

Morphological and microchemical signatures of alluvial gold and electrum grains from the Tcholliré gold district, northern Cameroon: Insights to potential epithermal gold system in the area

^{1,2*}Ralain Bryan Ngatcha, ³Kevin Ijunghi Ateh, ^{4,5}Akumbom Vishiti, ¹Ephesians Nchinda Ntantan, ¹Ngum Nelson Nsake, ¹Olivier Anoh Njoh, ^{1,6}Cheo Emmanuel Suh

¹Department of Geology, Mining and Environmental Science, Faculty of Science, The University of Bamenda, P.O. Box 39 Bambili, North West Region, Cameroon

²Department of Geology, Pan African University Life and Earth Sciences Institute (PAULESI), University of Ibadan, Ibadan, Nigeria

³Department of Mining and Mineral Engineering, National Higher Polytechnic Institute (NAHPI), The University of Bamenda, P.O. Box 39, Bambili, North West Region, Cameroon.

⁴Department of Civil Engineering, The University Institute of Technology (IUT), University of Douala, P.O. Box 8698 Douala, Littoral Region, Cameroon

⁵Laboratory of Geosciences, Natural Resources and Environment, Department of Earth Sciences, Faculty of Science, University of Douala, P.O. Box 24157, Douala, Littoral Region, Cameroon.

⁶Economic Geology Unit, Department of Geology, University of Buea, P.O. Box 63, Buea, South West Region, Cameroon

*Corresponding author: bryanngatcha@gmail.com

Abstract

The Tcholliré district, located in the Adamawa-Yadé Domain (AYD) of the Neoproterozoic Fold Belt of Cameroon (NFBC), hosts some alluvial gold mining sites. The morphological and chemical signatures of the alluvial gold grains from these mining sites are yet to be described. Thus, we describe for the first time the morphology, microtexture, and chemical features of gold and electrum grains and other heavy minerals, notably cassiterite, recovered from stream sediments from the Tcholliré district drainage system, discuss distance-to-source, and trace the possible source(s) of gold mineralization and type. A total of 33 gold-electrum grains recovered from the gravel layer in two pits dug along stream channels were analysed by scanning electron microscopy (SEM)-energy dispersive spectroscopy (EDS) and electron probe microanalyses (EMPA). The gold grains display angular, irregular to sub-rounded morphologies, indicating a close distance hypogene source. Gold in the concentrate is associated with phases such as zircon, cassiterite, and sulfides (e.g., anglesite and tetrahedrite). Inclusions such as quartz, clay minerals, and ilmenite occur in the gold grains and point to a granitoid-related host. Gold grains are mainly alloyed with Ag and Cu with contents as high as 67.17 wt. % Ag (electrum) and 23.54 wt. % Cu. These are the highest combined Ag and Cu values reported in gold grains in Cameroon thus far. The variation in the concentration of Au and Ag from core to rim is slightly heterogeneous. Such elevated Ag contents in the rim section reflects recently liberated grains from the source. The compositional range of Ag and Cu coupled with the presence of electrum and cassiterite are consistent with a single high-sulfidation and high-temperature magmatic-hydrothermal origin possibly linked to epithermal activity of the Cameroon Volcanic Line.

Keywords: Alluvial gold, morphology, microtexture, microchemical signature, Tcholliré district, Cameroon

Received: 20/04/2024

Accepted: 01/05/2024

<https://dx.doi.org/10.4314/jcas.v20i2.7>

© The Authors. This work is published under the Creative Commons Attribution 4.0 International Licence.

Résumé

Le district de Tcholliré, situé dans le Domaine de l'Adamawa-Yadé (AYD) de la Ceinture Plissée Néoprotérozoïque du Cameroun (NFBC), abrite quelques sites d'exploitation aurifère alluviale. Les signatures morphologiques et chimiques des grains d'or alluviaux de ces sites miniers restent à décrire. Ainsi, nous décrivons pour la première fois la morphologie, la microtexture et les caractéristiques chimiques des grains d'or et d'électrum et d'autres minéraux lourds, notamment la cassitérite, récupérés à partir de sédiments fluviaux du système de drainage du district de Tcholliré, discutons de la distance jusqu'à la source et retraçons la source(s) possible(s) de minéralisation et type d'or. Un total de 33 grains d'or-électrum récupérés de la couche de gravier dans deux fosses creusées le long des canaux de cours d'eau ont été analysés par microscopie électronique à balayage (MEB), spectroscopie à dispersion d'énergie (EDS) et microanalyses par sonde électronique (EMPA). Les grains d'or présentent des morphologies angulaires, irrégulières à sous-arrondies, indiquant une source hypogène à proximité. L'or dans le concentré est associé à des phases telles que le zircon, la cassitérite et les sulfures (par exemple l'anglésite et la tétraédrite). Des inclusions telles que du quartz, des minéraux argileux et de l'ilménite sont présentes dans les grains d'or et indiquent un hôte lié aux granitoïdes. Les grains d'or sont principalement alliés à l'Ag et au Cu avec des teneurs allant jusqu'à 67,17 en poids. % Ag (électrum) et 23,54 en poids. %Cu. Il s'agit des valeurs combinées Ag et Cu les plus élevées signalées jusqu'à présent dans les grains d'or au Cameroun. La variation de la concentration en Au et Ag du noyau au bord est légèrement hétérogène. De telles teneurs élevées en Ag dans la section du bord reflètent les grains récemment libérés de la source. La gamme de composition d'Ag et de Cu couplée à la présence d'électrum et de cassitérite sont cohérentes avec une seule origine magmatique-hydrothermale à haute sulfuration et à haute température, éventuellement liée à l'activité épithermale de la ligne volcanique du Cameroun.

Mots clés : Or alluvial, morphologie, microtexture, signature microchimique, district de Tcholliré, Cameroun

1.0 Introduction

Over time, discovering new mineral resources has been more difficult. This has prompted the development of indicator mineral techniques in recent decades meant to identify a broad range of mineral deposits in regions with thick overburden (Averill, 2011). Gold, because of its clear link to the source mineralization, chemical stability such that the particle endures in the surficial environment, and physical resilience, is generally regarded as a proxy for local or regional hypogene mineralization (McClenaghan and Cabri, 2011), both for the exploration of gold itself and for some other metalliferous mineralization where gold is an accessory (Chapman et al., 2021). The successful establishment of placer-lode relationships and deposit style characteristics has been demonstrated by the combination of morphological and microchemical features of gold

grains (Chapman and Mortensen, 2006; Chapman et al., 2018; Fuanya et al., 2019; NguimatsiaDongmo et al., 2019; Ateh et al., 2021; Ketchaya et al., 2022; Ngouabe et al., 2022).

Estimating the transport distance that gold grains travel from their source has been shown to be possible with the use of the morphologies and microtextures of the grains such as roundness (Townley et al., 2003; Barrios et al., 2015; Fuanya et al., 2019; Ateh et al., 2021). The chemical features of gold particles worldwide have shed more light on the nature of hypogene sources (Chapman et al., 2010; Omang et al., 2015; Leal et al., 2021). Au grains are a natural alloy of Au, Ag, and Cu in varying amounts depending on the conditions of ore formation. Different varieties of gold have unique alloy compositions and, consequently, unique microchemical signatures.

These signatures have been compiled for orogenic gold systems (Chapman et al., 2010), oxidizing chloride hydrothermal systems (Chapman et al., 2009), skarn- and intrusion-related gold systems (Potter and Styles, 2003), and epithermal vein systems (Chapman and Mortensen, 2006).

Along these lines, some studies have been conducted in Cameroon to identify primary gold mineralization sources in vast drainage systems downstream of possible catchment regions. These studies used analyses, such as scanning electron microscopy (SEM)-energy dispersive spectroscopy (EDS) and electron probe microanalyses (EMPA), LA-ICP-MS to characterize the gold grains. The majority of these studies were carried out in the gold mining districts in the eastern part of Cameroon, with the results suggesting an orogenic style of mineralization in which gold occurs in quartz veins as free gold and associated with felsic intrusions (Omang et al., 2015; Vishiti et al., 2015; Ateh et al., 2021). Many of the prospective locations that were identified are now important mining sites. In the southern part of the country, the primary mineralization is still elusive, although gold chemistry and stream sediment geochemistry indicate an interaction of the mineralization with basic rocks, notably amphibolite and metadolerite (Omang et al., 2015; Fuanya et al., 2019; Nguimatsia Dongmo et al., 2019). The northern part of the country is equally known for its gold occurrences and important artisanal mining sites in areas like Meiganga, Gamba, Rey Bouba, and Dourou Tchaga (Ngouabe et al., 2022; Ngounouno et al., 2022, Fig. 1b and c). Despite these gold occurrences relatively few studies have been done to uncover its primary mineralization style, as well as, gold source(s) actively mined by local artisans. Recent research in the Meiganga area by Ngouabe et al. (2022) suggests a hydrothermal gold-quartz-sulfide system driven by ultramafic intrusion. In the Gamba district

(about 170 km NW of Meiganga), the microchemical fingerprints of placer gold grains also indicate a hydrothermal-orogenic source (Ketchaya et al., 2022, 2024). Mineral inclusions in the gold grains, such as phosphates (apatites), oxides (such as magnetite, ilmenite, and hematite), and silicates (such as zircon, titanite, quartz, muscovites, biotite, actinolite, titanite, albite, and almandine), emphasize the magmatic and metamorphic conditions of formation for the hypogene source. Ngounouno et al. (2022), describe primary gold mineralization in the Dourou Tchaga area (about 50 km north of Gamba) to occur in sinistral steeply dipping, ENE–WSW-trending laminated quartz-sulfide veins hosted by high-grade metamorphic paragneiss and orthogneiss.

The primary gold source(s) as well as mineralization type in the Tcholliré gold district remain poorly documented in this district. Additionally, it is unknown whether all the gold within the alluvial deposit is placer or authigenic. Information from alluvial gold grains morphology and Au-Ag-Cu alloy composition can be very significant, as it can reveal if the grains are close to the source, whether they are sourced from a single style of mineralization or whether several sources contributed within the same locality. Furthermore, the identification of economically viable sites along the drainage system is a priority for unexplored areas.

The present research is the first approach to apply the study of the morphology, microtexture and chemical features of gold grains and other heavy minerals recovered from stream sediments from the Tcholliré district drainage system, to test transport/morphological models and to trace the possible source(s) of gold mineralization and type. Specifically, this research offers a first attempt to characterize the composition of gold derived from high-sulphidation granite-associated mineralization in such environment.

2. Regional and local geology

The Tcholliré district belongs to the Northern Domain of the Neoproterozoic Fold Belt of Cameroon (NFBC), north of the Congo Craton (Fig. 1a). The NFBC also known as the Pan-African North Equatorial Fold Belt, is the southernmost branch of the Pan-African-Braziliano belt (Toteu et al., 2004), regarded to have formed during the collision between the Congo-São Francisco Craton, West African Craton and the Sahara metacraton (Toteu et al.,

2004). In Cameroon, the Neoproterozoic Fold Belt extends over almost the entire territory and is bordered to the south by the Ntem complex (northern part of the Congo craton). The NFBC is subdivided into three lithological domains, bound by Pan-African transcurrent shear zones (Fig. 1b). These domains, from south to north (Toteu et al., 2004), are: i) the Southern Domain; ii) the Central Domain; and iii) the Northern Domain that continues into the Mayo-Kebbi Domain of SW Chad (Penaye et al., 2006).

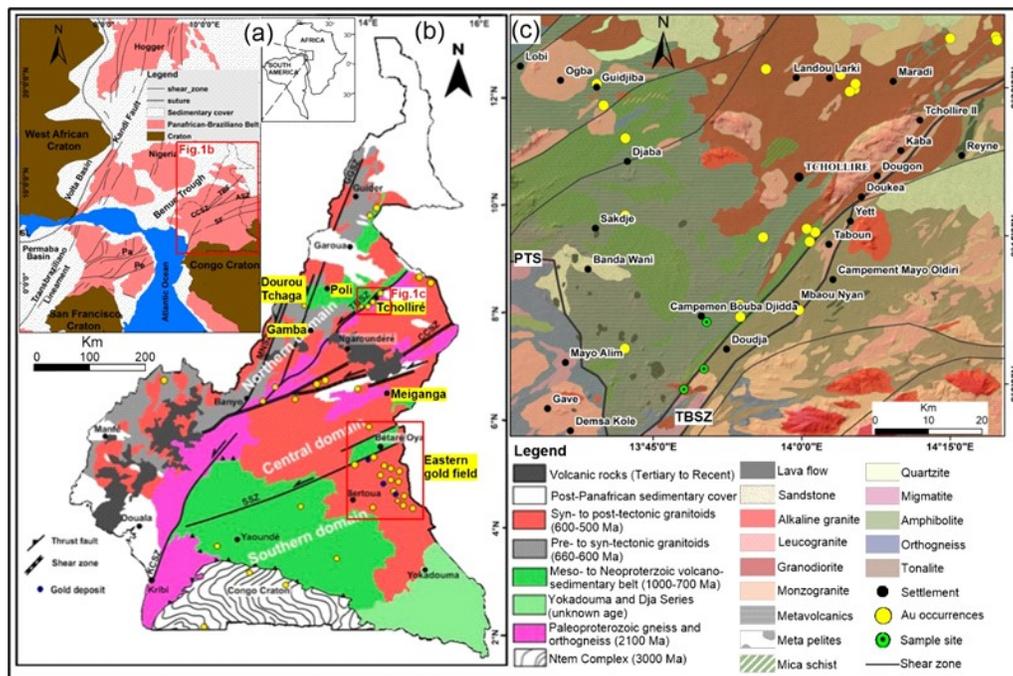


Figure 1. (a) Pre-drift reconstruction of western Gondwana land. The Central Africa Fold Belt (CAFB) bordering the northern part of the Congo Craton is defined by the Yaoundé domain (YD), Oubangide fold belt (OFB), Adamawa-Yadé domain (AYD) and Northwestern Cameroon domain (NWCD). It extends westward into the Borborema Province as the Pernambuco domain (PD) and Sergipano domain (SD). (b) Simplified geological map of Cameroon (adopted from Ngounouno et al., 2022) showing the location of the study area (white square) and major lithotectonic domains. KCSZ = Kribi-Campo shear zone; CCSZ = Central Cameroon shear zone; SSZ = Sanaga shear zone; TBSZ = Tcholliré-Banyo shear zone; MNZS = Mayo-Noli shear zone; GGSZ = Godé-Gormaya shear zone. (c) Geology of the Tcholliré district extracted from the PRECASEM geological map (Delor et al., 2021). Major shear zones in the area (Tcholliré Banyo Shear zone, TBSZ, Poli Thrust System, PTS) trend NE-SW and constitute potential host to gold mineralization.

The Northern Domain currently constitutes the only clearly identified Neoproterozoic magmatic arc north of the Congo Craton (Penaye et al., 2006; Isseini et al., 2012; Bouyo Houketchang et al., 2016). This domain consists of: (1) Neoproterozoic low- to high-grade schists and gneisses of volcanic and volcano-sedimentary

origin, exemplified by the Poli-Léré Group (Toteu et al., 2022). The metavolcanics consist of rhyolites and tholeiitic basalts that were emplaced in an extensional crustal environment beginning at about 830 Ma. Based on the presence of trondhjemite pebbles in volcanoclastic rocks dated at 734 ± 14 Ma (Toteu et al., 2006), 700 ± 10 Ma

metabasalt associated with the Zalbi Group, and detrital zircons from the Poli basin dated between 920 and 630 Ma (Toteu et al., 2006; Bouyo Houketchang et al., 2015), it can be hypothesized that there was long-lived plutonic and volcanic activity in the area. Also, Pan-African pre-, syn-, to late-tectonic granitoids (diorites, granodiorites, and granites) of calc-alkaline composition were emplaced between 660 and 600 Ma (Bouyo Houketchang et al., 2016; Toteu et al., 2022 and references therein). A multitude of remnant basins that rest unconformably on the deformed Poli Group (the most significant are the Mangbaï and Balché basins, located NE and SW of Garoua, respectively) likely represents molasses deposited about 580 Ma ago. The post-tectonic magmatism consisting of mafic and felsic dykes cross-cut by subcircular granites and syenites; the Godé and Zalbi granites, respectively, are the best-represented examples of late magmatism in the Poli and Leré regions (Isseini et al., 2012).

The tectono-metamorphic evolution of this domain is characterized by polyphase deformations and low- to high-grade metamorphism. The high-grade granulite facies metamorphism is dated at c. 600 Ma (Bouyo Houketchang et al., 2009). D_1 and D_2 deformations show ductile behavior under amphibolite to granulite facies, followed by retrogression into greenschist facies. According to Ngounouno et al. (2022), D_3 and D_4 are characterized by ductile-brittle and late-brittle structures. D_3 is characterized by NE-SW to N-S trending sinistral shear zones, locally associated with south-vergent thrusts. D_4 is associated with WNW-ESE to NE-SW trending dextral shear zones.

Primary gold mineralization in this domain has so far been described only in the Dourou Tchaga area (Ngounouno et al., 2022) and the Pala region located in the northeastern prolongation of the

Northern domain into South-West Chad (Tchameni et al., 2013). However, the recent work of Anaba Fotze et al. (2023) attempts to delineate potential structural features associated with gold occurrence within the Tcholliré district using combine aeromagnetic and field data. In this domain gold occurs both as free visible grains and disseminations in quartz-sulfide veins and wall rock alteration zones. In the Dourou Tchaga area, the quartz-sulfide (e.g., galena, sphalerite, pyrite and chalcopyrite) veins are hosted by high-grade metamorphic paragneiss and orthogneiss associated with the D_3 sinistral shear zone. Proximal sericite-ankerite-calcite-epidote and distal epidote-amphibole-quartz assemblages are characteristic alteration signatures related to the auriferous veins. The gold-bearing veins are massive or laminated, steeply dipping, and trend ENE-WSW. Data on fluid inclusions and alteration assemblages indicate that a rise in fO_2 brought on by changes in fluid pressure in the shear zone is what led to the precipitation of gold in quartz veins. Gold mineralization in the Pala region is classified as mesozonal orogenic gold (Pan-African) and is hosted by the Tcholliré-Banyo shear zone in mid-crustal schist and granite wall rocks (Tchameni et al., 2013). Primary gold mineralization here is associated to chalcopyrite-pyrite-bearing quartz veins, brecciated and silicified zones and shear zones distributed along granite intrusions. These veins generally trend N-S to NNE-SSW or NW-SE and are interpreted as extensional shear fractures related to regional NE-SW-trending sinistral strike-slip shear zones. The hydrothermal fluids likely formed along active continental margin during collisional orogeny and subsequently migrated during strike-slip deformation. The distribution of mineralization along the granite intrusion suggests that magmatism played a major role in the distribution and remobilisation of gold in sulfides minerals (Tchameni et al., 2013).

3. Sampling and analytical methods

3.1 Sample collection and preparation

Alluvial artisanal gold mining in the Tcholliré district is rapidly expanding. The mining here is mainly on stream or river beds (Fig. 2a), the majority of which completely dry out during the dry season. The samples used in this study include stream sediments recovered from the gravel layer

in two of the four pits dug along stream channels to a maximum depth of 2 m (Fig. 2b). The recovered bulk sediment samples were panned and gold/electrum grains were obtained by hand-picking under a binocular microscope from previously dried heavy mineral fractions. A total of 33 grains were hand-picked under a binocular microscope.

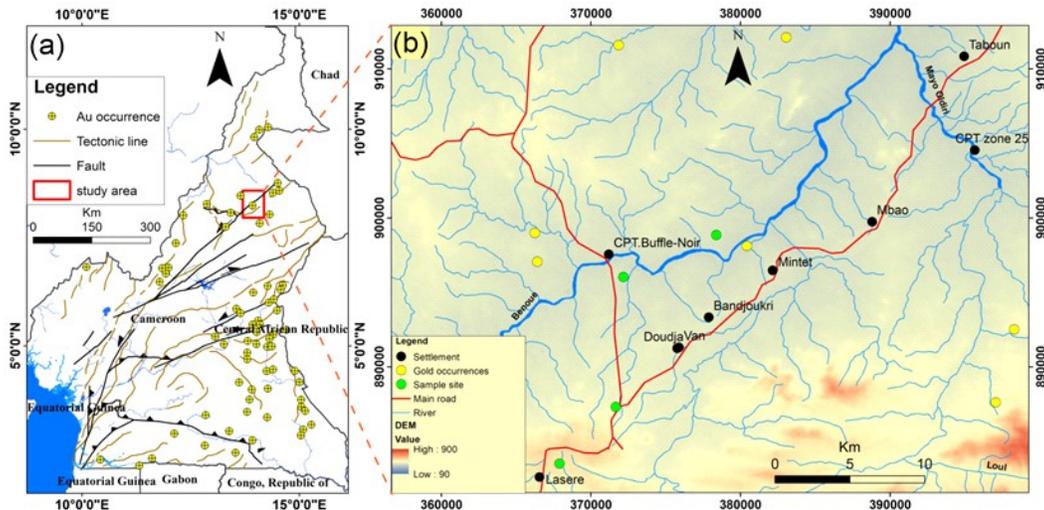


Figure 2. (a) Map of Cameroon showing the distribution of Au occurrences. (b) Sample location sites on the Tcholliré district drainage map.

3.2 Gold grain morphology and microchemistry

Gold grains including other heavy minerals (sulphides, zircon, and cassiterite) from the concentrate were embedded in epoxy resin and polished down to a $0.3 \mu\text{m}$ thickness using diamond abrasive sequential grits to expose grain interiors following the method described in Melchiorre and Henderson (2019). The gold grains' morphology was studied at California State University, San Bernardino, USA, using a Fisher-Phenom XL scanning electron microscope (SEM) set to an acceleration voltage of 15 kV to produce secondary electron (SE) and backscatter electron (BSE) images. The same instrument was utilized to analyze the gold grains by scanning electron microprobe (SEM) imaging, mapping, and energy dispersive spectroscopy analysis (EDS). Standard off-peak interference and matrix corrections were applied to the analysis.

The microchemistry of the grains from the concentrates was determined using an electron microprobe analyzer equipped with a wavelength dispersive spectrometry (WDS) at the same facility. Prior to grain analysis, the WDS was calibrated to a set of purchased house standards of gold-silver-copper alloy metals. Care was taken to minimize artifacts during sample preparation. The error associated with the trace element analyses is less than $\pm 0.2 \text{ wt.}\%$. Representative spots and regions were selected for analysis. A laboratory standard was run after every 10 analyses to ensure quality control of the data. A total of 43 spots, 1–4 spots per grain, were analyzed by EMPA for Au, Ag, Cu, Hg, O, Si, Pb, Sb, C, Sn, Zr, Fe, As, Al, Mg, K, and Ti, on both the core and rim of the grains. The gold fineness was calculated using the formula $\text{Au} \times 1000 / \text{Ag} + \text{Au}$ (Hallbauer and Utter, 1977).

4. Results

Grain morphology, surface characteristics, and microchemistry

Gold grains recovered from the Tcholliré mining district display a variety of sizes and shapes (Fig. 3). The gold and electrum grains recovered from the gravel layer in the two pits at Lasere and Mintet are homogenous with well-developed rims. Reflectance in the gold grains varies from low at rims to high at cores and is homogenous in most grains (Fig. 3a-g). The grains generally range from 350 μm to 750 μm in size in the longest dimension.

They display angular, irregular with embayment to sub-rounded morphologies (Fig. 3 & Table 1). Some of the gold grains show irregular pitting surfaces and cavities. The pits are irregular to interconnected and occur predominantly at the margins (Fig. 3d-f). Inclusions of quartz, clay minerals, and ilmenite are entombed in the gold grains around such areas (Fig. 3 & Table 1). Other minerals recovered from the concentrate alongside the gold and electrum grains include anglesite (altered galena), tetrahedrite, zircon, and cassiterite (Fig. 3 & Table 1).

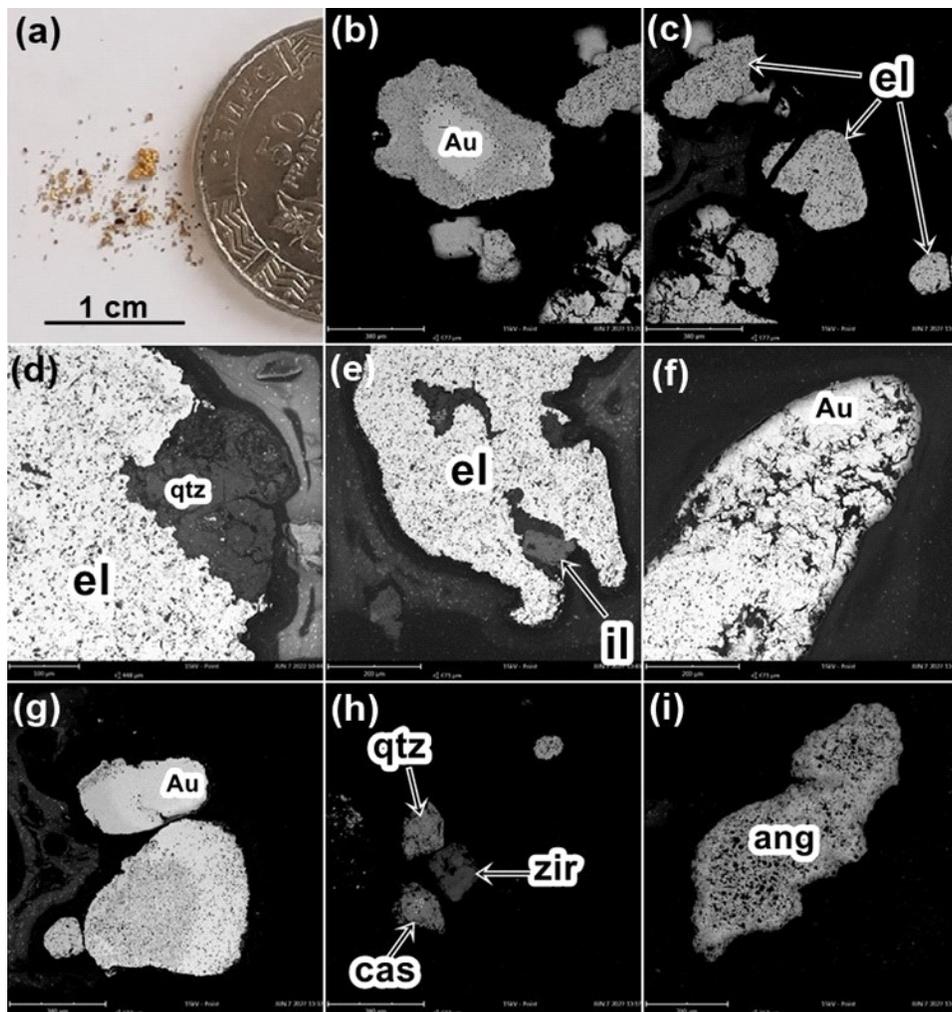


Figure 3. Gold-electrum grains recovered by panning from the Tcholliré district (a) and backscattered electron images (b-i). Brighter area due to relative enrichment of gold (e.g., core section in a) and the darker area are richer in silver and copper. The grains are unzoned, irregular to sub-rounded with pitting surfaces and cavities. Inclusions of quartz, ilmenite and clay material are noticeable around pitted grain margins (d-e).

Table 1. Au-Ag-Cu variation of gold grains from the Tcholliré district

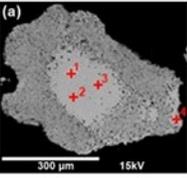
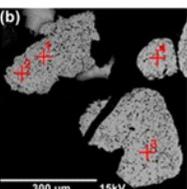
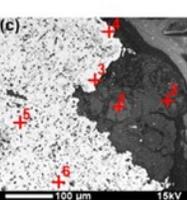
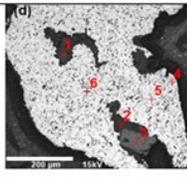
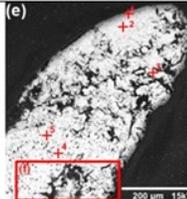
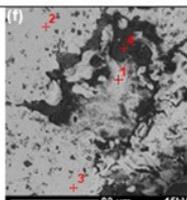
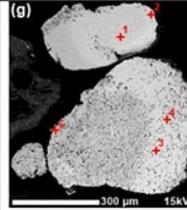
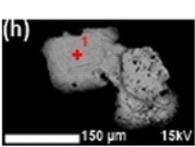
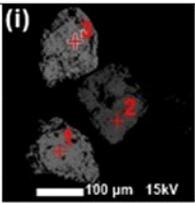
Sample	Grain/material	Shape	Pt.	Position	Content, wt. %												Total	Fineness
					Au	Ag	Cu	O	Fe	Si	Al	Mg	K	Ti	Hg			
	gold	angular	1	Core	100.	0.00	0.00									100	1000	
	gold		2	Core	0	0.00	4.59									100	1000	
	gold		3	Core	95.4	8.10	0.00									100	919	
	gold		4	Rim	1	12.2	0.00									100	878	
	electrum	angular	1	Core	43.9	56.0	0.00									100	439	
			2	Rim	4	6	0.00									100	544	
	electrum	irregular sub-rounded	3	Core	54.3	45.6	6.79									100	279	
	electrum		4	Core	5	5	0.00									100	396	
	quartz	irregular	1	Core				61.5	31.7	6.72						100		
	clay		2				6	2	34.2	12.9						100		
	electrum		3	Rim	51.1	48.9	0.00	52.2		3	7						100	511
			4	Rim	0	0	0.00	1									100	457
			5	Core	45.6	54.3	2.12										100	456
			6	Core	9	1	1.83										100	531
	clay	angular	1					57.0	11.1	19.9	11.3					100		
	clay		2			0.55		7	5	9	0	2.35	1.7			100		
	ilmenite	irregular	3	Core				52.8	2.15	22.6	17.7			33.12		100		
			4	Rim	50.0	48.2	1.71	6	36.6	4	1				100	509		
	electrum		5	Core	3	7	0.77	30.2	1							100	527	
			6	Core	52.2	46.9	0.00	6								100	434	
	gold	sub-rounded	1	Rim	99.3	0.68	0.00									100	993	
			2	Rim	2	0.00	0.00									100	1000	
			3	Rim	100.	4.42	0.00									100	956	
			4	Core	0	45.7	3.50									100	526	
			5	Core	95.5	6	0.00									100	541	
						8	45.8											
	electrum		1	Core	56.4	41.6	1.90									100	576	
			2	Core	9	1	0.00									100	566	
	clay		3	Rim	56.6	43.3	1.04									100	528	
			4		1	9		33.8	5.90	31.1	22.1	2.97	3.9	6		100		
	electrum	sub-rounded	1	Core	60.4	16.0	23.5									100	790	
			2	Rim	0	6	4									100	1000	
	tetrahedrite	sub-rounded	3	Core	89.1	0.00	10.8							52.5		100		
			4	Core	7	47.5	3							0		100		
			5	Rim	0.00	0	0.00							0.00		100		
				0.00	62.8	37.1												
				0.00	2	7												
				0	100.	0.00												

Table 1. Continued
Au-Ag-Cu variation of gold grains from the Tcholliré district

	tetrahedrite	irregular	1	Core	0.00	92.4	7.58											100	878		
					Content, wt. %																
	cassiterite zircon quartz	sub- rounded angular sub- rounded	1	Core						53.4									100		
			2	Core						0	36.1									100	
			3	Core								4	3.09								100

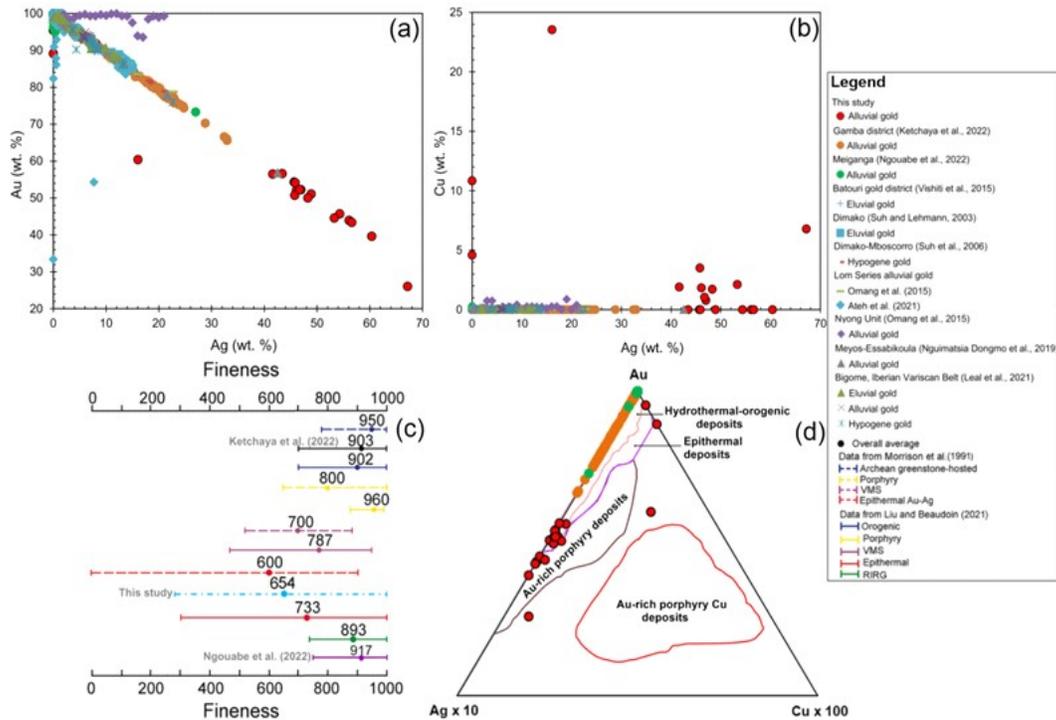


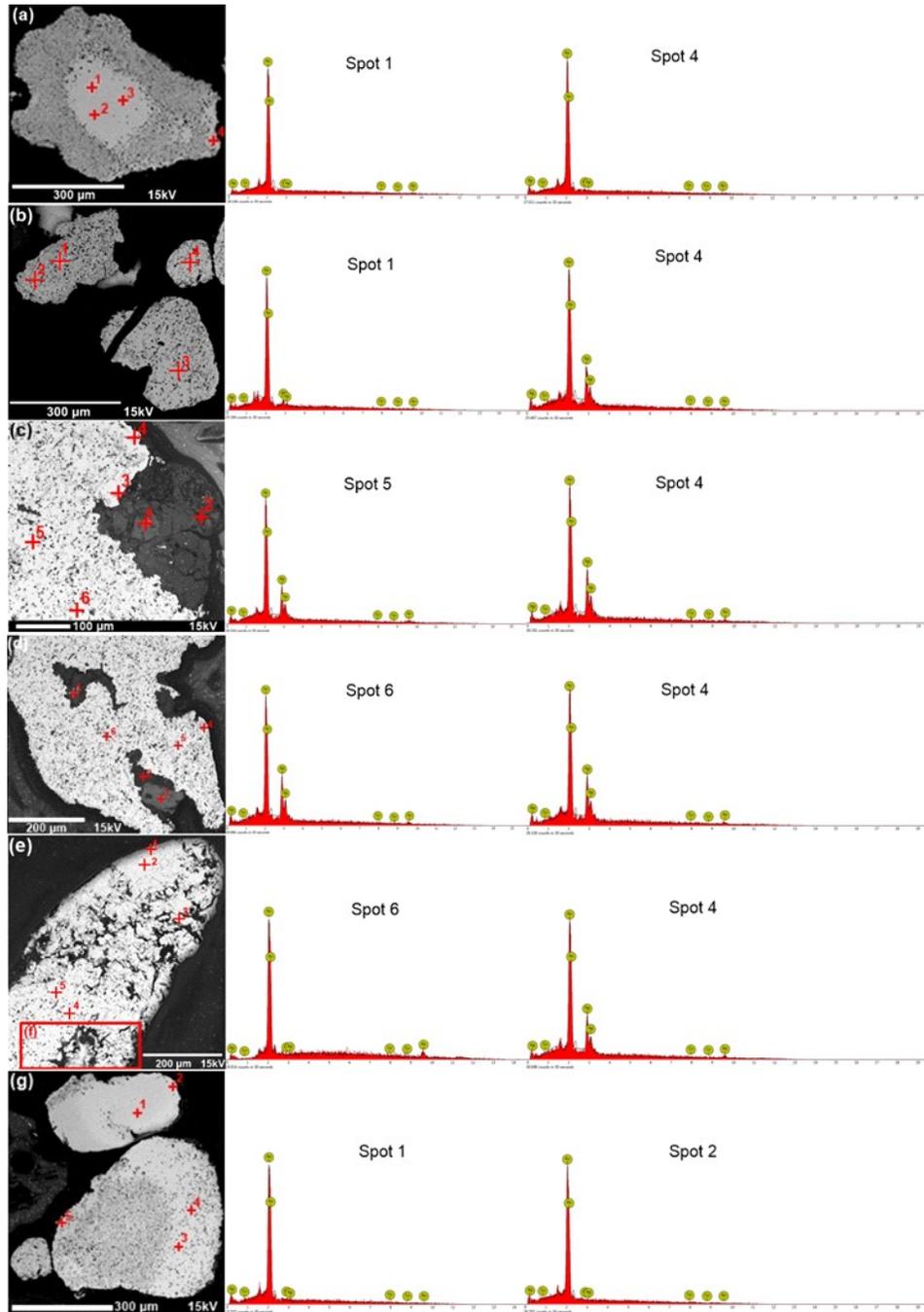
Figure 4. (a) Co-variance of Ag and Au for alluvial gold grain from the Tcholliré district compared with data from literature. Gold grains from Batouri are characterized by low to high Ag (69.17 wt. %) contents. (b) Co-variance of Ag and Cu for alluvial gold grains from the Tcholliré district. Copper contents are as high as 23.54 wt. %. (c) Comparison of range and overall average values of gold fineness from this study and data from literature. The fineness data for Archean greenstone-hosted, porphyry, VMS, and epithermal Au-Ag deposits are from Morrison et al. (1991) and Liu and Beaudoin (2021). (d) Ternary Au–(Ag x 10)–(Cu x 100) plot for alluvial gold grains from the Tcholliré district with epithermal, Au-rich porphyry, and Au-rich porphyry Cu deposits compositional fields of Townley et al. (2003). Data from the Gambe district (Ketchaya et al., 2022) and Meiganga area (Nguouabe et al., 2022) are plotted for comparison.

The gold grains are mainly alloyed with Ag and Cu with contents that reach a high of 67.17 wt. % Ag (electrum) and 23.54 wt. % Cu (Fig. 4). The variation in the concentration of Au and Ag from core to rim is slightly heterogeneous. There

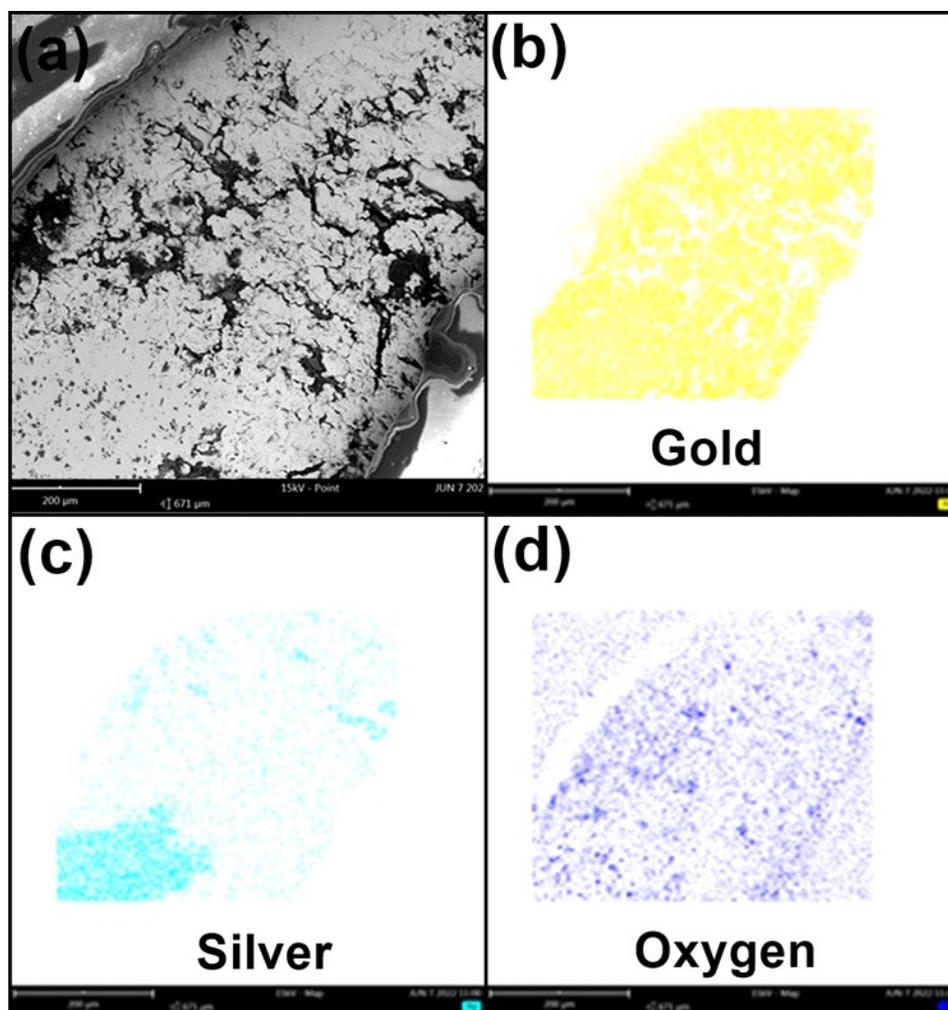
does not appear to be a correlation between Ag and Cu values. In most grains, the concentrations of gold increases towards the rim while the concentration of Ag increases towards the core. It is noteworthy that the difference in the

concentrations in such grains is in 10s wt. %. Gold fineness values vary between 279 and 1000 (avg. 654). Sulfides such as anglesite and chalcopyrite show sporadic gold content as low as 3.49 wt. % and Hg content as high as 52.50

wt. %, respectively. Energy-dispersive spectroscopy (EDS) patterns and EMPA maps are presented in Electronic Supplementary Material (ESM1 and 2).



ESM 1. BSE images indicating spots analyzed on the gold grains and their corresponding EDS patterns showing element variation in the various spots. Not all analyzed spots are presented here.



ESM 2. Individual maps indicating the distribution of Au, Ag, and O on the gold grain.

5. Discussion

5.1. Distance to source indicators

In the alluvial environment, morphology traits of gold grains have been widely exploited to provide valuable information about their distance-to-source of primary lode and the geological processes that have affected their transport and deposition (Townley et al., 2003; Barrios et al., 2015; Omang et al., 2015; Fuanya et al., 2019; Ateh et al., 2021; Leal et al., 2021; Ngouabe et al., 2022; Ketchaya et al., 2022). Angular to irregular gold grain morphologies are often indicative of newly liberated grains from the potential source rock and a relatively short distance of transportation (Chapman et al., 2010, 2018). During progressive transportation, the morphology evolves to sub-rounded and

elongated which indicates a moderate distance of transportation (Omang et al., 2015). Rounded grains, on the other hand, typically indicate longer transport distances and more extensive weathering (Melchiorre and Henderson, 2019). The angular to irregular shapes exhibited by some gold and sulfide grains (Fig. 3a-e, i), point to derivation from a source relatively close to the sampling point. The sub-rounded and elongated gold grains (Fig. 3f-g) are indications of moderate transportation from the catchment area.

The effects of supergene impacts are shown by alterations imprinted on the grains as a result of lengthy transportation subjecting them to intense physical and chemical weathering (Knight et al., 1999). The presence of such features on the grains

can also indicate the duration in the fluvial system (Ateh et al., 2021). The absence of striation marks and the restricted nature of pitted structures on angular to irregular gold grains are interpreted to indicate limited transport distance. Pits can develop and merge to form cavities during transportation. The cavities noted within the sub-rounded grain now filled with clay minerals (Fig. 3f) could have formed in this manner.

5.2. Microchemical signature of gold grains

The variation in the alloy composition of gold grains can serve as a guide to identifying the type of deposit and can provide valuable insights into the geological processes that have affected these minerals (Chapman et al., 2021). Alluvial gold samples from the Tcholliré district are mainly binary Au–Ag alloys. Trace elements occur in low quantities (below detection limits) except for Cu which shows significantly high values (Fig. 4 & Table 1). The increase in gold content from the core to the rim suggests a process of gold enrichment over time. This enrichment can occur through secondary mineralization processes like supergene enrichment (Ketchaya et al., 2024) or through the addition of gold from surrounding host rocks (Ehser et al., 2010). The absence of growth zones overprinting Au-rich cores with variable alloy composition suggests that the mineral system from Tcholliré is marked by single gold-forming hydrothermal event. This is similar to results from the Gamba district (Ketchaya et al., 2022, 2024) and the Lom Basin and Nyong Series (Omang et al., 2015; Ateh et al., 2021). The increase in gold content from the core to the rim therefore reflects progressive dissolution of Ag. The late stage of the hydrothermal event could have been Cu-bearing as most alluvial gold grains from the Tcholliré district with higher Cu content tend to be associated with lower-fineness gold (Leal et al., 2021). The large range of gold fineness values between 279 (electrum) and 1000 (pure gold) (avg. 654) from the Tcholliré district

overlaps the field of epithermal deposits (Fig. 5c) from Morrison et al. (1991) and Liu and Beaudoin (2021).

The variation of Cu within broadly homogenous Au–Ag alloys in gold detrital particles has been reported by Chapman et al. (2021). This seems likely to reflect subtle changes in the mineralizing fluid and/or conditions during gold precipitation (e.g., Gas'kov, 2017). The relatively high Cu values (1.04–23.54 wt. %) observed from this study are in line with the hypothesis of gold derivation from relatively high-temperature magmatic hydrothermal systems (Chapman et al., 2018). Gold mineralization reported in gresenized granite cupolas of Kirwans Hill and Batemans Creek, New Zealand (Pirajno and Bentley, 1985) and in the vicinity of Cornwall granite (Ehser et al., 2010) show mean Ag and Cu contents of 3–38 wt. % and 0.0022–0.039 wt. %, respectively. These values are comparable to those from the Tcholliré district, with a mean Ag value of 34 wt. % and a Cu value of 2.34 wt. % and the gold here occurs in association with cassiterite as well. They are however higher than those reported so far from the Meiganga (mean Ag 1.12 wt. % and Cu 0.07 wt. %) and Gamba district (ave. Ag 10 wt. % and Cu 0.0004 wt. %). This highlights a possible variation in gold sources and/or enrichment processes. The presence of disseminated gold with content up to 103.7 ppm have been reported in hydrothermally altered parts of granitoids in the eastern gold districts of Cameroon (Tata et al., 2018; Ngatcha et al., 2019). Nevertheless alluvial, eluvial and lode gold grains from this area show low mean Ag (6.35–14.04 wt. %) and Cu (0.01–0.06 wt. %) values (Suh and Lehmann, 2003; Suh et al., 2006; Omang et al., 2015; Vishiti et al., 2015; Ateh et al., 2021).

Gold mineralization style is usually inferred using ternary plots that utilize the variation in the Au–Ag–Cu alloy composition of gold grains (Townley

et al., 2003; Chapman and Mortensen, 2006; Chapman et al., 2010). The plot of the Tcholliré alluvial gold grains in the epithermal deposits field (Fig. 5d) further supports that epithermal high temperature hydrothermal fluids were the main source of gold enrichment.

According to Leal et al. (2021), an understanding of the auriferous vein/host rock mineralogy permits speculation on the inclusion suite that could be expected if larger sample suites were available, i.e. chalcopyrite, arsenopyrite, galena, and Bi-bearing minerals. The heavy mineral suits from which gold was recovered contained mineralogical phases such as zircon, cassiterite, and sulfides (e.g., anglesite and tetrahedrite). Additionally, inclusions of quartz, clay minerals, and ilmenite entombed in the gold grains (Fig. 3 & Table 1), suggest a possible vein-type mineralization and in host granitoids. The possible link with granites of the Cameroon Volcanic Line which are cassiterite-bearing is provided by the high Ag content in the gold-electrum grains.

6.0 Conclusions

The study's findings support the following conclusions:

1. The bulk of the gold grains recovered from the gravel layer of the Tcholliré district drainage system had morphological traits that point to the presence of a weathered prospective close distance hypogene source.
2. Inclusions of quartz, clay minerals, and ilmenite entombed in the gold grains and its association heavy mineral phases such as zircon, cassiterite, and sulfides (e.g., anglesite and tetrahedrite), suggest that the main hypogene gold source is part of an epithermal system involving quartz vein-type and granitoid-related.
3. The Au-Ag-Cu alloy composition of the alluvial gold grains with elevated Ag and Cu contents is consistent with a single high-sulphidation and high-temperature magmatic hydrothermal origin (epithermal). Temporal evolution in the mineralizing fluid is feasible.

The grains are not authigenic in origin. The variation from high to low Ag content in the core to rim sections of the gold grains has resulted in moderate gold fineness (ave. 654). Pointing to a low Ag leaching in the secondary environment as a result of the direct liberation of the gold grains from the source.

Declaration of Competing Interest

The authors declare that they have no known competing interests that could influence the work reported in this paper.

Acknowledgments

This work is part of the M.Sc dissertation of NEN. The laboratory analyses were conducted by Prof. Erik Melchiorre of UCSB within the cooperation framework with CES and we deeply appreciate his help. Funding to all the other authors through the Research Modernization Scheme of the Ministry of Higher Education, Cameroon is gratefully acknowledged.

References

- Anaba Fotze, Q.M., Palai, F., Bi-Alou, M.B., Lordon, A.E.D., Ndougsa-Mbarga, T., Fru, M.I. N., Lyonga, D.I., Rodo, G.N., 2023. Aeromagnetic and field data characterization of structural features for the delineation of potential gold mining sites in Northern Cameroon: a case study of Tchollire and environs. *ActaGeophysica*, 1-23.
- Ateh, K. I., Suh, C. E., Shuster, J., Shemang, E. M., Vishiti, A., Reith, F., & Southam, G. 2021. Alluvial gold in the BétaréOya drainage system, east Cameroon. *Journal of Sedimentary Environment*, 6, 201–212.
- Averill, S.A., 2001. The application of heavy indicator mineralogy in mineral exploration with emphasis on base metal indicators in glaciated metamorphic and plutonic terrains. *Geological Society, London, Special Publications*, 185(1), 69-81.
- Barrios, S., Merinero, R., Lozano, R., Orea, I., 2015. Morphogenesis and grain size variation of alluvial gold recovered in auriferous sediments of

the Tormes Basin (Iberian Peninsula) using a simple correspondence analysis. *Miner. Petrol.* 109, 679–691. <https://doi.org/10.1007/s00710-015-0399-x>.

Bouyo Houketchang, M., Penaye, J., Njel, U.O., Moussango, A.P.I., Sep, J.P.N., Nyama, B.A., Wassouo, W.J., Abaté, J.M.E., Yaya, F., Mahamat, A., Ye, H., Wu, F., 2016. Geochronological, geochemical and mineralogical constraints of emplacement depth of TTG suite from the Sinassi Batholith in the Central African Fold Belt (CAFB) of northern Cameroon: Implications for tectonomagmatic evolution. *J. Afr. Earth Sci.* 116, 9–41. <https://doi.org/10.1016/j.jafrearsci.2015.12.005>.

Bouyo Houketchang, M., Toteu, S.F., Deloule, E., Penaye, J., Van Schmus, W.R., 2009. UPb and Sm-Nd dating of high-pressure granulite from Tcholliré and Banyo regions: evidence for a Pan-African granulites facies Metamorphism in north-central Cameroon. *J. Afr. Earth Sci.* 54, 144–154.

Bouyo Houketchang, M., Zhao, Y., Penaye, J., Zhang, S.H., Njel, U.O., 2015. Neoproterozoic subduction-related metavolcanic and metasedimentary rocks from the Rey Bouba Greenstone Belt of north-central Cameroon in the Central African Fold Belt: New insights into a continental arc geodynamic setting. *Precambrian Res.* 261, 40–53. <https://doi.org/10.1016/j.precamres.2015.01.012>.

Chapman, R.J., Allan, M.M., Mortensen, J.K., Wrighton, T.M., Grimshaw, M.R., 2018. A new indicator mineral methodology based on a generic Bi–Pb–Te–S mineral inclusion signature in detrital gold from porphyry and low/intermediate sulfidation epithermal environments in Yukon Territory, Canada. *Miner Deposita*, 53, 815–834. <https://doi.org/10.1007/s00126-017-0782-0>

Chapman, R.J., Banks, D.A., Styles, M.T., Walshaw, R.D., Piazzolo, S., Morgan, D.J., Grimshaw, M.R., Spence-Jones, C.P., Matthews, T.J., Borovinskaya, O., 2021. Chemical and physical heterogeneity within native gold: implications for the design of gold particle

studies. *Miner Deposita*. <https://doi.org/10.1007/s00126-020-01036-x>.

Chapman, R.J., Leake, R.C., Bond, D.P.G., Stedra, V. and Fairgrieve, B., 2009. Chemical and mineralogical signatures of gold formed in oxidizing chloride hydrothermal systems and their significance within populations of placer gold grains collected during reconnaissance. *Economic Geology*, 104(4), 563–585.

Chapman, R.J., Mortensen, J.K., 2006. Application of microchemical characterization of placer gold grains to exploration for epithermal gold mineralization in regions of poor exposure. *J. Geochem. Explor.* 91, 1–26. <https://doi.org/10.1016/j.gexplo.2005.12.004>.

Chapman, R.J., Mortensen, J.K., Crawford, E.C., Lebarge, W., 2010. Microchemical Studies of Placer and Lode Gold in the Klondike District, Yukon, Canada: 1. Evidence for a Small, Gold-Rich, Orogenic Hydrothermal System in the Bonanza and Eldorado Creek Area. *Econ. Geol.* 105, 1369–1392. <https://doi.org/10.2113/econgeo.105.8.1369>.

Delor C., Bernard J., Tucker R.D., Roig J.-Y., BouyoHouketchang M., Couëffé R., Blein O. 2021. 1:1 000 000-scale geological map of Cameroon.

Ehser, A., Borg, G. and Pernicka, E., 2010. Fingerprinting of Cornish gold for provenancing prehistoric gold artefacts from Central Europe. In: Pal-Molnar, E. (ed.) IMA 2010: Bonds and Bridges. 20th General Meeting of the International Mineralogical Association, Budapest, *ActaMineralogica-Petrographica*, 6, 106.

Fuanya, C., Bolarinwa, A.T., Kankeu, B., Yongue, R.F., Ngatcha, R.B., Tangko, T.E., 2019. Morphological and chemical assessment of alluvial gold grains from Ako'ozam and Njabilobe, southwestern Cameroon. *Journal of African Earth Sciences*, 154, 111–119.

- Gas'kov, I.V., 2017. Major impurity elements in native gold and their association with gold mineralization settings in deposits of Asian folded areas. *Russian Geology and Geophysics*, 58, 1080–1092. <https://doi.org/10.1016/j.rgg.2017.08.004>
- Hallbauer, D.K., Utter, T., 1977. Geochemical and morphological characteristics of gold particles from recent river deposits and the fossil placers of the Witwatersrand. *Mineralium Deposita*, 12, 293-306.
- Isseini, M., André-Mayer, A.-S., Vanderhaeghe, O., Barbey, P., Deloule, E., 2012. A-type granites from the Pan-African orogenic belt in south-western Chad constrained using geochemistry, Sr–Nd isotopes and U–Pb geochronology. *Lithos* 153, 39–52. <https://doi.org/10.1016/j.lithos.2012.07.014>.
- Ketchaya, Y.B., Dong, G., Santosh, M., Lemdjou, Y.B., 2022. Microchemical signatures of placer gold grains from the Gamba district, northern Cameroon: Implications for possible bedrock sources. *Ore Geology Reviews*, 141, 104640. <https://doi.org/10.1016/j.oregeorev.2021.104640>
- Ketchaya, Y.B., Zhou, T., Santosh, M., Li, B., Quaye, J.A. and Hamukwaya, S.L., 2024. Supergene gold transformations of the placer gold deposits from the Gamba district in northern Cameroon: Implications for secondary and nano-particulate gold formations. *Ore Geology Reviews*, 105948. <https://doi.org/10.1016/j.oregeorev.2024.105948>
- Knight, J.B., Morison, S.R., Mortensen, J.K., 1999. The relationship between placer gold particle shape, rimming, and distance of fluvial transport as exemplified by gold from the Klondike District, Yukon Territory, Canada. *Econ. Geol.* 94, 635–648.
- Leal, S., Lima, A. and Noronha, F., 2021. Characterization of heavy mineral concentrates and detrital gold particles from the Bigorne granite-hosted gold deposit in the Iberian Variscan Belt. Geological Society, London, Special Publications, 516, 383 – 399. <https://doi.org/10.1144/SP516-2020-217>
- Liu, H., Beaudoin, G., 2021. Geochemical signatures in native gold derived from Aube-bearing ore deposits. *Ore Geol. Rev.* 104066 <https://doi.org/10.1016/j.oregeorev.2021.104066>.
- McClenaghan, M.B., Cabri, L.J., 2011. Review of gold and platinum group element (PGE) indicator minerals methods for surficial sediment sampling. Melchiorre, E.B., Henderson, J., 2019. Topographic gradients and lode gold sourcing recorded by placer gold morphology, geochemistry, and mineral inclusions in the east fork San Gabriel River, California, U.S.A. *Ore Geol. Rev.* 109, 348–357. <https://doi.org/10.1016/j.oregeorev.2019.04.022>.
- Morrison, G.W., Rose, W.J., Jaireth, S., 1991. Geological and geochemical controls on the silver content (fineness) of gold in gold-silver deposits. *Ore Geol. Rev.* 6, 333–364. [https://doi.org/10.1016/0169-1368\(91\)90009-V](https://doi.org/10.1016/0169-1368(91)90009-V).
- Ngatcha, R.B., Okunlola, O.A., Suh, C.E., Ateh, K.I., Hofmann, A., 2019. Petrochemical characterization of Neoproterozoic Colomine granitoids, SE Cameroon: implications for gold mineralization. *Lithos* 344–345, 175–192.
- Ngouabe, E.G.T., Vishiti, A., Nforba, M.T., Rossouw, R., Etame, J., Suh, C.E., 2022. Morphology and composition of alluvial gold from the Meiganga area, northern Cameroon: implications for provenance. *Journal of Sedimentary Environments*, 7(4), 671-689. <https://doi.org/10.1007/s43217-022-00115-5>
- Ngounouno, F.Y., Negue, E.N., Kolb, J., Walter, B., Soh, A.C.T., Patten, C. and Ngounouno, I., 2022. Tectonic setting, fluid inclusion and gold mineralization of the southwest Poli region (northern Cameroon Domain). *Journal of African Earth Sciences*, 194, p.104579. <https://doi.org/10.1016/j.jafrearsci.2022.104579>
- Nguimatsia Dongmo, F.W., Chapman, R.J., Bolarinwa, A.T., Yongue, R.F., Banks, D.A., Olajide-Kayode, J.O., 2019. Microchemical characterization of placer gold grains from the Meyos-Essabikoula area, Ntem complex, southern Cameroon. *J. Afr. Earth Sc.* 151, 189–201. <https://doi.org/10.1016/j.jafrearsci.2018.12.006>.

- Omang, B.O., Suh, C.E., Lehmann, B., Vishiti, A., Chombong, N.N., Fon, A.N., Egbe, J.A., Shemang, E.M., 2015. Microchemical signature of alluvial gold from two contrasting terrains in Cameroon. *J. Afr. Earth Sc.* 14.
- Penaye, J., Kröner, A., Toteu, S.F., Van Schmus, W.R., Doumnang, J.C., 2006. Evolution of the Mayo Kebbi region as revealed by zircon dating: an early (ca. 740 Ma) Pan-African magmatic arc in southwestern Chad. *Journal of African Earth Sciences*, 44(4-5), 530-542. <https://doi.org/10.1016/j.jafrearsci.2005.11.018>.
- Pirajno, F. and Bentley, P.N. 1985. Greisen-related scheelite, gold and sulphide mineralization at Kirwans Hill and Bateman Creek, Reefton District, New Zealand. *New Zealand Journal of Geology and Geophysics*, 28, 97-109, <https://doi.org/10.1080/00288306.1985.10422279>
- Potter, M., Styles, M.T., 2003. Gold characterisation as a guide to bedrock sources for the Estero Hondo alluvial gold mine, western Ecuador. *Appl. Earth Sci.* 112, 297-304. <https://doi.org/10.1179/037174503225011261>.
- Suh, C.E., Lehmann, B., 2003. Morphology and electron-probe microanalysis of residual gold-grains at Dimako, Southeast Cameroon. *njmm* 2003, 255-275. <https://doi.org/10.1127/0028-3649/2003/2003-0255>.
- Suh, C.E., Lehmann, B., Mafany, G.T., 2006. Geology and geochemical aspects of lode gold mineralization at Dimako-Mboscorro, SE Cameroon. *Geochem.: Explor. Environ., Anal.* 6, 295-309. <https://doi.org/10.1144/1467-7873/06-110>.
- Tata, E., Suh, C.E., Vishiti, A., Shemang, E.M., Fon, A.N., Ateh, K.I., Chombong, N.N., 2018. Wallrock alteration categories and their geochemical signatures in gold-bearing Neoproterozoic granitoids, Batouri gold district, southeastern Cameroon. *Geochem. Explor. Environ. Anal.* <https://doi.org/10.1144/geea2016-017>.
- Tchameni, R., Doumnang, J.C., Deudibaye, M., Branquet, Y., 2013. On the occurrence of gold mineralization in the Pala Neoproterozoic formations, South-Western Chad. *J. Afr. Earth Sc.* 84, 36-46. <https://doi.org/10.1016/j.jafrearsci.2013.03.002>.
- Toteu, S.F., de Wit, M., Penaye, J., Drost, K., Tait, J.A., Bouyo, M.H., Van Schmus, W.R., Jelsma, H., Moloto-A-Kenguemba, G.R., da Silva Filho, A.F. and Lerouge, C., 2022. Geochronology and correlations in the Central African Fold Belt along the northern edge of the Congo Craton: New insights from U-Pb dating of zircons from Cameroon, Central African Republic, and southwestern Chad. *Gondwana Research*, 107, pp.296-324. <https://doi.org/10.1016/j.gr.2022.03.010>.
- Toteu, S.F., Fouateu, R.Y., Penaye, J., Tchakounte, J., Mouangue, A.C.S., Van Schmus, W.R., Deloule, E., Stendal, H., 2006. U-Pb dating of plutonic rocks involved in the nappe tectonic in southern Cameroon: consequence for the Pan-African orogenic evolution of the central African fold belt. *J. Afr. Earth Sci.* 44, 479-493. <https://doi.org/10.1016/j.jafrearsci.2005.11.015>.
- Toteu, S.F., Penaye, J., PoudjomDjomani, Y., 2004. Geodynamic evolution of the PanAfrican belt in central Africa with special reference to Cameroon. *Can. J. Earth Sci.* 41, 73-85. <https://doi.org/10.1139/e03-079>.
- Townley, B.K., H´erail, G., MaksaeV, V., Palacios, C., de Parseval, P., Sepulveda, F., Orellana, R., Rivas, P., Ulloa, C., 2003. Gold grain morphology and composition as an exploration tool: application to gold exploration in covered areas. *Geochem.: Explor. Environ., Anal.* 3, 29-38. <https://doi.org/10.1144/1467-787302-042>.
- Vishiti, A., Suh, C.E., Lehmann, B., Egbe, J.A., Shemang, E.M., 2015. Gold grade variation and particle microchemistry in exploration pits of the Batouri gold district, SE Cameroon. *J. Afr. Earth Sc.* 111, 1-13. <https://doi.org/10.1016/j.jafrearsci.2015.07.010>.