts of the belt, late- to post-collisional deformation was accompanied by widespread fluid circulation and the intrusion of structurally controlled quartz veins, pegmatites, and granitoid intrusions genetically related to gold and rare-metal mineralisation [1, 3].

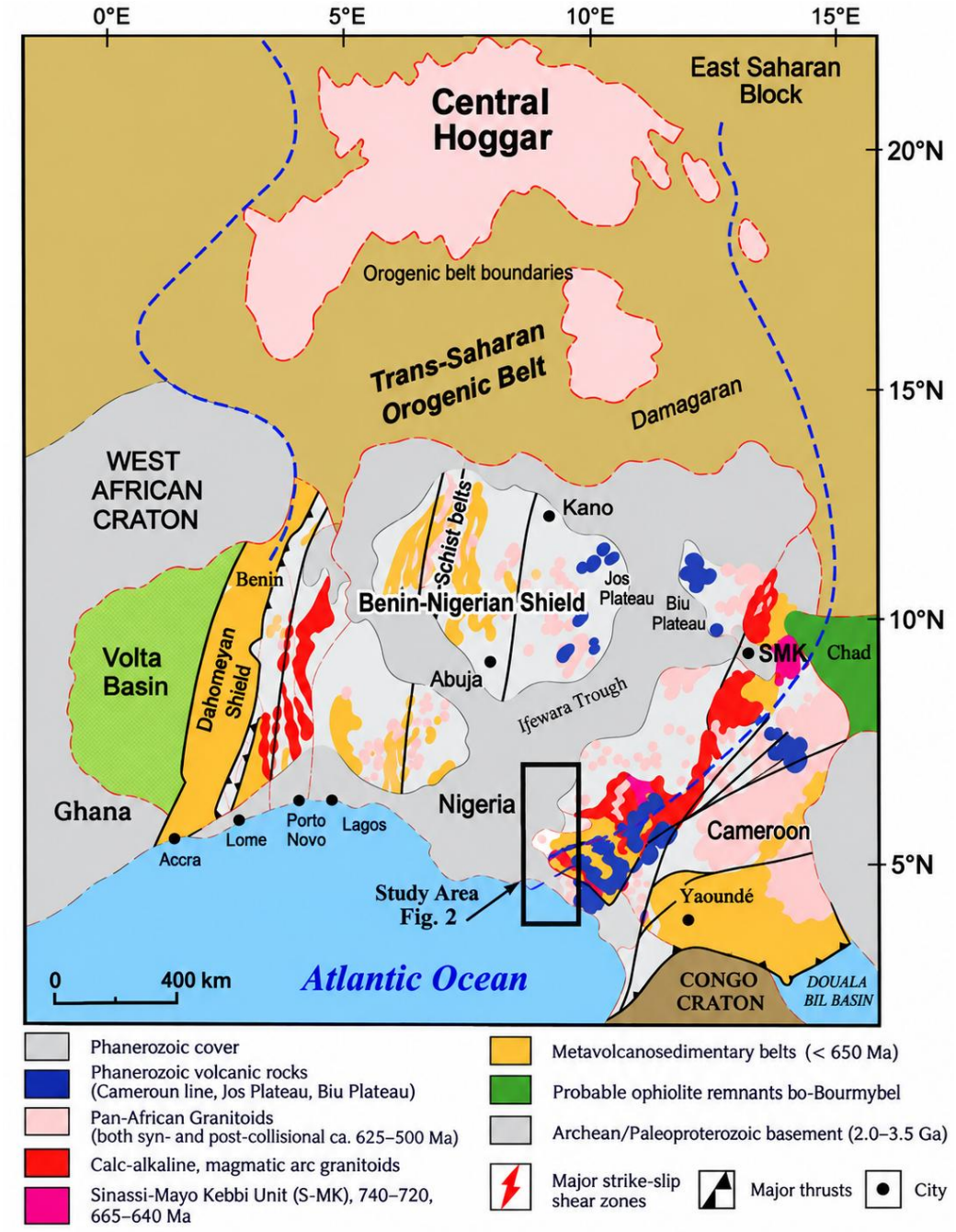


Fig. 1 Regional geological framework of the Hoggar–Air–Nigeria Province. The map shows the Neoproterozoic Trans-Saharan Orogenic Belt formed during terrane amalgamation between the West African Craton, Congo Craton, and the East Saharan Block. The figure highlights the tectonic position of the Nigerian Basement Complex within the Pan-African mobile belt and provides the regional context for Basement terranes of southeastern Nigeria discussed in this study (modified after [24])

The Nigerian Basement Complex represents the eastern continuation of this mobile belt and consists predominantly of migmatite–gneiss complexes, schist belts, Pan-African granitoids, and minor supracrustal assemblages variably affected by high-grade metamorphism and polyphase

deformation [14, 24]. Geochronological studies indicate that the Basement preserves evidence of both Archean–Paleoproterozoic crustal inheritance and Neoproterozoic tectono-magmatic reworking during the Pan-African orogeny [17, 23, 24]. Regional deformation is characterized by penetrative foliations, ductile shear zones, fold systems, and brittle–ductile fracture networks that collectively controlled magma emplacement and hydrothermal fluid migration [14, 25].

The Oban Massif and Obudu Plateau constitute the principal Basement uplifts of southeastern Nigeria and preserve some of the most extensive exposures of crystalline rocks within the Eastern Nigerian segment of the Pan-African belt (Fig. 2).

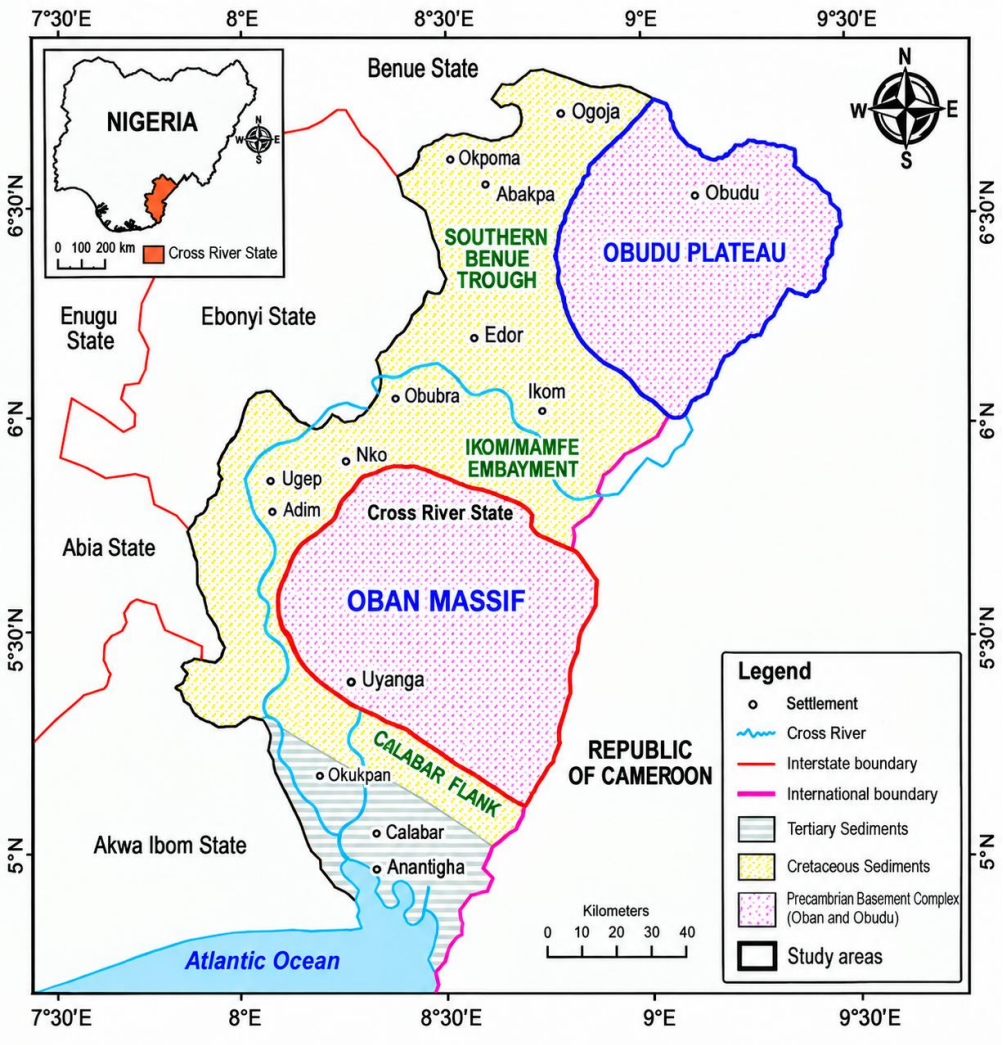


Fig. 2 Location map of the Oban Massif and Obudu Plateau within Cross River State, southeastern Nigeria. Inset shows the position of Cross River State within Nigeria. (Modified after [26])

The Oban Massif forms part of the western extension of the Cameroon Basement domain and is composed mainly of migmatitic and granitic gneisses, amphibolites, mica schists, phyllites, charnockites, and syn- to post-tectonic granitoids intruded by abundant pegmatites and quartz veins

[16, 17, 27]. Rb–Sr isotopic studies indicate dominant Pan-African ages with evidence of older crustal inheritance [17].

Structurally, the massif is characterized by dominant NW–SE foliations and shear fabrics associated with transpressional deformation during the late stages of the Pan-African orogeny [28]. Quartz veining is particularly intense along lithological contacts and sheared margins between gneisses and schists, where hydrothermal alteration assemblages including sericitization, silicification, chloritization, and sulphidation are locally developed [29, 30]. Pyrite ± arsenopyrite occurrences documented within the eastern flank of the massif further indicate hydrothermal fluid interaction and possible sulphide-associated gold mineralization. In addition, the occurrence of Sn–Ta–Nb–Cs–Be–Li-bearing pegmatites [31, 32] suggests the involvement of evolved magmatic fluids and late-stage rare-metal enrichment processes comparable to other Pan-African rare-metal provinces in Central Africa.

The Obudu Plateau, located northeast of the Oban Massif (Fig 2), is similarly underlain by high-grade metamorphic and igneous rocks including granitic gneisses, migmatites, quartzites, amphibolites, and schists intruded by late Pan-African granitoids, pegmatites, and charnockitic bodies [33, 34]. The Plateau records intense ductile deformation and regional metamorphism accompanied by emplacement of porphyritic granites and extensive quartz veining. Structural trends are predominantly NE–SW and locally intersect older fabrics, reflecting multiphase tectonic reactivation during Pan-African deformation. Folded quartz veins and brittle–ductile shear zones indicate progressive deformation during late-stage hydrothermal activity [32]. Hydrothermal assemblages composed of quartz–sericite–chlorite–pyrite ± galena have been reported along fracture-controlled vein systems and sheared granitoid contacts [35], suggesting favourable conditions for structurally controlled fluid focusing and mineral precipitation.

The contrasting structural orientations of the NW–SE-trending Oban shear systems and NE–SW-trending Obudu deformation corridor may reflect partitioned strain within the eastern Nigerian segment of the Pan-African mobile belt. These crustal-scale structures and their subsidiary splays, jogs, and intersections likely acted as major conduits for hydrothermal fluid migration and ore deposition, consistent with structural controls documented in orogenic gold provinces worldwide [1, 6, 36]. Despite increasing artisanal exploitation of placer gold occurrences within both terranes, the metallogenic relationships between deformation, granitoid magmatism, hydrothermal alteration, and gold mineralization remain poorly constrained.

1.1.1 Local Geology and Field Characteristics

Field investigations within the Oban Massif and Obudu Plateau reveal widespread evidence of hydrothermal activity spatially associated with deformation structures, quartz veining, and granitoid emplacement. In the Oban Massif (Fig. 3), gold-bearing drainages are developed predominantly within terrains underlain by migmatitic gneisses, mica schists, amphibolites, and granitoid intrusions. Quartz veins occur as massive, laminated, boudinaged, and brecciated bodies emplaced along foliations, fractures, and shear planes, with vein thickness varying from a few centimetres to several metres. Much veins exhibit evidence of multiple deformation episodes including folding, recrystallization, and brittle reactivation. Hydrothermal alteration is common along vein margins and adjacent wall rocks, particularly in sheared contacts between gneisses and schists where sericitization, silicification, chloritization, ferruginization, and local sulphidation are developed. Disseminated pyrite and minor arsenopyrite were observed in altered quartz-rich zones, especially along the eastern flank of the massif, supporting previous reports of sulphide-associated hydrothermal mineralization.

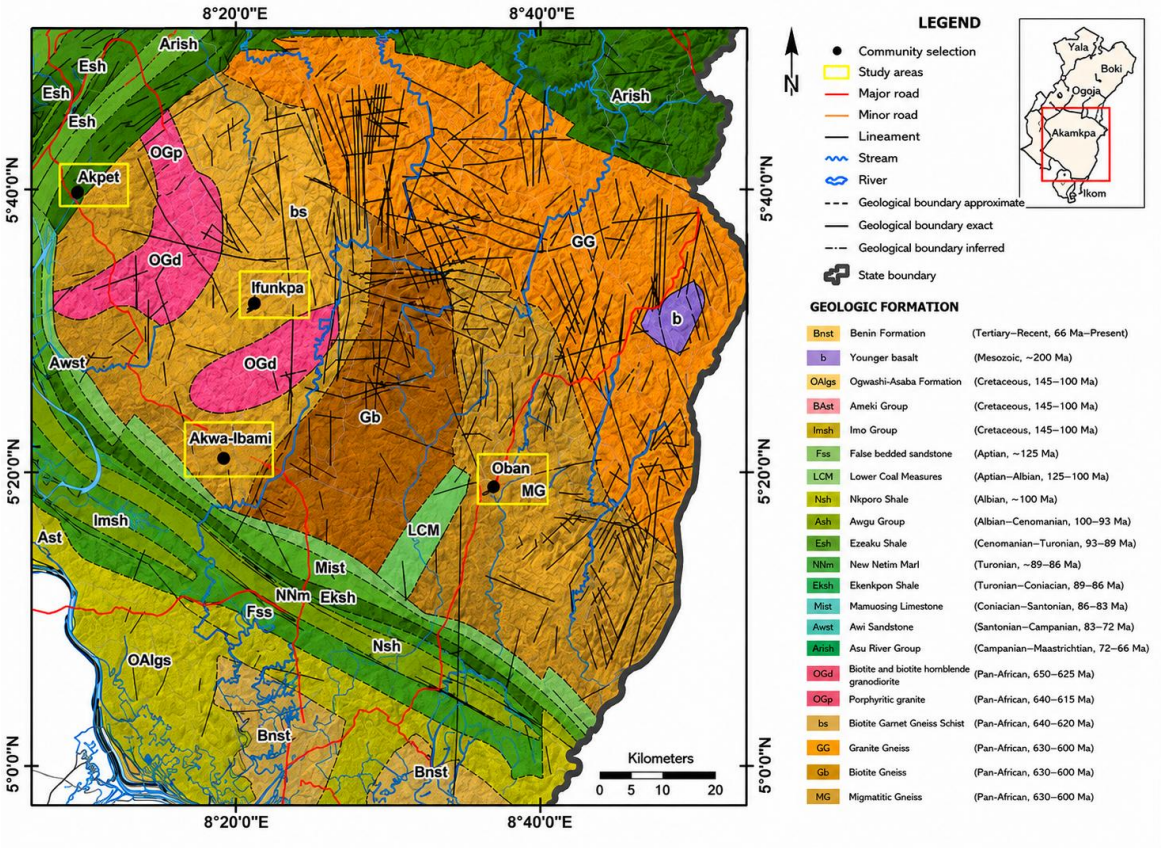


Fig. 3 Geological map of the Oban Massif and adjoining areas showing dominant lithologies, structural lineaments, and the four stream drainages sampled (Akpet, Akwa-Ibami, Ifunkpa, and Oban)

Pegmatitic intrusions are abundant within the Oban area and commonly occur as discordant dykes cutting gneissic fabrics and granitoid bodies. Several pegmatites contain cassiterite-bearing and rare-metal mineral assemblages including Nb–Ta oxides, muscovite, tourmaline, and beryl, indicating fractionated granitic melts and late-stage magmatic-hydrothermal fluid evolution. The close spatial association between pegmatites, quartz veins, and sheared lithological contacts suggests a structurally controlled hydrothermal system with possible overlap between orogenic and intrusion-related mineralizing processes.

In the Obudu Plateau (Fig. 4), gold-bearing streams drain high-relief terrains dominated by granitic gneisses, migmatites, quartzites, amphibolites, and porphyritic granitoids. Quartz veins are widespread and typically occur as folded, discontinuous, and locally stockwork-like bodies associated with brittle–ductile shear zones and fracture corridors. Alteration assemblages dominated by quartz, sericite, chlorite, and disseminated pyrite ± galena occur within vein selvages and altered granitoid margins. In contrast to the Oban Massif, sulphide mineralization in the Obudu Plateau is generally less abundant in outcrop, although ferruginized and silicified fracture systems are common.

Field relationships indicate that deformation and hydrothermal veining in both basements are structurally controlled, with mineralized zones preferentially localized along shear intersections, fracture splays, lithological contacts, and zones of enhanced brittle–ductile reactivation. Extensive tropical weathering has resulted in the development of thick lateritic profiles and widespread alluvial redistribution of resistant heavy minerals within active stream channels (Fig. 5). Artisanal mining activities (Fig. 6) are concentrated mainly within these alluvial environments where gold occurs as fine flakes, nuggets, and composite grains within modern stream sediments and eluvial accumulations. The preservation of abundant placer gold within structurally controlled drainage systems suggests relatively proximal bedrock sources and supports the interpretation of localized hydrothermal mineralization within these two basements.

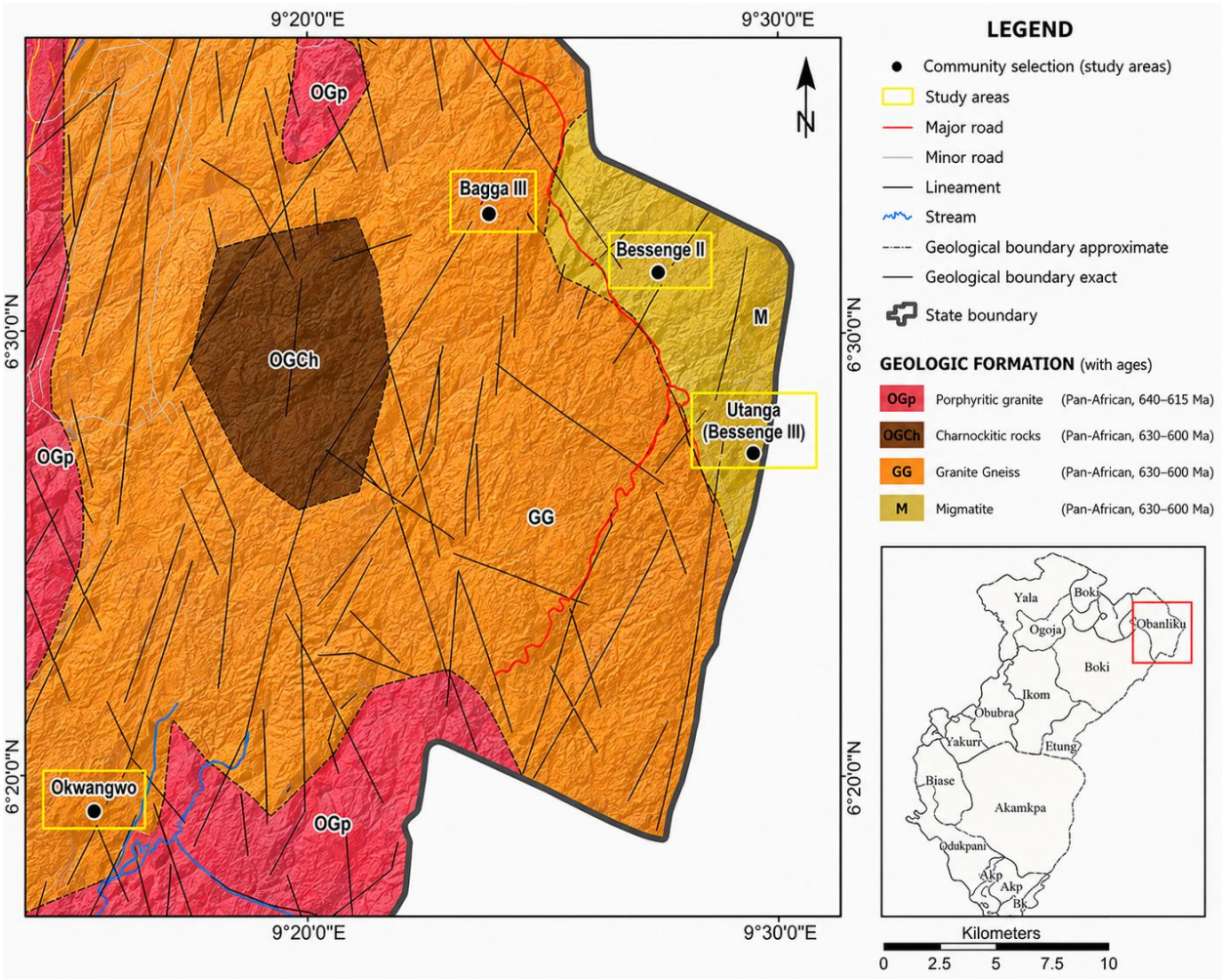


Fig. 4 Geological map of the Obudu Plateau showing dominant lithologies, structural lineaments, and the four stream drainages sampled (Bagga, Bessenge, Okwangwo and Utanga)



Fig. 5 Representative sample collection sites in the Obudu plateau. a-d: A pictorial representation of sampling carried out at a consistent depth (at the B-horizon) within a depth of 0.5–1.5 m for soil and stream sediments



Fig. 6 Artisanal gold mining activities in the study areas: (a, c) Obudu Plateau; (b, d) Oban Massif

2. Materials and Methods

2.1 Stream-sediment sampling and preparation

A total of 120 stream sediment samples were collected from 8 active drainage systems in the Oban Massif and Obudu Plateau during field investigations carried out between November and December, 2025. To maximize lithological and hydrodynamic representation in each drainage basin, a stratified sampling scheme from upstream to downstream was applied. Four drainages were sampled in the Oban Massif (Akpet, Akwa-Ibami, Ifunkpa and Oban streams) and four in the Obudu Plateau (Bagga, Bessenge, Okwangwo and Utanga streams), with fifteen samples taken from each drainage system.

Sediment samples (Fig. 7) were taken from the active channel approximately 10–30 cm below the sediment–water interface to avoid contamination by recent surface inputs. Fine grained sediment fractions were selectively sampled from low energy depositional environments such as point bars, inner meanders and sediment traps where heavy minerals tend to be concentrated. We collected approximately 2–3 kg of sediment per site using plastic sampling tools, and stored samples in labelled polyethylene bags.

Samples were air dried at room temperature in the laboratory, manually disaggregated and homogenised prior to quartering. Representative subsamples were sieved to <75 μm for geochemical analysis and the balance retained for heavy-mineral concentrate and gold-grain recovery.



Fig. 7 (a-b) A pictorial representation of samples collected from stream channels along Obudu plateau

2.2 Geochemical analysis

Prepared sediment samples were analysed for major oxides and trace elements by inductively coupled plasma–mass spectrometry (ICP–MS) after four-acid total digestion ($HF–HClO_4–HNO_3–HCl$) at Activation Laboratories Ltd. (Actlabs), Ontario, Canada. Gold concentrations were determined in ppb after digestion of 30 g aliquots. Major elements and selected pathfinder elements typically associated with hydrothermal gold mineralisation were included in the analytical suite, including As, Sb, Cu, Pb, Zn, Mo, Ba, U, Sn, and W.

Quality assurance and quality control (QA/QC) procedures included the routine insertion of analytical blanks, sample duplicates and certified internal laboratory reference materials at a frequency of one blank, one duplicate and three standards per batch of twenty samples. The analytical precision for most elements was generally better than ± 10% above three times the detection limit.

2.3 Gold-grain recovery and preparation

The retained portions of the stream-sediment samples were processed by wet panning to obtain heavy-mineral concentrates. Visible gold grains (Fig. 8) were handpicked under a binocular microscope using non-metallic tools to prevent contamination. Recovered grains were cleaned ultrasonically in distilled water, mounted in epoxy resin, and polished to expose internal surfaces for microanalytical investigation at Clausthal university of Technology (TUC, Germany).



Fig. 8 Panned gold samples from the study areas: (a, c) Obudu Plateau; (b, d) Oban Massif

2.4 SEM imaging and mineral inclusion analysis

The gold grain morphology and mineral inclusion assemblages were investigated using a Fisher–Phenom XL scanning electron microscope (SEM) at the University of Queensland, Australia. Surface morphology was studied by secondary electron (SE) imaging at 1–2 kV and internal compositional heterogeneities and mineral inclusions by backscattered electron (BSE) imaging at 15–20 kV. The elemental composition of inclusions and associated phases was determined semi-quantitatively by the energy dispersive spectrometry (EDS).

Morphological classification was done on grain shape, roundness and edge preservation, deformation features and surface textures using approaches commonly applied to placer gold studies [9]. Instead, the mineral inclusions were identified on the basis of elemental composition and textural relations within the host gold grains.

2.5 EPMA-WDS microchemical analysis

Quantitative gold-alloy compositions were determined using a CAMECA SX Five field-emission electron probe microanalyser (FE-EPMA) operated in wavelength-dispersive spectrometry (WDS) mode. Analytical conditions consisted of an accelerating voltage of 15 kV and beam current of 30 nA, with calibration performed against appropriate metallic and mineral standards. Major alloying elements analysed included Au, Ag, and Cu. Gold fineness values were calculated using the expression after Hallbauer and Utter [37], where Au and Ag represent weight percentages of gold and silver, respectively. Internal compositional zoning and elemental variability were evaluated using multiple point analyses across individual grains.

2.6 Statistical and comparative analyses

Geochemical datasets were processed using IBM SPSS Statistics version 27. Prior to statistical treatment, elemental concentrations were log-transformed to reduce skewness and standardized using Z-score normalization. Descriptive statistics, Pearson correlation analysis, and Q-mode Hierarchical Cluster Analysis (HCA) employing Ward's linkage method were used to evaluate elemental associations and metallogenic relationships between drainage systems.

Geochemical anomaly thresholds were calculated using the robust median + 2 median absolute deviation (MAD) approach of Reimann et al. [38], which minimizes the influence of extreme outliers commonly associated with mineralized terrains. Gold-alloy compositions were further evaluated using the Au–(Ag × 10)–(Cu × 100) ternary discrimination diagram of Poulsen et al. [39] and Chapman et al. [8, 40] to assess possible genetic affinities between the studied gold grains and established deposit classes.

Comparative evaluation was undertaken against published gold microchemical datasets from selected Pan-African and Precambrian gold provinces including the Igarra schist belt of Nigeria, the Lom Series, Bétaré-Oya, Batouri, Dimako–Mboscorro, Bigorne, and Minvoul regions of Cameroon and Gabon [41–45].

3. Results

3.1. Stream-sediment geochemistry

Stream sediments from both the Oban Massif and Obudu Plateau are dominated by SiO_2 (87–89 wt%), with subordinate Al_2O_3 (3–8 wt%) and Fe_2O_3 (2–3 wt%) (Tables 1 and 2). The compositions reflect derivation from intensely weathered quartz-rich basement lithologies dominated by granitoid gneisses, migmatites, and associated supracrustal rocks. Lithophile elements including Ba (56–353 ppm), Zr (139–276 ppm), Th (12.8–16.1 ppm), and K_2O (1.2–2.5 wt%) are consistently enriched across both basements, indicating significant contributions from felsic source rocks and accessory mineral assemblages.

Ferromagnesian elements show greater spatial variability. Chromium ranges from 240 to 377 ppm, Ni from 9 to 32 ppm, and V from 10 to 19 ppm, with the highest concentrations recorded in Akpet drainage within the Oban Massif and Utanga drainage within the Obudu Plateau. These enrichments reflect contributions from amphibolitic and mafic lithologies exposed within both basement terranes.

Gold concentrations exhibit marked differences between the two study areas. Stream sediments from the Oban Massif yield mean Au concentrations ranging from 1 to 36 ppb, with maximum values of 88 ppb recorded in the Akwa-Ibami and Ifunkpa drainages (Table 1). In contrast, Obudu Plateau drainages contain consistently elevated gold concentrations, with mean values between 28 and 56 ppb and a maximum value of 99 ppb recorded in the Okwangwo drainage, representing the highest concentration measured in the study (Table 2).

Application of the robust median + 2 MAD anomaly threshold method identified distinct anomalous populations in both areas. Threshold values of 38 ppb and 64 ppb were calculated for the Oban Massif and Obudu Plateau, respectively. Eight samples from the Oban Massif and six from the Obudu Plateau exceed these thresholds and define priority target areas for follow-up exploration.

A notable feature of the dataset is the greater geochemical variability displayed by the Oban Massif relative to the Obudu Plateau. Gold concentrations in Oban drainages vary over nearly two orders of magnitude and are accompanied by substantial fluctuations in hydrothermal pathfinder elements. By contrast, Obudu drainages exhibit comparatively uniform elemental distributions and consistently elevated gold contents.

Ultramafic lithologies, with the highest values in Akpet (Oban) and Utanga (Obudu) drainages (Tables 1 and 2).

Table 1. Stream-sediment geochemistry (ICP-MS) summary for the four Oban Massif drainages (n = 15 per stream). Major elements in wt%; Au in ppb; all other elements in ppm.

Element	Akpet mean (range)	Akwa-Ibami mean (range)	Ifunkpa mean (range)	Oban mean (range)
SiO_2 (wt%)	87.8 (82.0–89.8)	88.2 (86.8–92.7)	86.5 (81.9–89.4)	88.7 (86.0–91.2)
Al_2O_3 (wt%)	3.81 (2.0–4.9)	3.55 (2.0–5.8)	5.27 (2.9–7.2)	3.14 (2.0–5.7)
Fe_2O_3 (wt%)	2.65 (2.0–3.1)	2.39 (1.1–3.9)	2.60 (1.0–4.4)	2.17 (1.0–3.8)
K_2O (wt%)	1.53 (1.0–3.0)	1.79 (1.0–2.8)	1.85 (1.0–3.1)	1.39 (0.7–2.2)
Au (ppb)	1.0 (0–4)	29 (2–88)	31 (11–88)	36 (1–67)
Cu (ppm)	12.0 (6–16)	5.4 (1–12)	11.6 (10–13)	14.3 (12–17)
Pb (ppm)	12.9 (11–16)	9.3 (4–13)	9.6 (6–13)	17.3 (11–22)
Zn (ppm)	14.9 (12–18)	12.7 (10–15)	12.7 (7–19)	17.2 (14–23)
S (ppm)	76 (55–89)	78 (41–91)	51 (21–90)	43 (31–57)
Cr (ppm)	316 (203–481)	268 (122–489)	240 (90–479)	259 (112–424)
Ni (ppm)	16.4 (13–21)	9.3 (1–16)	12.5 (9–16)	15.8 (12–18)
Ba (ppm)	267 (112–367)	279 (123–542)	311 (102–542)	57 (21–91)
Zr (ppm)	256 (119–381)	189 (78–332)	139 (31–257)	274 (212–341)
Th (ppm)	16.0 (12–21)	13.2 (11–17)	12.8 (11–17)	13.1 (10–17)
Mo (ppm)	6.7 (4.0–8.4)	4.9 (2.0–7.7)	5.4 (2.6–8.1)	9.2 (5.2–15.2)

Table 2. Stream-sediment geochemistry (ICP-MS) summary for the four Obudu Plateau drainages (n = 15 per stream). Major elements in wt%; Au in ppb; all other elements in ppm.

Element	Bagga mean (range)	Bessenge mean (range)	Okwangwo mean (range)	Utanga mean (range)
SiO_2 (wt%)	87.1 (81.2–93.3)	84.2 (81.2–90.2)	87.4 (81.2–89.1)	89.9 (86.6–93.1)
Al_2O_3 (wt%)	3.98 (2.0–13.2)	8.09 (2.3–13.2)	4.50 (2.1–13.2)	3.40 (2.1–4.2)
Fe_2O_3 (wt%)	2.12 (1.0–3.0)	3.37 (2.0–5.0)	3.18 (2.2–4.9)	2.62 (1.0–4.3)
K_2O (wt%)	1.20 (0.9–2.1)	1.27 (1.0–2.1)	1.74 (1.0–3.2)	2.45 (1.0–4.2)
Au (ppb)	34 (11–67)	28 (1–56)	56 (11–99)	41 (14–78)
Cu (ppm)	14.2 (12–18)	13.4 (11–16)	15.4 (12–19)	17.6 (12–33)
Pb (ppm)	12.6 (10–16)	12.8 (11–15)	12.2 (10–15)	15.5 (12–21)
Zn (ppm)	17.8 (13–33)	15.7 (13–21)	18.5 (14–31)	16.8 (13–21)
S (ppm)	63 (42–90)	65 (30–91)	77 (60–91)	71 (20–89)
Cr (ppm)	349 (211–502)	322 (102–490)	377 (221–492)	333 (221–505)
Ni (ppm)	17.7 (16–21)	16.4 (13–18)	19.8 (17–24)	32.0 (16–61)
Ba (ppm)	353 (221–512)	261 (21–361)	299 (212–362)	277 (203–369)
Zr (ppm)	267 (209–412)	271 (221–410)	257 (210–331)	259 (203–334)
Th (ppm)	15.9 (12–23)	15.0 (13–18)	16.1 (13–19)	15.8 (13–20)
U (ppm)	1.98 (1.2–3.3)	2.71 (1.2–5.2)	2.72 (1.4–5.7)	3.28 (1.3–7.5)

Mean Au concentrations differ markedly between the two terrains. Oban Massif streams yield mean Au of 1.0–36 ppb with maxima of 88 ppb (Ifunkpa, Akwa-Ibami); Obudu Plateau streams yield mean Au of 28–56 ppb with the maximum of 99 ppb in Okwangwo — the highest in the dataset. Au anomaly thresholds (median + 2 MAD) are 38 ppb (Oban) and 64 ppb (Obudu); eight Oban samples and six Obudu samples exceed the respective thresholds, defining priority follow-up zones. HCA dendrograms reveal a marked contrast between the terrains. In the Oban Massif (Fig. 9), four

interpretable clusters are consistent across all four drainages: (i) Au–Pb–Zn–Cu–S–Mo (hydrothermal pathfinder cluster, with Co in Akpet and Akwa-Ibami); (ii) Cr–Ni–V–MgO–Fe_2O_3 (mafic-amphibolitic source); (iii) SiO_2–Al_2O_3–K_2O–Cs–Ba (felsic-granitoid lithophile); and (iv) Zr–Hf–Th–Y–U (heavy-mineral / accessory). The presence of Au within the pathfinder cluster is diagnostic of active hydrothermal control on present-day gold dispersion.

In the Obudu Plateau (Fig. 10), HCA dendrograms are more diffuse: Au does not cluster with the classical orogenic pathfinders (As–Sb–Cu–Pb–Zn–S) but associates weakly with K_2O, Cs, U, TiO_2 — a lithophile-leaning signature consistent with mature placer derivation from felsic granitoid bedrock; S forms an independent cluster with Cu and Fe_2O_3, suggesting decoupling of the residual sulphide phase from the gold dispersion path. Pearson correlations (Table 3) corroborate this contrast: Au correlates significantly with S, Cu, As, Sb, Pb, Zn, and Mo in the Oban Massif ($r = +0.41$ to $+0.65$; $p < 0.05$) but only with K_2O, Ba, U, and Y in the Obudu Plateau ($r = +0.31$ to $+0.44$; $p < 0.05$).

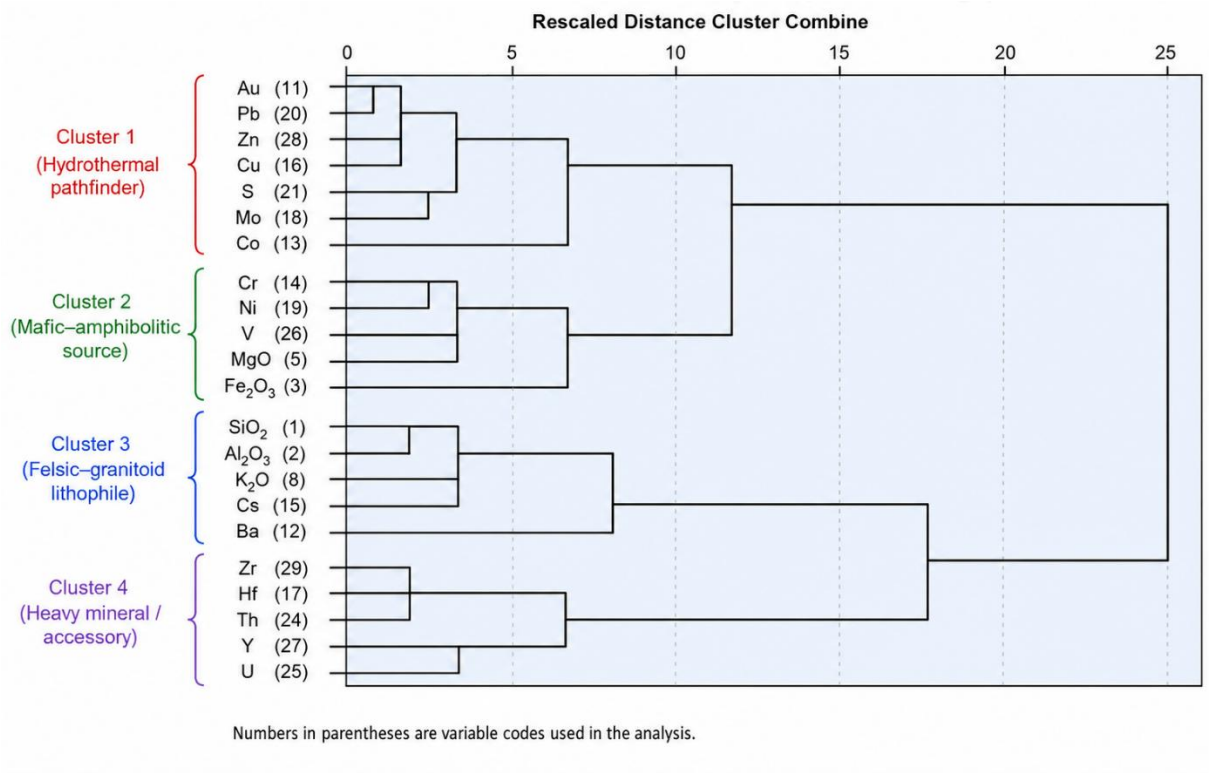


Fig. 9 HCA dendrogram (Ward's linkage) for stream-sediment geochemistry of a representative Oban Massif drainage. Note the coherent Au–Pb–Zn–Cu–S hydrothermal pathfinder cluster and the distinct Cr–Ni–V mafic-source cluster

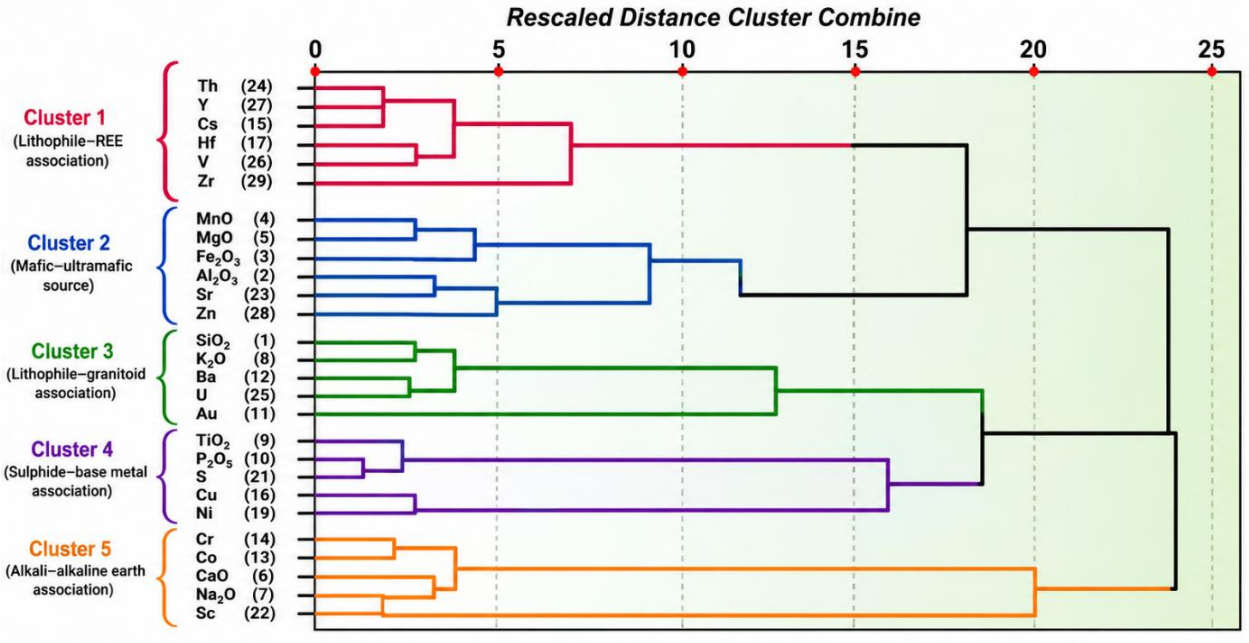


Fig. 10 HCA dendrogram for a representative Obudu Plateau drainage. Au clusters near K_2O–Cs–TiO_2–U (lithophile elements) rather than with the hydrothermal pathfinder suite; S forms an independent cluster with Cu–Fe_2O_3

Table 3. Pearson correlation coefficients (r) between Au and key pathfinder elements within each terrain (n = 60 per terrain). Significant correlations ($p < 0.05$) shown with asterisk; n.s. = not significant.

Element	Oban Massif r	Obudu Plateau r
S	+0.62*	+0.08 (n.s.)
Cu	+0.54*	+0.21 (n.s.)
Pb	+0.49*	+0.15 (n.s.)
Zn	+0.41*	+0.18 (n.s.)
Sb	+0.58*	+0.03 (n.s.)
As	+0.65*	+0.05 (n.s.)
Mo	+0.45*	+0.02 (n.s.)
Ba	−0.18	+0.36*
K_2O	−0.10	+0.44*
U	+0.14	+0.39*
Y	+0.05	+0.31*

3.2 Element associations and dispersion patterns

Multivariate statistical analyses reveal fundamentally different geochemical signatures between the Oban massif and the Obudu plateau.

In the Oban Massif, Hierarchical Cluster Analysis consistently groups Au with Pb, Zn, Cu, S, and Mo across all sampled drainages, forming a coherent hydrothermal pathfinder association. In the Akpet and Akwa-Ibami drainages, Co is also incorporated into this cluster. Separate clusters comprise: (i) Cr–Ni–V–MgO–Fe_2O_3, interpreted as reflecting mafic-amphibolitic source rocks; (ii) SiO_2–Al_2O_3–K_2O–Cs–Ba, representing felsic lithophile contributions; and (iii) Zr–Hf–Th–Y–U, reflecting heavy-mineral and accessory-mineral assemblages.

The association of Au with sulphur and base metals suggests a strong hydrothermal control on present-day sediment geochemistry and indicates derivation from sulphide-bearing mineralized source rocks rather than simple mechanical concentration of placer gold.

In contrast, the Obudu Plateau displays a more diffuse geochemical architecture. Gold shows little affinity for the classical hydrothermal pathfinder suite and instead exhibits weak associations with K_2O, Ba, U, Cs, and TiO_2. Sulphur forms an independent cluster together with Cu and Fe_2O_3, indicating a degree of decoupling between sulphide mineralization and gold dispersion. This pattern suggests derivation of gold from felsic magmatic sources and mature placer systems in which primary sulphide signatures have been largely removed by weathering. Pearson correlation analysis supports these observations (Table 3).

In the Oban Massif, Au displays statistically significant positive correlations with S, Cu, As, Sb, Pb, Zn, and Mo ($r = +0.41$ to $+0.65$; $p < 0.05$). Conversely, in the Obudu Plateau, significant correlations are restricted to K_2O, Ba, U, and Y ($r = +0.31$ to $+0.44$; $p < 0.05$), while correlations with sulphide-associated elements are generally weak or absent.

3.3 Gold-grain morphology and internal textures

Gold grains recovered from the Oban Massif exhibit considerable morphological diversity, ranging from angular and sub-angular forms to less common rounded varieties (Fig. 11). Grain sizes vary from approximately 250 μm to more than 500 μm. Many grains preserve sharp crystal faces, irregular edges, and primary morphological features, particularly within the Akwa-Ibami and Ifunkpa drainages.

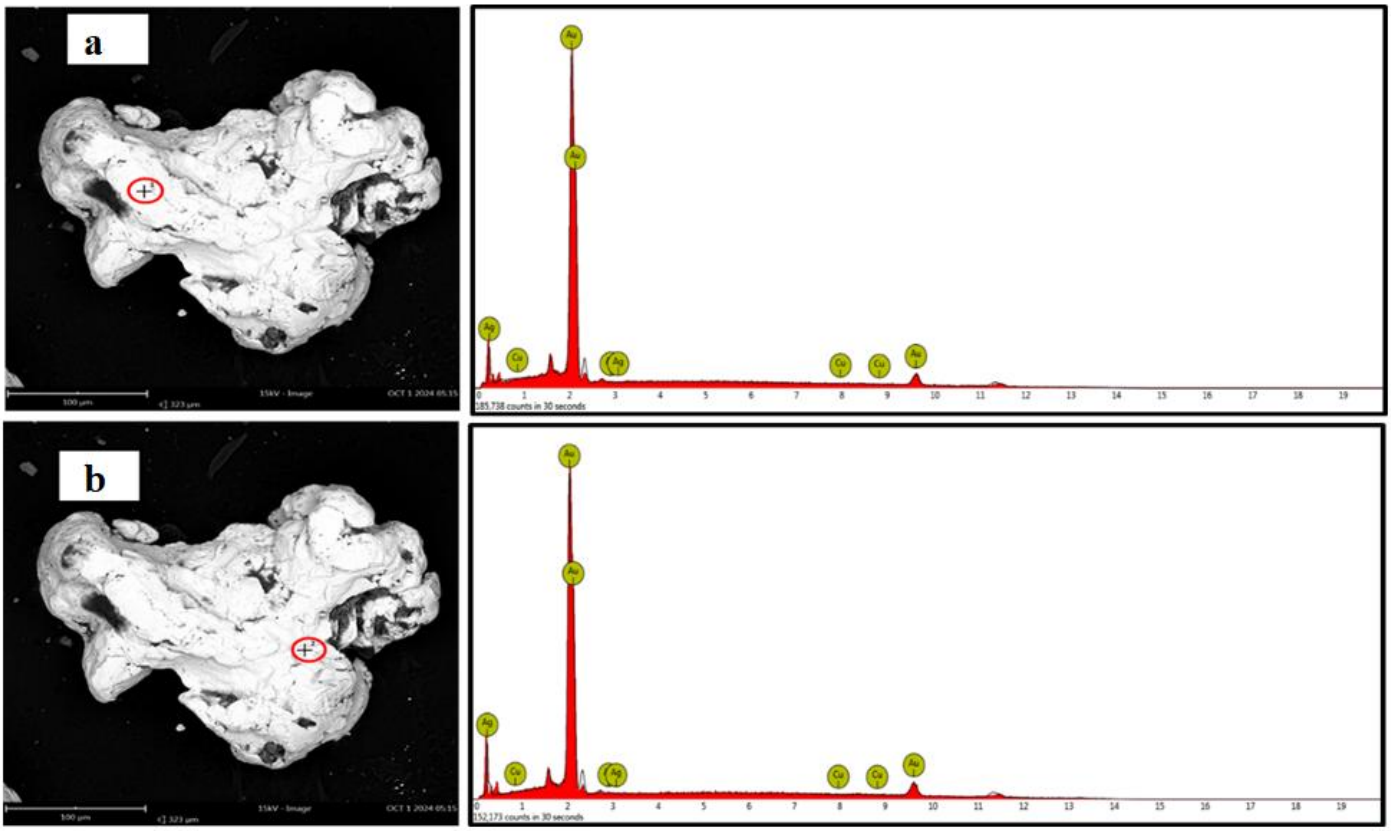


Fig. 11 Representative BSE image and EDS spectra of a heterogeneous, angular gold grain from the Akwa-Ibami stream (Oban Massif). Red circles mark analytical spots represent the analytical spots labelled as a-b.

Backscattered electron imaging reveals complex internal structures characterized by patchy compositional zoning, embayed margins, micro-fractures, corrosion pits, and irregular Au-rich and Ag-rich domains. Several grains exhibit evidence of multiple episodes of dissolution and reprecipitation, producing heterogeneous textures that indicate incomplete chemical equilibration.

Gold grains from the Obudu Plateau differ markedly in appearance. Most grains are rounded to well-rounded and commonly display flattened morphologies consistent with prolonged fluvial transport (Fig. 12).

Internal textures are generally homogeneous, with limited evidence of compositional zoning. Smooth grain margins and locally developed Ag-depleted rims are common. These rims produce narrow Au-enriched outer zones surrounding relatively uniform grain interiors.

The contrasting morphology and texture of the two gold populations suggest significant differences in transport history, chemical evolution, and source characteristics.

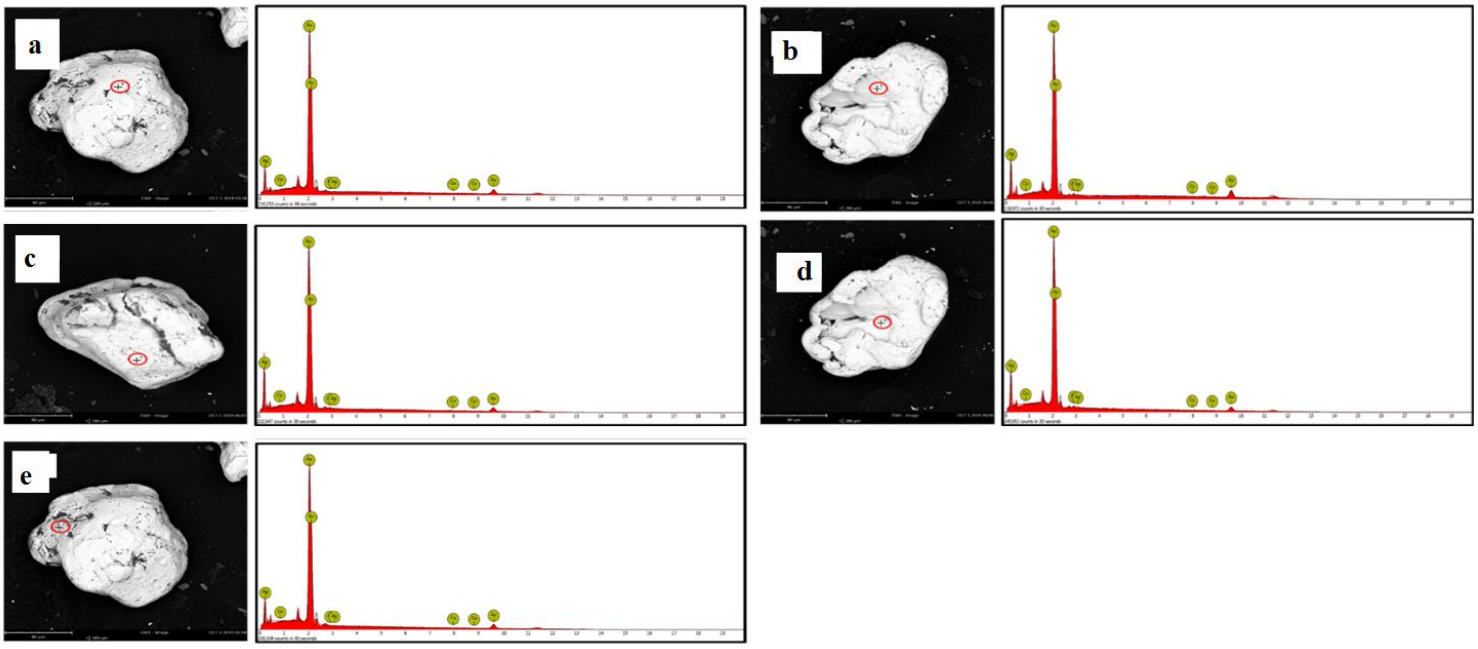


Fig. 12 Representative BSE image and EDS spectrum of a rounded, internally homogeneous gold grain from the Bessenge stream (Obudu Plateau). The very weak Ag signal records near-pure Au composition. The red circles represent the analytical spots labelled as A-E

3.4 Mineral inclusion assemblages

Mineral inclusions identified within the gold grains exhibit systematic differences between the two basements (Table 4). Gold grains from the Oban Massif contain inclusions of muscovite, quartz, calcite, clay minerals, cassiterite, and sericite/illite (Fig. 13). Muscovite and sericite-rich inclusions are particularly abundant in grains from the Ifunkpa and Akwa-Ibami drainages, whereas cassiterite was identified exclusively in grains from the Oban drainage.

Table 4. EPMA elemental composition (wt%) of mineral inclusions within alluvial gold grains, with inferred mineral identity.

Locality	O	Si	Al	K	Sn	Fe	Other	Mineral
Akwa-Ibami (Oban)	62.3	20.5	8.5	8.1	0.6	—	—	Muscovite
Akpet (Oban)	68.8	6.3	8.4	—	—	—	Ca 8.1; C 7.4	Calcite / clay
Oban stream	46.8	—	—	—	53.2	—	—	Cassiterite
Ifunkpa (Oban)	71.2	10.9	13.2	—	—	4.7	—	Sericite / illite
Utanga (Obudu)	66.7	17.5	7.2	6.4	—	—	Sr 2.2	Clay (K–Sr)
Bessenge (Obudu)	59.5	—	—	—	—	—	Ce 11.7; P 8.8; La 5.5; Nd 4.5	Monazite
Bagga (Obudu)	48.2	12.8	—	—	—	—	Zr 35.7; Nb 3.3	Zircon
Bagga (Obudu)	63.3	—	—	—	—	14.3	Ti 22.5	Ilmenite

The occurrence of sericite/illite inclusions is notable because these minerals are characteristic products of phyllic hydrothermal alteration. Likewise, cassiterite inclusions indicate interaction with

evolved Sn-bearing hydrothermal systems and suggest a genetic relationship with granite-associated mineralization.

In contrast, gold grains from the Obudu Plateau contain inclusions dominated by monazite, zircon, ilmenite, and clay-rich aggregates (Fig. 14). Monazite identified in Bessenge grains exhibits a characteristic Ce–La–Nd–P signature, whereas zircon and ilmenite are most common in Bagga samples.

Compared with the Oban Massif, inclusion assemblages in the Obudu Plateau are dominated by magmatic accessory minerals rather than hydrothermal alteration products. These assemblages point to a stronger felsic igneous contribution and indicate close association between gold mineralization and granitoid source rocks.

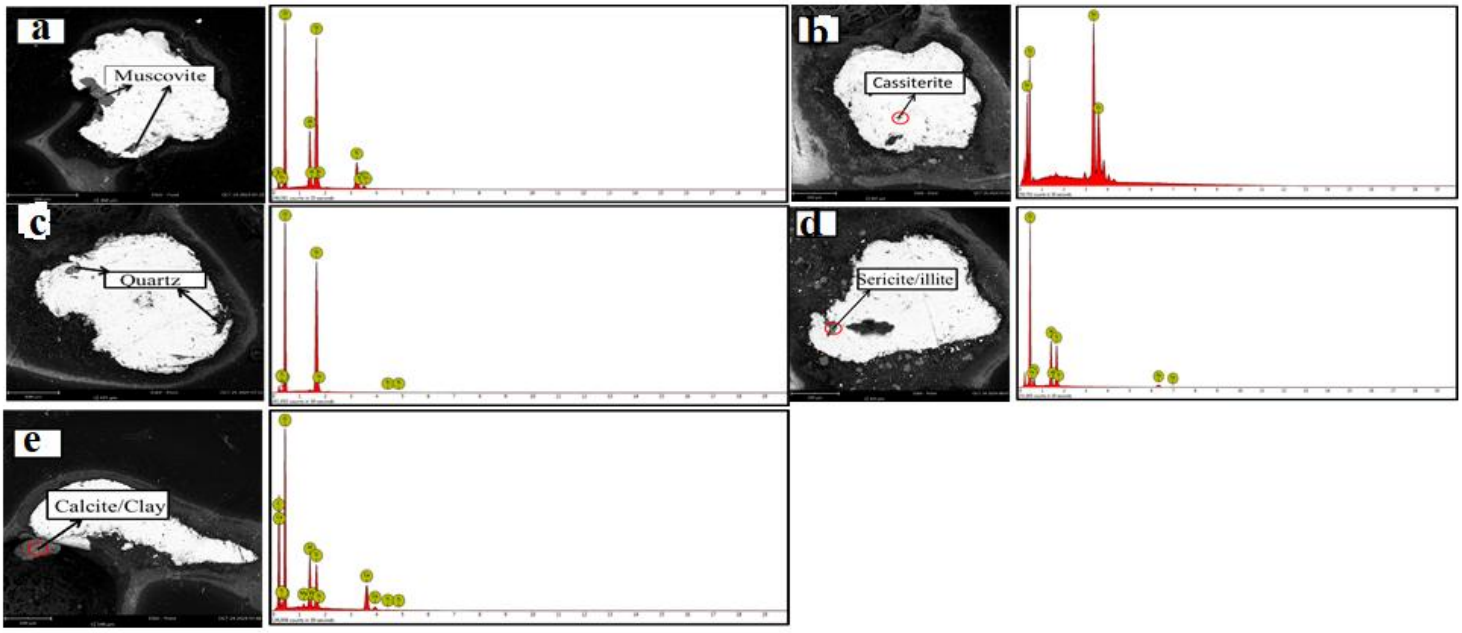


Fig. 13 BSE images and EDS spectra of inclusions in the gold grains of Oban massif (Akwa-Ibami stream (a), Akpet stream (b-c), Oban stream (d), and Ifunkpa stream (e)).

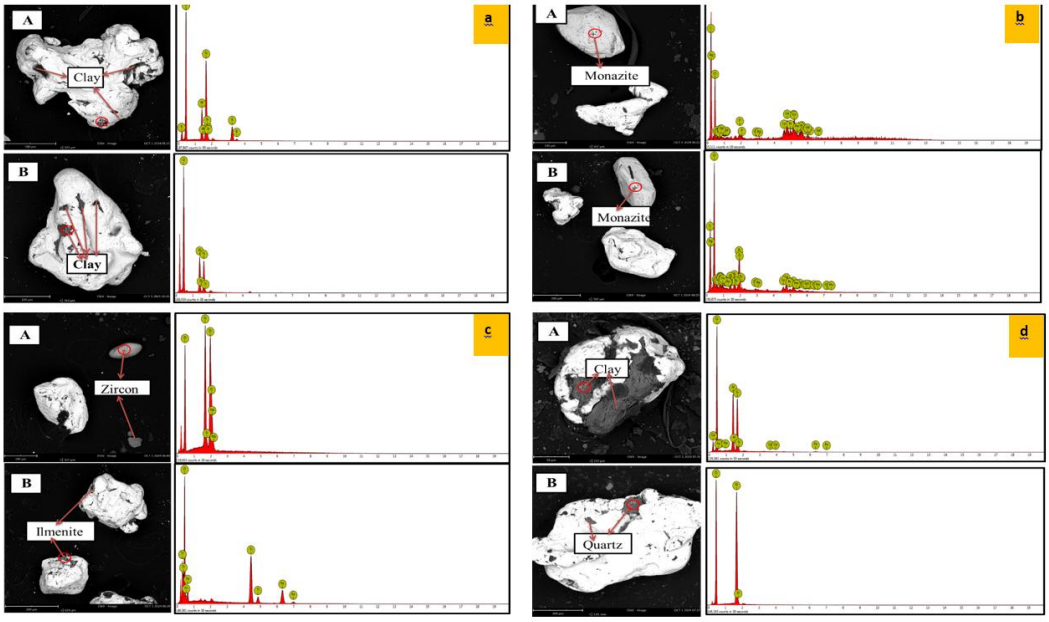


Fig. 14 BSE images and EDS spectra of inclusions in gold grains from Obudu plateau ((a) Utanga stream, (b) Bessenge stream (A and B), (c) Baga stream (A and B), and (d) Okwangwo stream (A and B))

3.5 Gold alloy chemistry and fineness

Electron probe microanalysis demonstrates substantial compositional differences between gold populations from Oban massif and Obudu plateau (Table 5 and 6). Gold grains from the Oban Massif contain Au concentrations ranging from 75.4 to 100.0 wt%, Ag concentrations between 0 and 21.2 wt%, and Cu concentrations up to 3.4 wt%. Corresponding fineness values range from 781 to 1000. Marked intra- and inter-drainage variability is evident. Akpet grains display the widest compositional spread and the lowest fineness values (804–976), whereas Akwa-Ibami grains are comparatively homogeneous (917–983). Gold populations from the Oban and Ifunkpa drainages exhibit distinctly bimodal fineness distributions characterized by both high-fineness (>990) and Ag-rich low-fineness (~780–850) populations (Fig. 15, Fig. 16). Core-to-rim Ag depletion is common and locally produces fineness increases of more than 100 units from grain interiors to margins.

Gold from the Obudu Plateau is considerably more homogeneous. Alloy compositions range from 96.6 to 100.0 wt% Au, 0 to 2.5 wt% Ag, and 0 to 1.3 wt% Cu, with a single anomalous grain from

Utanga containing 38.7 wt% Ag. Fineness values are tightly clustered between 987 and 1000, and numerous grains from the Bagga and Okwangwo drainages approach pure gold compositions. The average fineness difference between the two terranes exceeds 100 units, highlighting a major contrast in alloy chemistry and suggesting fundamentally different mineralizing environments.

Gold fineness from the Obudu Plateau and Oban Massif was compared with other gold fineness worldwide and presented in Fig. 17.

Table 5. Representative EPMA-WDS analyses (wt%) of gold grains from the Oban Massif.

Stream	Grain–spot	Zone	Au	Ag	Cu	Fineness
Akwa-Ibami	1A	Core	91.72	8.28	0.00	917
Akwa-Ibami	2A	Core	96.04	2.71	1.25	973
Akwa-Ibami	2B	Rim	97.75	1.85	0.40	981
Akwa-Ibami	3A	Core	98.28	1.72	0.00	983
Akpet	1A	Core	90.12	9.43	0.45	905
Akpet	2A	Core	80.44	19.56	0.00	804
Akpet	3A	Rim	100.00	0.00	0.00	1000
Oban stream	1B	Core	89.18	9.84	0.99	901
Oban stream	2A	Rim	99.55	0.00	0.45	1000
Oban stream	3A	Core	92.87	6.33	0.80	936
Ifunkpa	1A	Core	86.70	13.30	0.00	867
Ifunkpa	2B	Core	75.39	21.17	3.45	781
Ifunkpa	3A	Core	100.00	0.00	0.00	1000

Table 6. Representative EPMA-WDS analyses (wt%) of gold grains from the Obudu Plateau.

Stream	Grain–spot	Zone	Au	Ag	Cu	Fineness
Utanga	1A	Core	100.00	0.00	0.00	1000
Utanga	2B	Core	97.87	0.81	1.31	987
Utanga	3A	Rim	60.57	38.69	0.74	988
Bessenge	1A	Core	99.57	0.00	0.43	996
Bessenge	2A	Core	98.53	1.22	0.25	997
Bessenge	2B	Core	96.65	2.48	0.87	991
Bessenge	3A	Rim	96.55	2.46	0.98	990
Bagga	1A	Core	100.00	0.00	0.00	1000
Bagga	2A	Core	99.34	0.66	0.00	1000
Bagga	3A	Core	99.38	0.00	0.62	994
Okwangwo	1A	Core	100.00	0.00	0.00	1000
Okwangwo	1B	Core	97.46	1.45	1.09	989
Okwangwo	3A	Core	99.05	0.00	0.95	991

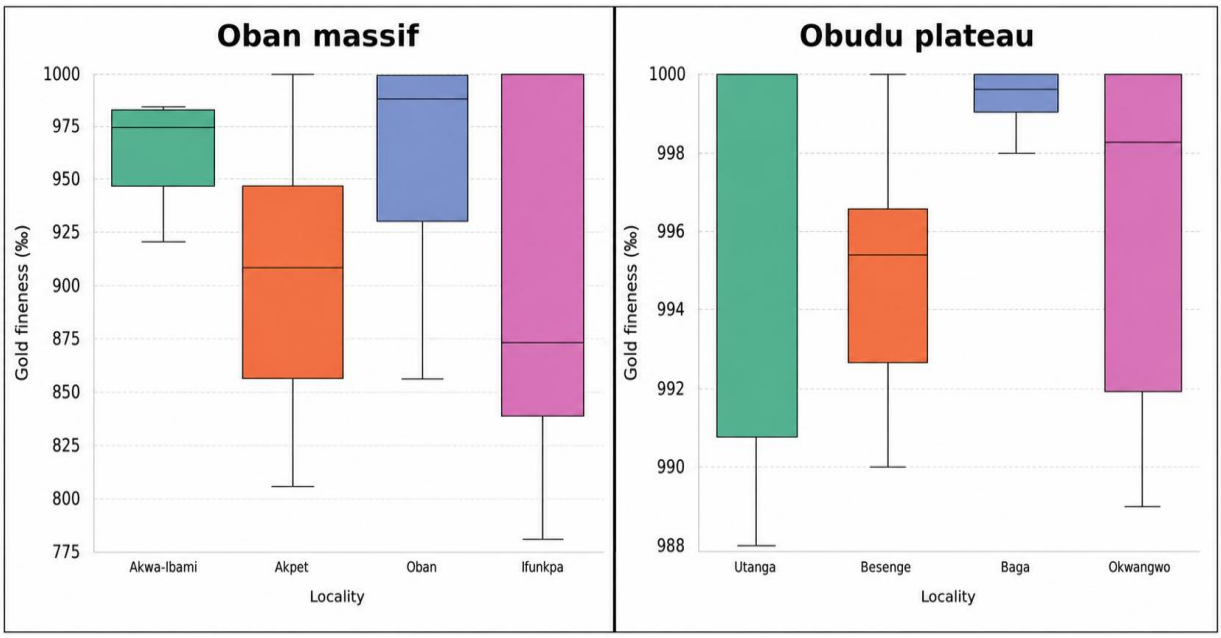


Fig.15 Within-terrain fineness variation across the study areas: Oban Massif streams (Akpet records the lowest values (mean ≈ 891); Akwa-Ibami the most homogeneous (≈ 963); Oban and Ifunkpa span the full range from Ag-rich (≈ 780) to pure Au (1000)). Obudu Plateau streams (All four streams record consistently high fineness (> 988); Bagga shows the highest median (≈ 1000)). Gold fineness (GF) is the proportion of Au in a native − gold grain, expressed in parts per thousand (‰). ($GF = \frac{Au}{Au+Ag} X \frac{1000}{1}$), where Au and Ag are the concentrations of gold and silver, usually reported in wt%

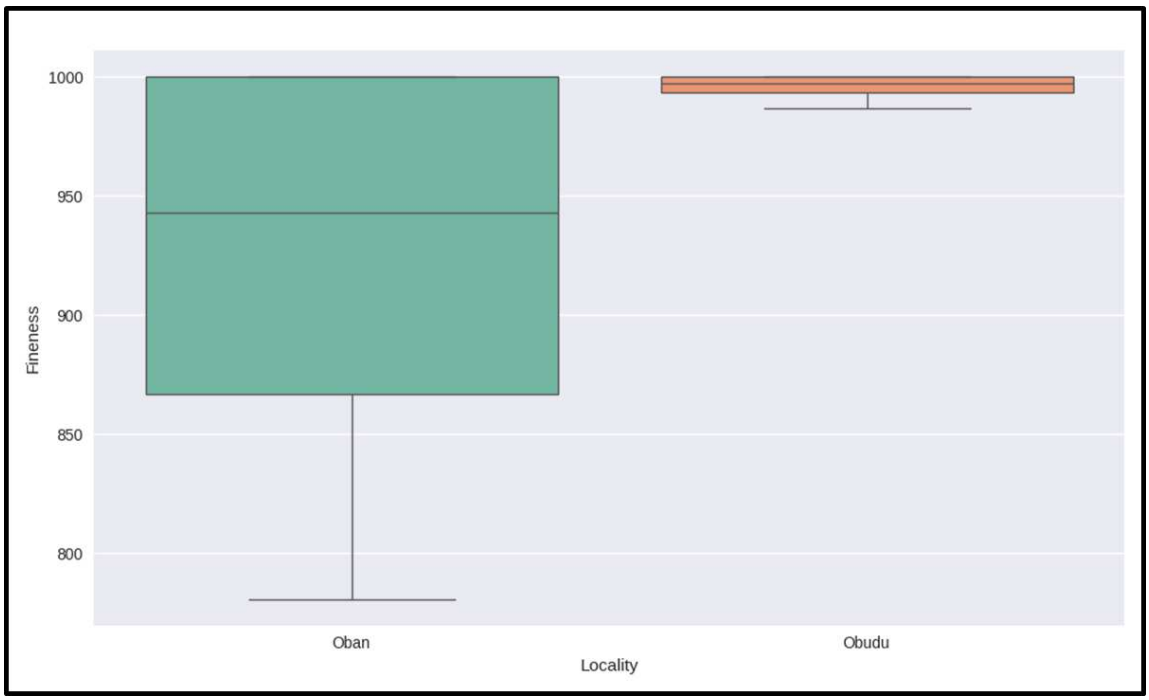


Fig. 16 Box plot comparing gold fineness across the Oban Massif and Obudu Plateau. Oban gold spans 781–1000 (median ≈ 943) while Obudu gold is tightly clustered between 987 and 1000

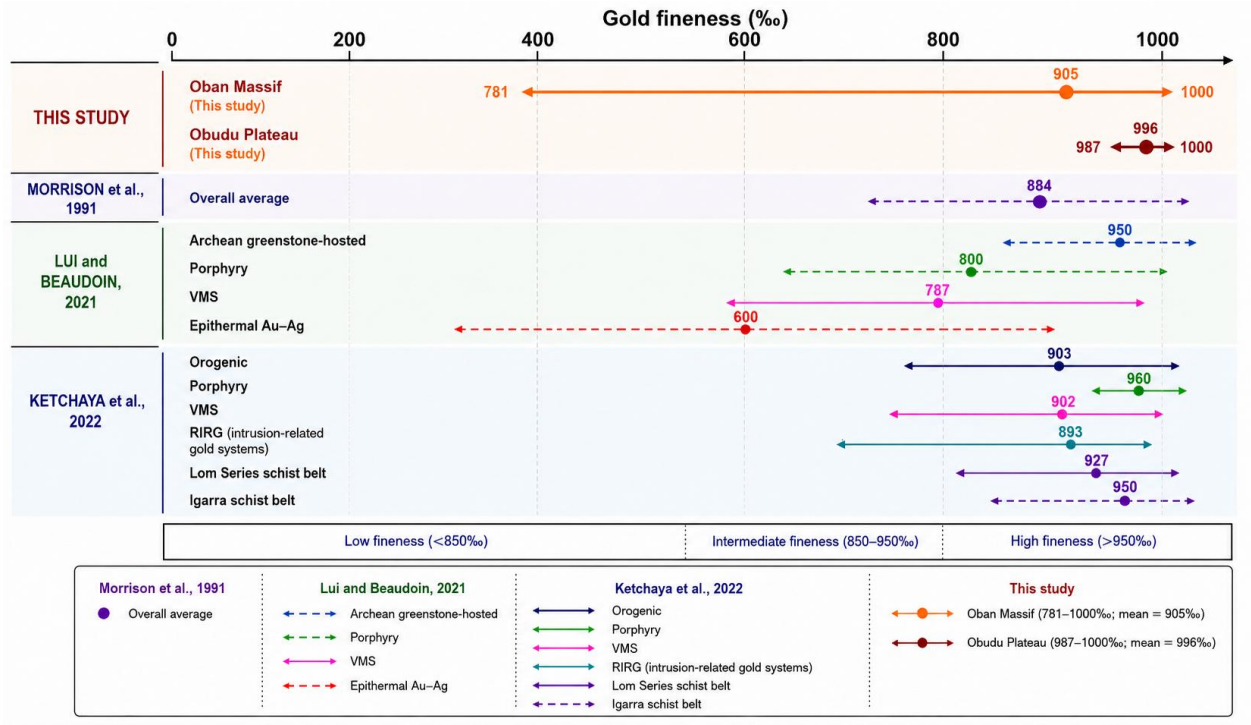


Fig. 17 Comparison of gold fineness ranges from the Oban Massif and Obudu Plateau (this study) with global deposit-class compilations [46, 47]. Gold fineness (GF) is the proportion of Au in a native – gold grain, expressed in parts per thousand (‰). ($GF = \frac{Au}{Au+Ag} X \frac{1000}{1}$), where Au and Ag are the concentrations of gold and silver, usually reported in wt%

3.6 Mineralization styles and potential gold sources in Oban Massif and Obudu Plateau

The Au – (Ag 10)–(Cu 100) compositional discrimination diagram for epithermal, Au-rich porphyry Cu, and Au-rich porphyry deposits, based on gold grains collected from the Oban Massif, is shown in Fig. 18 (A). Gold grains from the Oban Massif plot dominantly in the epithermal (ED) and Au-rich porphyry (GRPD) fields, with a subordinate spread toward the Au-rich porphyry Cu deposit (GRPCD) domain. Most data points cluster near the Au apex, reflecting high Au contents and relatively low Ag and Cu, consistent with the high fineness values obtained from EMPA analyses. A small but significant subset of grains trends toward the Cu-enriched side of the diagram, particularly from the Oban and Akpet streams.

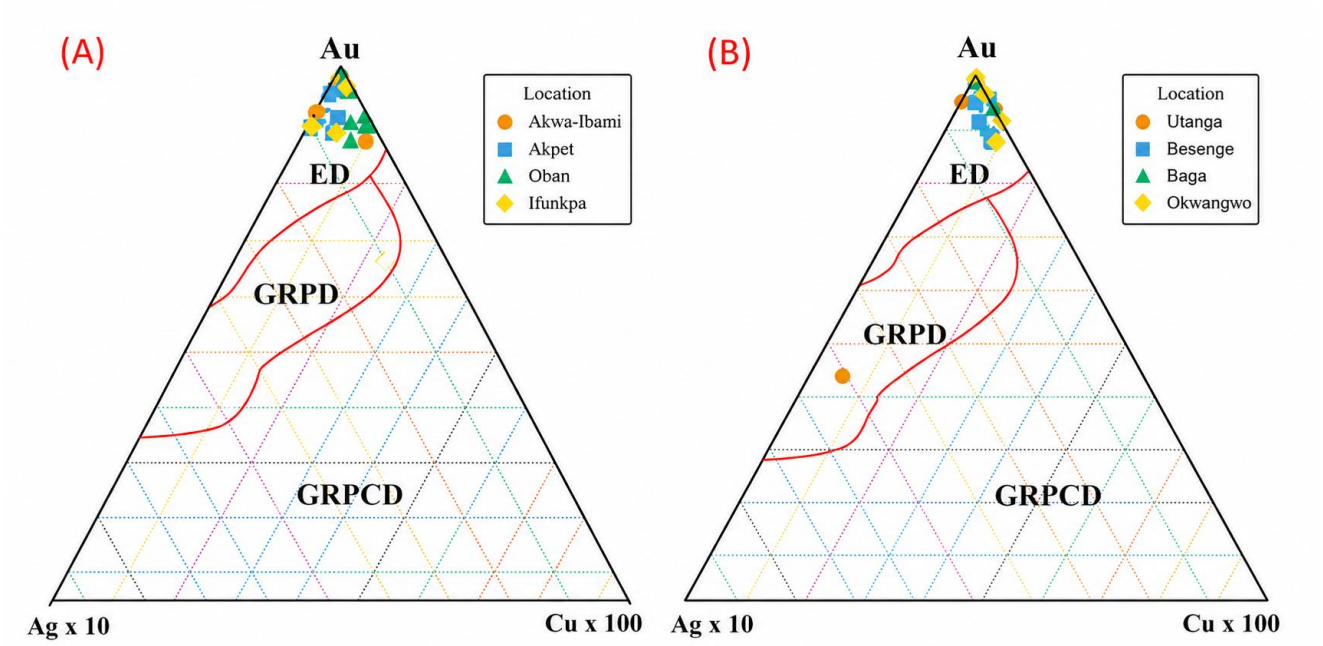


Fig. 18 Au –(Ag 10)–(Cu 100) compositional discrimination diagrams for epithermal, Au-rich porphyry Cu, and Au-rich porphyry deposits, based on gold grains collected from; (A) Oban massif and (B) Obudu plateau. ED = Epithermal Deposit, GRPD = Gold Rich Porphyry Deposit, GRPCD = Gold Rich Porphyry Copper Deposit

The Au –(Ag 10)–(Cu 100) compositional discrimination diagram for epithermal, Au-rich porphyry Cu, and Au-rich porphyry deposits, based on gold grains from the Obudu Plateau, is shown in Fig. 18(B) . Gold grains from the Obudu Plateau also plot near the Au apex, but with a more coherent and systematic trend toward the GRPD and GRPCD fields than those from the Oban Massif. Compared with Oban, Obudu gold shows slightly higher Cu enrichment and a more restricted Ag variation, reflecting stronger magmatic control on gold chemistry.

The clustering of data points along the GRPD–GRPCD boundary indicates a genetic continuum between Au-rich porphyry systems and Cu-bearing porphyry environments, consistent with the very high fineness values and low Ag content observed in EMPA data.

Plot of Au (wt.%) versus Ag (wt.%) for gold grains from the study areas was compared with gold deposits globally and is presented in Fig. 19.

Gold grains from the Oban Massif follow a well-defined inverse Au–Ag trend, with Au contents typically ranging from ~78–98 wt.% and Ag contents generally below 25 wt.%. Most data points

closely overlap with fields defined by orogenic gold systems in the Igarra schist belt (Nigeria), the Lom Series schist belt (Cameroon), and other Eastern Cameroon goldfields.

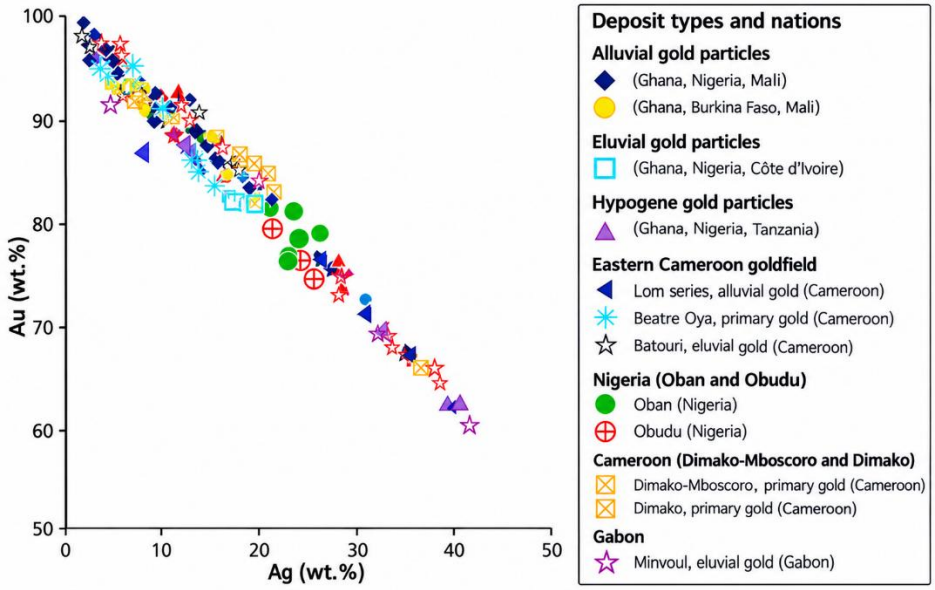


Fig. 19 Au (wt.%) versus Ag (wt.%) plots comparing gold from the Oban Massif and Obudu Plateau with gold deposits worldwide

Grains from Obudu Plateau cluster more tightly toward the high-Au, low-Ag end of the spectrum, with Au contents commonly exceeding 90 wt.% and Ag rarely exceeding 15 wt.%. Compared with the Oban Massif, Obudu Plateau gold shows reduced dispersion along the Au–Ag trend. Oban Massif gold shows broader compositional scatter, whereas Obudu Plateau gold is more.

Comparative synthesis of key geochemical, microchemical, and morphological parameters between the Oban Massif and Obudu Plateau gold-forming systems is presented in Table 7.

Table 7. Comparative synthesis of key geochemical, microchemical, and morphological parameters between the Oban Massif and Obudu Plateau gold-forming systems.

Parameter	Oban Massif	Obudu Plateau
Au in stream sediment (mean)	1.0–36 ppb	28–56 ppb
Au maximum (single sample)	88 ppb	99 ppb
Anomaly threshold (median + 2 MAD)	38 ppb	64 ppb
Au pathfinder cluster (HCA)	Au–As–Sb–Cu–Pb–Zn–S–Mo	Au–K_2O–Ba–U–Y (lithophile)
Au–S correlation (r)	+0.62*	+0.08 (n.s.)
Grain morphology	Angular; heterogeneous	Rounded; homogeneous
Au (wt%; EPMA)	75.4 – 100.0	96.6 – 100.0
Ag (wt%; EPMA)	0 – 21.2	0 – 2.5
Fineness range (mean)	781 – 1000 (≈ 905)	987 – 1000 (≈ 996)
Inclusion suite	Sericite, cassiterite, muscovite, calcite/clay	Monazite, zircon, ilmenite, clay

Au–Ag–Cu ternary field	ED – GRPD – GRPCD (broad)	GRPD – GRPCD boundary (tight)
Global analogues	Igarra; Lom Series; eastern Cameroon	Porphyry / granitoid-related
Inferred deposit class	Orogenic + intrusion-related (Sn)	Magmatic-hydrothermal (porphyry-related)
Transport indicator	Proximal; short fluvial transport	Distal; advanced modification

4. Discussion

4.1. Distinct gold populations and their metallogenic significance

The most significant outcome of this study is the recognition of two chemically and metallogenically distinct gold populations within a relatively narrow segment of the Pan-African basement of south-eastern Nigeria. The distinction is consistently expressed in stream-sediment geochemistry, gold-grain morphology, mineral inclusion assemblages, and alloy chemistry, indicating that the observed differences are primary metallogenic features rather than products of differential weathering or sedimentary sorting.

Gold from the Oban Massif is characterized by moderate fineness, heterogeneous internal textures, angular to sub-angular morphologies, and mineral inclusions dominated by sericite/illite, muscovite, quartz, calcite, and cassiterite (Fig. 15 and 16, Fig. 11, Fig 13. These characteristics are accompanied by a coherent Au–As–Sb–Cu–Pb–Zn–S–Mo geochemical association in stream sediments (Fig 9). Collectively, these features are typical of hydrothermal gold systems in which gold deposition is closely linked to sulphide precipitation within structurally focused fluid pathways [1, 48, 49].

In contrast, gold from the Obudu Plateau displays remarkably high fineness, homogeneous internal compositions, rounded morphologies, and inclusion assemblages dominated by monazite, zircon, and ilmenite (Fig. 15 and 16, Fig. 12, Fig. 14). The corresponding stream-sediment geochemistry lacks strong associations with classical sulphide pathfinders and instead exhibits weak but consistent relationships with lithophile elements such as K, Ba, U, and Y (Fig. 10). These features indicate a metallogenic environment fundamentally different from that recorded in the Oban Massif and suggest a stronger contribution from evolved granitoid-related hydrothermal systems.

The existence of these contrasting signatures within adjacent crustal blocks demonstrates that south-eastern Nigeria preserves substantially greater metallogenic diversity than previously recognized. More importantly, it indicates that multiple mineralizing processes operated during the late stages of Pan-African tectonic evolution, producing distinct gold systems within a common orogenic framework.

4.2. Controls on gold chemistry and mineral inclusion assemblages

Mineral inclusions preserved within detrital gold provide direct evidence of the mineralogical environment in which gold crystallized and therefore constitute one of the most powerful indicators of deposit affinity [49–52].

The sericite/illite inclusions identified in Ifunkpa gold grains are particularly significant because they record phyllic-style hydrothermal alteration commonly associated with structurally controlled gold mineralization. Likewise, the occurrence of muscovite and quartz inclusions is consistent with precipitation from hydrothermal fluids interacting with metamorphic and granitoid host rocks.

The identification of cassiterite within gold from the Oban drainage (Fig. 13) is especially noteworthy. Cassiterite is rarely reported as an inclusion in detrital gold and is commonly associated with highly fractionated granitic systems. Its occurrence therefore suggests that at least part of the Oban gold system experienced interaction with Sn-bearing magmatic-hydrothermal fluids. This interpretation is supported independently by the widespread occurrence of Sn–Ta–Nb–Cs-bearing pegmatites within the massif and by minor Cu enrichment observed in some gold grains. Rather than indicating a purely orogenic system, the data favour a hybrid scenario in which structurally controlled hydrothermal mineralization was subsequently modified or augmented by late-stage granite-derived fluid

The Obudu Plateau presents a contrasting inclusion assemblage dominated by zircon, monazite, and ilmenite (Fig. 14). These minerals are common accessories in felsic magmatic systems and are not typical products of low-temperature hydrothermal alteration. Their preservation within gold grains implies close spatial and genetic relationships between gold precipitation and granitoid magmatism. Particularly noteworthy is the occurrence of monazite, which is characteristic of REE-enriched felsic systems and has been documented in several high-temperature magmatic-hydrothermal gold environments worldwide [53].

Gold-alloy chemistry supports these interpretations. Oban gold exhibits a wide compositional spectrum (fineness = 781–1000; Fig 16), indicating variable physicochemical conditions during gold precipitation and/or multiple mineralizing episodes. In contrast, Obudu gold is remarkably uniform (fineness 987–1000; Fig 16), suggesting formation from a chemically restricted and relatively homogeneous hydrothermal system. The strong compositional clustering of Obudu gold within the Au-rich sector of the Au–Ag–Cu discrimination diagram (Fig. 18B) further emphasizes its distinction from the more heterogeneous Oban population (Fig 18A).

4.3 Metallogenic evolution of the south-eastern Nigerian basement

The contrasting geochemical and microchemical signatures documented in this study can be integrated into a coherent metallogenic model for the south-eastern Nigerian basement (Fig. 20). The model reflects the complex tectono-magmatic evolution of the Nigeria–Cameroon sector of the Pan-African belt, which experienced continental collision, crustal thickening, regional metamorphism, transcurrent shearing, and voluminous granitoid magmatism between ca. 700 and 500 Ma [20, 54]. Such tectonic environments are capable of generating multiple gold-forming systems through the interaction of metamorphic devolatilization, crustal-scale fluid migration, and granitoid-derived hydrothermal activity [1, 48].

In the Oban Massif, several independent datasets support a predominantly shear-controlled hydrothermal system. The close association of Au with As, Sb, Cu, Pb, Zn, S, and Mo in stream sediments (Fig. 9) indicates a strong sulphide-related hydrothermal component, while the angular to sub-angular morphologies and heterogeneous internal textures of the gold grains (Fig. 11) suggest limited transport from nearby bedrock sources. Mineral inclusion assemblages dominated by sericite/illite, muscovite, quartz, calcite, and cassiterite (Fig. 13) record precipitation within hydrothermally altered wall rocks and imply interaction between mineralizing fluids and both metamorphic and granitoid lithologies. The wide fineness range (781–1000) and pronounced compositional heterogeneity (Fig. 15 & 16) further indicate variable physicochemical conditions during gold precipitation. Collectively, these

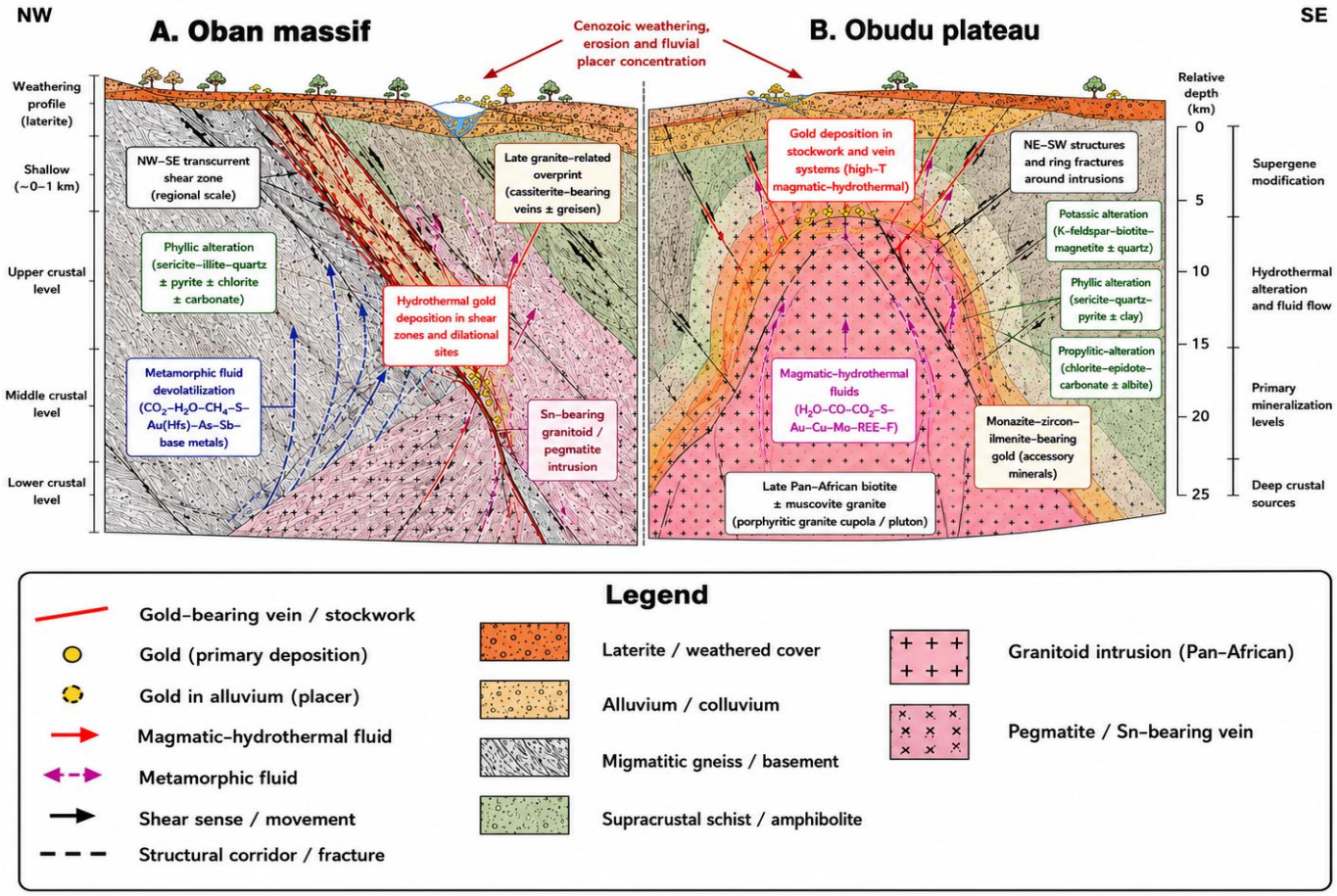


Fig. 20 Conceptual two-stage metallogenic model for gold mineralization in the southeastern Nigerian Pan-African basement. Stage 1 (Late Pan-African, ~600–550 Ma): shear-hosted orogenic-hydrothermal mineralization in the Oban Massif along NW–SE structural corridors, producing electrum of moderate fineness and subsequently overprinted by granite-related (Sn-bearing) hydrothermal activity; and granitoid-related magmatic-hydrothermal mineralization in the Obudu Plateau along NE–SW structural corridors adjacent to late Pan-African granitoid intrusions, producing high-fineness gold. Stage 2 (Cenozoic–Recent): prolonged tropical weathering, erosion, and fluvial reworking resulted in supergene modification and concentration of gold into modern placer deposits

features are consistent with mineralization from metamorphic-hydrothermal fluids channelled along the regional NW–SE shear network, with gold deposition promoted by pressure fluctuations, fluid–rock interaction, sulphidation, and cooling within structurally prepared sites. The occurrence of cassiterite inclusions and the regional abundance of Sn–Ta–Nb-bearing pegmatites suggest that this structurally controlled gold system was subsequently overprinted by late-stage granite-derived hydrothermal fluids.

The Obudu Plateau records a markedly different metallogenic signature. Stream-sediment geochemistry reveals weak but persistent associations between Au and lithophile elements such as K, Ba, U, and Y (Fig. 10), while gold grains display rounded morphologies, homogeneous internal textures (Fig 12**)**, and consistently high fineness values (987–1000) (Fig. 16). The predominance of monazite, zircon, and ilmenite inclusions (14) indicates a close relationship between gold mineralization and evolved felsic magmatism. Unlike the Oban Massif, classical sulphide pathfinders exhibit little or no systematic association with Au, suggesting that sulphide precipitation played a comparatively minor role in gold deposition. The strong clustering of Obudu compositions within the Au-rich sector of the Au–Ag–Cu discrimination diagram (Fig. 18) further supports derivation from a chemically distinct hydrothermal system. These characteristics are most consistent with a granitoid-related magmatic-hydrothermal environment in which gold-bearing fluids were generated during the late stages of granitoid crystallization and emplaced along structurally favourable conduits adjacent to intrusive centres. Although the present data do not unequivocally demonstrate a porphyry system in the strict economic-geological sense, they indicate a clear high-temperature magmatic-hydrothermal affinity that differs fundamentally from the deformation-dominated system recognized in the Oban Massif.

The juxtaposition of these contrasting signatures within a single Pan-African basement transect demonstrates that southeastern Nigeria preserves evidence for multiple, broadly contemporaneous mineralizing processes operating during the waning stages of the Pan-African orogeny (Fig. 20). The Oban Massif records gold mineralization principally associated with deformation-driven hydrothermal fluid flow and local granite-related overprinting, whereas the Obudu Plateau records a stronger contribution from granitoid-derived hydrothermal processes. The resulting metallogenic heterogeneity emphasizes the importance of integrating geochemical, microchemical, and mineralogical datasets when evaluating gold systems in deeply weathered Precambrian regions.

4.4 Regional and global implications

The results have implications extending beyond south-eastern Nigeria. Across many Precambrian terranes, gold mineralization is commonly assigned to a single dominant deposit class, often on the basis of limited geological observations or regional tectonic setting. The present study demonstrates that adjacent crustal blocks within a single Pan-African segment may host fundamentally different gold systems despite sharing broadly similar lithological and tectonic histories.

This observation is particularly relevant to the Pan-African belts of West and Central Africa, where large areas remain underexplored and where placer gold occurrences frequently constitute the only available evidence for mineralization. The combined use of stream-sediment geochemistry, detrital

gold morphology, mineral inclusion analysis, and EPMA alloy chemistry provides a practical methodology for distinguishing between contrasting mineralizing environments in regions lacking bedrock exposure.

Furthermore, the study contributes one of the few integrated gold microchemical datasets currently available from the eastern Nigerian sector of the Pan-African belt. Comparison with published datasets from Nigeria, Cameroon, Gabon, and other Precambrian provinces (Fig. 19) suggests that gold-alloy chemistry retains useful information regarding ore-forming conditions even after prolonged tropical weathering and fluvial transport. The results therefore reinforce the value of detrital gold as a tracer of concealed mineralization in deeply weathered tropical terranes.

4.5 Exploration implications

The contrasting metallogenic signatures identified in this study provide distinct exploration vectors for each region. In the Oban Massif, the most prospective targets are major NW–SE shear zones, subsidiary fracture intersections, and contacts between granitoids and supracrustal rocks. Stream-sediment anomalies characterized by elevated Au accompanied by As, Sb, Cu, Pb, Zn, S, and Mo represent the most reliable indicators of mineralization (Supplementary Fig. 9). Sericitization, silicification, sulphidation, and the presence of cassiterite-bearing hydrothermal systems should be regarded as favourable exploration criteria.

In the Obudu Plateau, exploration should focus on structurally controlled zones surrounding late Pan-African granitoids, particularly where quartz veining and hydrothermal alteration coincide with elevated Au, K, Ba, and U concentrations. The occurrence of high-fineness gold (Fig.16) containing monazite, zircon, and ilmenite inclusions may provide a useful indicator of granitoid-related mineralization even where classical sulphide pathfinders are absent.

4.6 Limitations and future work

Although the results provide compelling evidence for metallogenic heterogeneity within the south-eastern Nigerian basement, several uncertainties remain. The number of gold grains analysed from individual drainages is sufficient for first-order discrimination but remains below the population sizes recommended for robust statistical characterization of complex gold populations. Expanded gold-grain datasets would allow more rigorous assessment of compositional sub-populations and transport effects.

Future work should prioritize fluid-inclusion microthermometry, stable isotope studies (S–O–H–C), Pb isotope analysis of sulphides, and direct geochronological constraints on mineralization. U–Pb

dating of monazite inclusions from Obudu gold, in particular, offers a promising avenue for testing the proposed granitoid-related model. In addition, integrated geophysical surveys and targeted drilling will be required to establish the geometry, grade, and economic significance of the inferred primary mineralized systems.

5. Conclusions

This study presents the first integrated metallogenic investigation of gold mineralization in the Pan-African basement terranes of south-eastern Nigeria, combining stream-sediment geochemistry, gold-grain morphology, EPMA-WDS microchemistry, mineral inclusion analysis, and deposit-affinity discrimination. The results demonstrate that two geochemically and metallogenically distinct gold systems occur within a relatively short (~200 km) segment of contiguous Pan-African crust.

Gold from the Oban Massif is characterized by angular to sub-angular morphologies, heterogeneous internal textures, moderate fineness values (mean ≈ 905), and mineral inclusion assemblages dominated by sericite/illite, muscovite, calcite/clay, and cassiterite. These features are accompanied by a coherent Au–As–Sb–Cu–Pb–Zn–S–Mo geochemical association in stream sediments and significant correlations between Au and sulphide-related pathfinder elements, indicating a predominantly shear-controlled hydrothermal system. The occurrence of cassiterite inclusions and the regional abundance of Sn-bearing pegmatites further suggest a late-stage granite-related hydrothermal overprint on an otherwise orogenic gold system.

In contrast, gold from the Obudu Plateau displays rounded morphologies, homogeneous internal compositions, exceptionally high fineness values (mean ≈ 996), and inclusion assemblages dominated by monazite, zircon, and ilmenite. Stream sediments are characterized by a diffuse Au–K_2O–Ba–U lithophile association and the absence of significant correlations between Au and classical sulphide pathfinders. Together, these features indicate a chemically distinct granitoid-related magmatic-hydrothermal system, interpreted here as having a porphyry-style affinity. To our knowledge, this represents the first recognition of such a gold system within the southeastern Nigerian basement.

The Au–(Ag × 10)–(Cu × 100) discrimination diagrams independently corroborate the distinction between the two mineralizing environments, with Oban gold spanning the epithermal deposit (ED), gold-rich porphyry deposit (GRPD), and gold-rich porphyry copper deposit (GRPCD) continuum, whereas Obudu gold clusters tightly along the GRPD–GRPCD boundary. Comparison with published datasets from Nigeria, Cameroon, and other Precambrian terranes further demonstrates

that the Oban Massif exhibits strong similarities to established orogenic gold systems of the Cameroon Mobile Belt and the Igarra Schist Belt, whereas the Obudu Plateau defines a more unusual high-fineness granitoid-related gold population.

Integration of the geological, geochemical, and microchemical datasets supports a two-stage metallogenic model. The first stage involved Late Pan-African (~600–550 Ma) primary gold emplacement during regional tectono-magmatic evolution, producing structurally controlled hydrothermal mineralization in the Oban Massif and granitoid-related magmatic-hydrothermal mineralization in the Obudu Plateau. The second stage involved prolonged Cenozoic weathering, erosion, and fluvial reworking, resulting in the placer gold concentrations presently exploited throughout the region.

Beyond establishing a new metallogenic framework for southeastern Nigeria, this study highlights the value of integrating detrital gold microchemistry with stream-sediment geochemistry for resolving concealed mineralization in deeply weathered Precambrian terranes. The results provide practical exploration criteria for future work, including targeting NW–SE shear zones associated with sericitization, cassiterite occurrence, and Au–As–Sb–Cu–Pb–Zn–S anomalies in the Oban Massif, and NE–SW structural corridors adjacent to late granitoid intrusions characterized by monazite-bearing gold and elevated Au–K_2O–Ba–U signatures in the Obudu Plateau. Priority follow-up areas include the upper Ifunkpa, Oban, and Akwa-Ibami drainages of the Oban Massif and the upper Okwangwo drainage of the Obudu Plateau.

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This work was carried out in collaboration between all authors. Author Asinya, E. A. carried out fieldwork, analyzed the data and wrote the first draft of the manuscript. Author Oha, I. A., proof read the final draft. Authors Omang, O. O. and Akumbom, V. designed the study. Authors Ukwang, E. E. and Onwuka, O. S. checked the protocol of the study and evaluated data quality. Authors Odey, J. U. and Omeka, E. O. managed the literature searches. Author Ibe, C. U. developed the model in the study. Author Undinmwen, E. checked the grammar and language. All authors read and approved the final manuscript.

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All ICP-MS bulk geochemistry, EPMA spot analyses, and SEM imagery are available from the corresponding author upon reasonable request. Supplementary tables of full per-sample geochemistry and per-grain EPMA spot analyses are provided are available.

Consent to Participate and Consent to Publish:

Informed consent to participate in the study and consent to publish were obtained from all individuals whose identifiable images appear in the manuscript. All individuals whose identifiable images are included in the manuscript are above 18 years of age. They were informed of the intended use of their images and provided consent for their publication.

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