

Article

Mineralogical, Petrological, 3D Modeling Study and Geostatistical Mineral Resources Estimation of the Zone C Gold Prospect, Kofi (Mali)

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Abstract

A 3D model integrating mineralogical, petrological, and geostatistical resource estimation was developed for Zone C of the Kofi Birimian gold deposit in Western Mali. Petrographic analysis identified two forms of gold mineralization: (i) native gold or electrum inclusions within pyrite, and (ii) disseminated native gold along pyrite fractures. Four types of hydrothermal alteration—epidotization, chloritization, carbonatization, and albitization—were observed microscopically. Statistical analysis of geochemical data classified five lithologies: mafic dyke, felsic dyke, diabase, faulted breccia, and intermediate quartz diorite. Minerals identified petrographically were corroborated by multivariate correlations among elements (Cr, Fe, Ni, Al, Ti, Na, and Ca), as revealed by Principal Component Analysis (PCA). A 3D borehole-based model revealed spatial correlations between hydrothermal alteration zones and associated geochemical anomalies, notably tourmalinization (B) and albitization (Na), with the latter serving as a key indicator for new exploration targets. The spatial associations of anomalous Ag, B, Hg, As, and Na commonly linked to tourmalinization suggest favorable zones for gold and silver mineralization. Geostatistical analysis identified isotropic continuous mineralized structures for most elements, including gold. Spherical isotropic variograms with ranges from 35 to 75 m were fitted for in situ resource estimation (e.g., silver $\approx$ 40 m; gold $\approx$ 60 m). The resulting estimated resources (indicated + inferred), based on a 1.0 g/t Au cut-off, are 2.476 Mt at 3.5 g/t Au indicated (0.278 Moz or 8.67 t), and 1.254 Mt at 2.78 g/t Au inferred (0.112 Moz or 3.49 t). This study provides a framework for identifying new mineralized zones, and the multidisciplinary approach demonstrates the connections between mineralogy and the information embedded in geochemical datasets, which are revealed through appropriate tools and an understanding of the underlying processes.

Keywords: orogenic gold; greenstone belt; geothermometer; geostatistical analysis; 3D modeling



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1. Introduction

Orogenic gold deposits are hydrothermal in origin and account for over 75% of historical gold production (Figure 1). They formed over a 3 billion year span from the Middle Archean to the Phanerozoic periods [1,2] and are typically found in deformed upper to mid-crustal blocks (5–20 km depth), often localized along major shear zones that channel deep-seated hydrothermal fluids [3]. These deposits commonly occur in metamorphosed

fore-arc and back-arc settings. Secondary and tertiary crustal structures further drive fluid flow, often associated with magma cooling, leading to localized gold deposition [2].

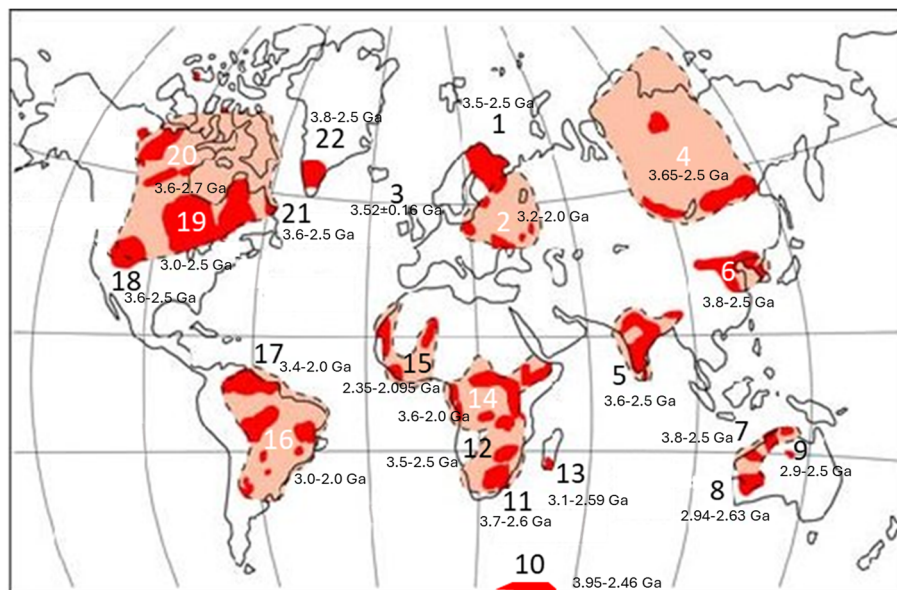


Figure 1. World distribution of major Precambrian provinces and their ages (after [4–6]), showing outcropping Archean formations (in red), covered by sedimentary formations (in orange). (1) Baltic Shield; (2) Ukrainian Shield; (3) Scottish Shield; (4) Siberian Shield; (5) Indian Shield; (6) Sino-Korean Shield; (7) Pilbara Craton; (8) Yilgarn Craton; (9) Northern Australia Block; (10) Napier Complex; (11) Kaapvaal Craton; (12) Zimbabwe Craton; (13) Madagascar Craton; (14) Central Africa Craton; (15) West Africa Shield; (16) Sao Francisco Craton; (17) Guyana Shield; (18) Wyoming Province; (19) Superior Province; (20) Slave Province; (21) Labrador Shield; (22) North Atlantic Craton and Greenland Shield.

Their temporal distribution peaks during the Neoproterozoic (2.8–2.5 Ga), Paleoproterozoic (2.1–1.8 Ga), and Phanerozoic (500–50 Ma) eras, with a notable gap from 1.8 to 0.8 Ga—the so called *boring billion*, reflecting supercontinent (Wilson) cycles that control fluid mobilization through tectonic amalgamation and breakup [7,8].

The primary source of mineralizing fluids is the metamorphic devolatilization of supracrustal rocks (e.g., hydrated basalts, sediments), although magmatic fluids may contribute in some cases (e.g., alkaline and sanukitoid associated deposits) [9,10]. These fluids have low-salinity (1–6 wt.% NaCl eq.), CO₂-rich metamorphic waters, typically comprising H₂O–NaCl ± CH₄ ± N₂ [11]. Metals such as Au, Ag, As, and Sb are leached from host rocks and associated sulfides (e.g., pyrite, arsenopyrite) during deformation and metamorphism. Mineralization commonly occurs in quartz-carbonate veins, and gold is present as native metal or lattice-bound within sulfides (“invisible gold”). Isotope values δ¹⁸O (1.8 to 10.9‰), δD (−99 to −62.9‰), and (δ³⁴S ≈ +5.5 to +13.3‰) indicate metamorphic water and a crustal sulfur source [12].

The Birimian gold deposits of the West African Craton (WAC) exemplify this setting, with major potential found in Burkina Faso, Senegal, Ghana, and Côte d’Ivoire. In Western Mali, in the Kédougou–Kénieba inlier, major deposits located in Sadiola, Yatéla, Loulo, and Tabakoto (Table 1) align along shear zones linked to the Senegal–Mali shear zone. These deposits show diverse geological controls, complex mineralization systems, and variable alteration styles, which all pose notable exploration challenges [13].

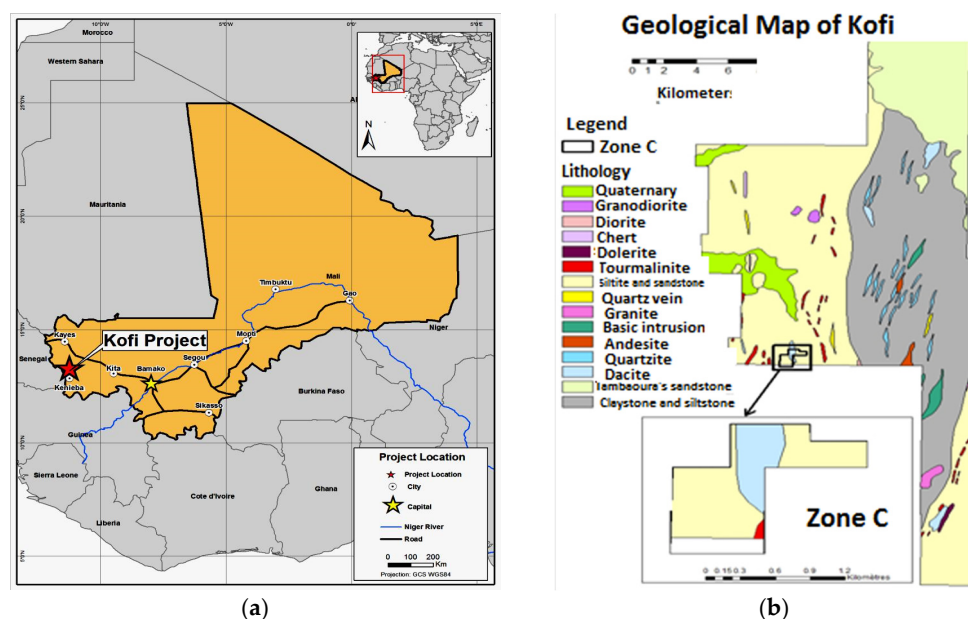
Table 1. Tonnage and grade of some major gold deposits in Mali [3].

Deposits	Tonnage (Mt)	Grade (g/t)	Source	Comments
Sadiola	22.30	3.30	[14]	AngloGold Ashanti Mali
Yatéla	7.60	1.40	[14]	Proven and probable resources
Loulo	39.97	4.93	[15]	Proven and probable resources
Tabakoto	4.40	4.60	[16]	Proven and probable resources

This study reinterprets mineralization at the Kofi Zone C project, located southwest of the Loulo deposit and ~400 km west of Bamako, Mali [17] (Figure 2). Borehole geochemical data were reprocessed using a multidisciplinary approach that integrates petrology, mineralogy, 3D geomodeling, and geostatistical methods, including the following:

- Macroscopic rock descriptions and thin-section analysis using optical microscopy, scanning electron microscopy (SEM), and electron microprobe to establish paragenesis (Interested reader can find details on instrumentation and procedures at <https://georessources.univ-lorraine.fr/en/content/equipment> accessed on 15 May 2025);
- Using univariate and multivariate statistical analyses of geochemical data to characterize element distributions, identify correlations, and assess lithological controls;
- Three-dimensional grade modeling to delineate anomalous zones. The objectives are to characterize mineralization and geological controls at Zone C and to identify previously overlooked but potentially mineralized areas. Ultimately, this methodology supports exploration in underrecognized prospective zones.

This multidisciplinary approach highlights the connection between petrology, mineralogy, and geochemistry, revealed through appropriate tools and a solid understanding of the underlying processes. This demonstrates the effectiveness of an integrated strategy for identifying promising exploration targets.

**Figure 2.** Cont.

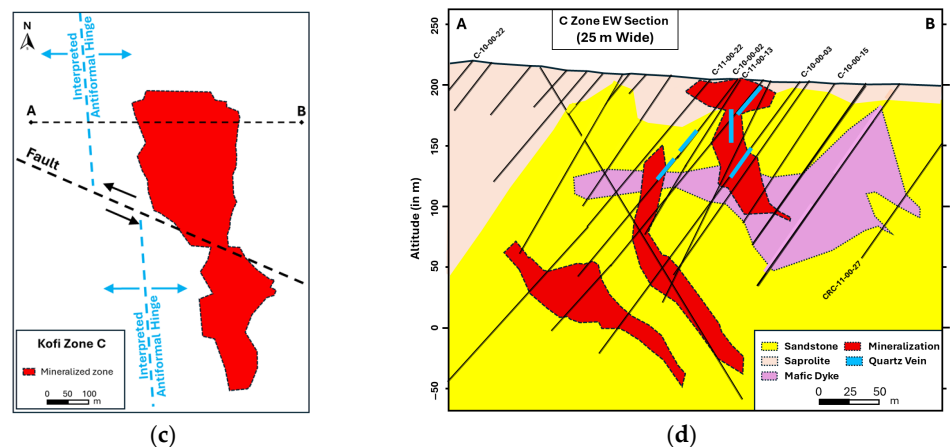


Figure 2. (a,b) Geological maps of the Kofi zone C (rectangle) project. (c) Detailed projection map of the mineralized Kofi. (d) Simplified vertical cross section along line (AB) (modified from [3,17]).

2. Regional Geology of the Kofi Area

This study focuses on the Archean–Paleoproterozoic (Birimian) Kédougou–Kéniéba inlier of the WAC (A general WAC geological settings is presented in Appendix C), specifically the Kofi area (Figure 2) [18]. This Birimian greenstone belt, which hosts significant precious and base metal deposits, extends across Niger, Burkina Faso, Benin, Togo, Ghana, Côte d’Ivoire, Mali, Guinea, Liberia, and Senegal [19,20]. The Kofi area is characterized by quartzite, sandstone, conglomerate, and associated formations, including limestone encountered during drilling.

2.1. Regional Geological Settings of the Kofi Area

The Kofi area, located within the Kédougou–Kéniéba inlier within the broader Dialé–Daléma Supergroup, comprises both Archean and Paleoproterozoic (Birimian) units [18]. The Archean–Proterozoic basement consists of gneisses and granites, with isoclinal folding within a sedimentary and volcano-sedimentary greenstone belt [19–22]. Birimian greenstone belts, covering approximately 350,000 km², are widespread across West Africa, including Niger, Burkina Faso, Benin, Togo, Ghana, Côte d’Ivoire, Mali, Guinea, Liberia, and Senegal.

Stratigraphically, three major lithological units are recognized within the Birimian series [23,24] (Figure 2b): (i) The Saboussiré Formation (Mako), composed mainly of mafic volcanic rocks with minor volcano-sedimentary intercalations, hosts the Sabodala gold deposit in eastern Senegal. (ii) The Kéniébandi Intermediate Formation (Dialé Supergroup) being primarily sedimentary with minor volcanic input, is characterized by flysch-type textures and relatively flat structures. (iii) The Kofi Formation (Daléma Supergroup), the uppermost sedimentary unit, hosts major gold deposits such as Sadiola, Yatéla, Tabakoto, and Loulo. It consists mainly of marine sedimentary rocks overlying sparse volcanoclastic layers and is locally intruded by felsic to mafic plutons [24].

Some authors [18] group the Kofi and Kéniébandi formations into the broader Dialé–Daléma Supergroup. It is traditionally divided into three lithological groups [16]: (i) limestone, found along the western edge of Zone C; (ii) silicate rocks; and (iii) clastic rocks, including sandstones and siltstones (turbidites) hosting tourmalinite, diorite, and quartzite (Figure 2b).

These units form a volcano-sedimentary sequence (quartzite, sandstone, conglomerate, limestone, etc.) intruded by multiple generations of felsic and mafic dikes and sills. The area also includes large magmatic complexes comprising both plutonic rocks (granites and granodiorites) and hypovolcanic rocks (microdiorites, granodiorites, and albitites) [25]. Tourmalinite in the area is of hydrothermal origin, and the associated alteration processes contribute to the high porosity observed in the coarse clastic units [16].

2.2. Mineralization of the Kofi Zone C

Gold mineralization in Kofi Zone C is controlled by structural and geochemical processes associated with the Kédougou–Kénieba Inlier (KKI). Key factors include (i) *Structural controls*: Mineralization is associated with N-S and NE-SW trending conductive lineaments, which are secondary splays of the Senegal–Malian Shear Zone (SMSZ). These structures facilitated fluid flow and gold deposition during deformation events. Metasedimentary rocks, metamorphosed under greenschist–to amphibolite facies, provided permeable pathways for hydrothermal fluids. (ii) *Host rocks and mineralization style*: Gold is hosted in sulfide-bearing quartz-albite veins enriched in arsenopyrite, forming stockworks within intensely silicified zones. Mineralized tourmaline sandstones, aligned with NE-SW/N-S structures, are also found in nearby deposits (e.g., Loulo), suggesting similar mineralization processes at Kofi Zone C [24,26]. (iii) *Geochemical and geophysical signatures*: High-conductivity zones detected by airborne electromagnetic (AEM) surveys often correspond to gold-related structures including shear zones, sulfide- or graphite-rich lithologies, silicified zones with conductive alteration halos (sericite, chlorite, carbonate), and tourmaline-rich sandstones (e.g., Loulo). Fault-slip-driven hydrogen (H₂) generation created reducing conditions that destabilized gold-bisulfite complexes, leading to native gold precipitation within sulfide phases (e.g., arsenopyrite) or silicified zones [11,26,27].

2.2.1. Macroscopic Description

Sedimentary features in the Kofi area, including grain size, structures, and facies, along with disseminated sulfides in fine-grained sediments, suggest a low-energy and confined depositional environment. Subsequent tectono-hydrothermal activity led to the formation of crosscutting quartz veins. Petrographic analysis shows host rocks composed of feldspar, carbonate, electrum, and disseminated gold [3]. Strong alteration zones rich in carbonates, silicification, and chlorite reflect hydrothermal processes linked to gold mineralization.

Quartz veins, locally containing iron-carbonate, sericite, and syenite fragments, commonly intrude detrital sedimentary breccias, conglomerates, and dolomite. Most veins exhibit brittle fault breccia textures, indicating proximity to shear zones. These quartz-dominant breccias are often crosscut by pyrite and, less frequently, sphalerite veinlets, typically accompanied by albitization. High-porosity core samples exhibit open-space textures within intensely silicified fault zones, whereas lower-porosity samples display varied vein morphologies. The main alteration types observed microscopically are albitization, chloritization, and epidotization (Figures 3 and 4a,b). Zone C features a distinctive “banded” or “striped” breccia, characterized by rhythmic alternations of whitish and grey layers [28] (Figure 3), resembling mineralized textures typical of Mississippi Valley-type lead–zinc deposits [29]. Microscopically, the primary alteration sequence includes early albitization and chloritization, followed by late-stage epidote (Figure 4).

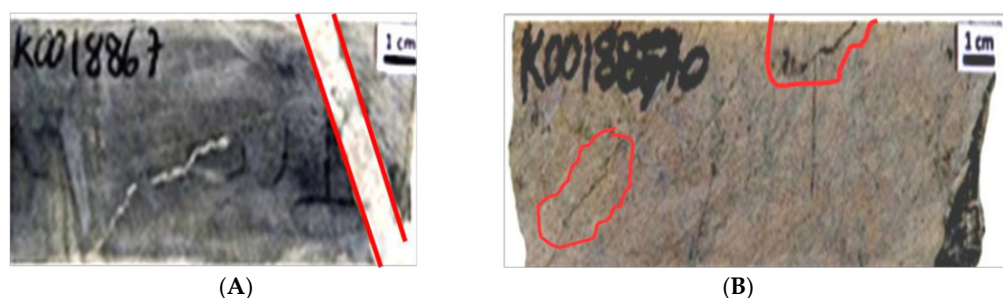


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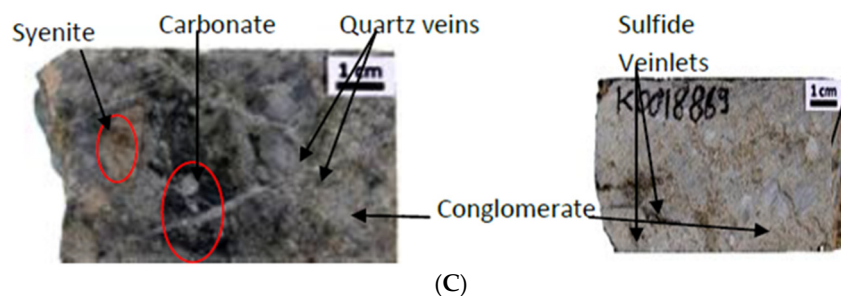


Figure 3. Petrological samples (e.g., K66–70) showing alteration zones (after [3]). Sample depth and geological context are detailed in Appendix A, Table A1. (A): n° K67 Metamorphic rock intruded by a quartz vein (red lines) (146 m depth). (B): n° K70 Various alterations cross-cut by veinlets of sulfides (red circle) (96.8 m depth). (C): n° K66 core sample exhibits (left) conglomerate cut by quartz veins and syenite dykes, (right) with sulfide veinlets (128 m depth).

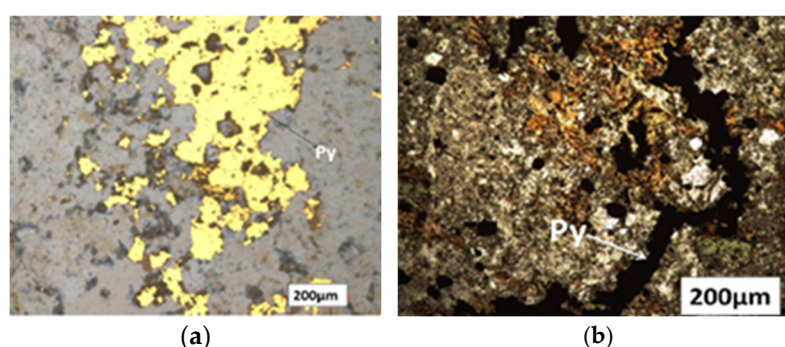


Figure 4. n° K72-1 thin sections; reflected light (a) shows deformed and scattered pyrite grains; transmitted light (b) highlights pyrite along fractures (112.5 m depth). Abbreviations: Py: pyrite (after [3]).

2.2.2. Microscopic Description

Twelve core samples from various depths, including both mineralized and non-mineralized zones, were selected for thin-section preparation (see Appendix A, Table A1). Thirty polished thin sections from Kofi Zone C were analyzed petrographically and mineralogically. Optical microscopy and SEM (backscattered mode) revealed two main gold-related sulfide events, dominated by pyrite and arsenopyrite (Figure 5). Visible gold and gold associated with silver are commonly observed. Gold occurs as ~40–50 μm grains within pyrite fractures (Figure 5A–C) or ~100 μm inclusions in pyrite (Figure 5D), either as native gold or as electrum. These features indicate two gold mineralization events: firstly, early deposition of native gold and electrum as blebs within pyrite, and secondly, a later phase where pure gold precipitated along pyrite fractures (Figure 5A).

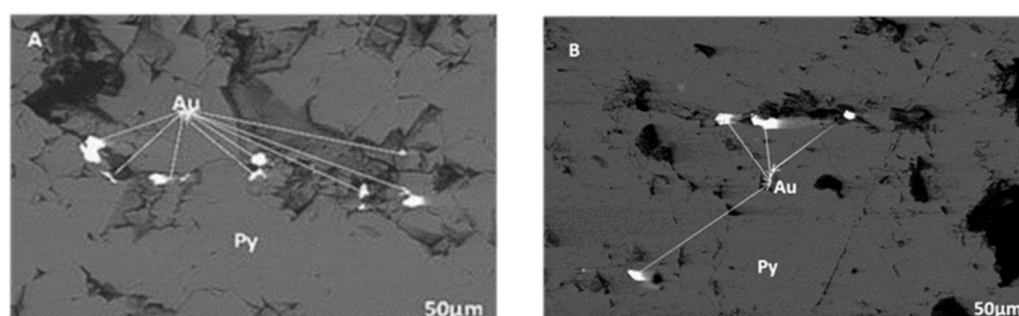


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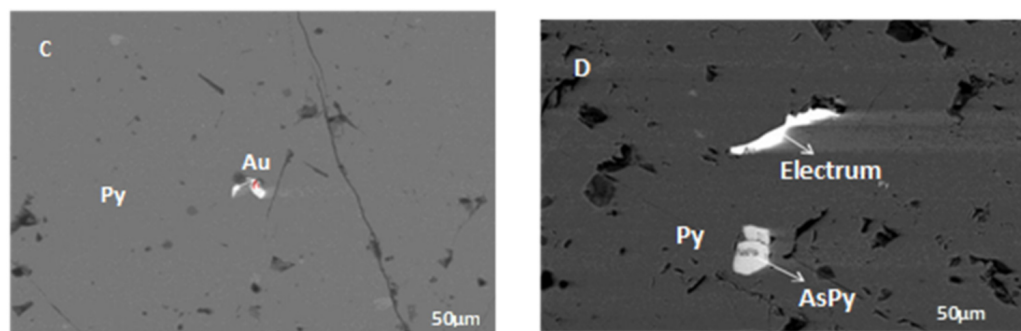


Figure 5. Gold occurrences in thin-section n° K72-3: (A) Dissemminated gold in pyrite fractures. (B) Dissemminated gold within pyrite. (C) Gold inclusions in pyrite. (D) Gold in electrum. Abbreviations: Au, gold; Py, pyrite; AsPy, arsenopyrite (after [3]). n° K72-3 thin section (SEM analyses) (112.5 m depth).

These findings have important implications for optimizing ore-processing methods, particularly for gold-silver separation. Analysis of sample drill C-10-14 (96–207 m depth) revealed gold grades ranging from 2 to 16 ppm (Altered fault breccia zone Qz stockwork), while no detectable gold was found in other core samples or quartz veins that have been analyzed by SEM (Figure 5).

The relative mineral paragenetic sequence, including late-stage mineralization, was determined through thin-section observations and is presented in Figure 6b. Quartz, calcite, chlorite, feldspar, pyrite, arsenopyrite, gold, and electrum occur as inclusions, indicating early precipitation prior to fracturing. In contrast, galena, sphalerite, rutile, monazite, and late-stage gold are found in fractures, suggesting a subsequent mineralization phase.

2.2.3. Chlorite Petrography and Geothermobarometers

Chlorite compositions were determined using electron microprobe analysis (EPMA) (Table A2), based on a theoretical formula with 14 oxygen atoms per half-cell: $[(\text{Fe}, \text{Mg}, \text{Al})_6(\text{Si}, \text{Al})_4\text{O}_{10}(\text{OH})_8]$ and temperature estimates (Table A3 and Figure 6a) showed no clear correlation with chlorite chemistry. Al^{iv} (tetrahedral Al) ranges from 0.90 to 1.22 atoms per formula unit (apfu), and the $\text{Fe}/(\text{Fe} + \text{Mg})$ ratio varies from 0.48 to 0.61, except for sample K66, which shows a notably low ratio of 0.20. This chemical consistency supports the use of chlorite as a geothermometer for hydrothermal events.

Geothermometry and Barometry: Empirical chlorite geothermometers based on Al^{iv} and $\text{Fe}/[\text{Fe} + \text{Mg}]$ ratios have been proposed in several studies [30–35]. Formation temperatures were estimated between 250 °C and 350 °C using Al^{iv} values calibrated with the Cathelineau thermometer (referred to as MC88) [30]. The Jowett thermometer (referred to as WJ91) [31] yielded comparable results (see Tables A3 and A4), while the MC88 model typically produces values ~10 °C lower than WJ91 due to uncorrected tetrahedral substitutions. Most samples show chlorite formation temperatures of 235–280 °C (WJ91), while samples K66, K72-2, and K72-3 record higher values of 310–335 °C, suggesting two distinct hydrothermal events. These temperatures align with petrographic observations and are consistent with greenschist-facies metamorphism typical of orogenic gold systems.

Pressure estimates derived from Ti-in-chlorite and Al^{vi} -chlorite barometry [36,37] indicate conditions corresponding to shallow to mid-crustal depths (5–9 km). The inferred reduced redox conditions are favorable for gold transport via bisulfide complexes. Variability in X_{Mg} reflects heterogeneity in host rocks and/or fluid compositions during deformation. A second, earlier chlorite generation (Table A4) records higher temperatures of 280–370 °C and pressures of 3.9–4.9 kbar, consistent with the greenschist-amphibolite transition and deeper crustal levels (13–16 km). Redox conditions near the fayalite-magnetite-

quartz (FMQ) buffer (± 1 log unit) further support a mid-crustal metamorphic setting typical of orogenic gold systems.

Arsenopyrite Geothermometer: Arsenopyrite is a reliable geothermometer in hydrothermal systems due to predictable variations in iron and arsenic content, and trace element substitutions linked to temperature. Formation temperatures for selected samples from the Kofi area were estimated by fitting equilibrium curves from T-X diagrams along the pyrite–loellingite join (Figure 6c; [38,39]), using cubic polynomial equations (Table 2; full results in Table A5). Two temperature groups were identified.

Table 2. Arsenopyrite geothermometers fitted using cubic polynomials: $T(^{\circ}\text{C}) = \sum_{i=0}^3 a_i \text{As}^i$.

Equilibrium Curve	a_0	a_1	a_2	a_3	R^2
asp + py + As $\pm e^1$	−6430 2662	525 238	−14.0 7.0	0.1341 0.0695	1
asp + py $\pm e$	−17,280 2770	1430 245	−39.1 7.2	0.3661 0.0700	0.999

¹ fitted error on coefficients.

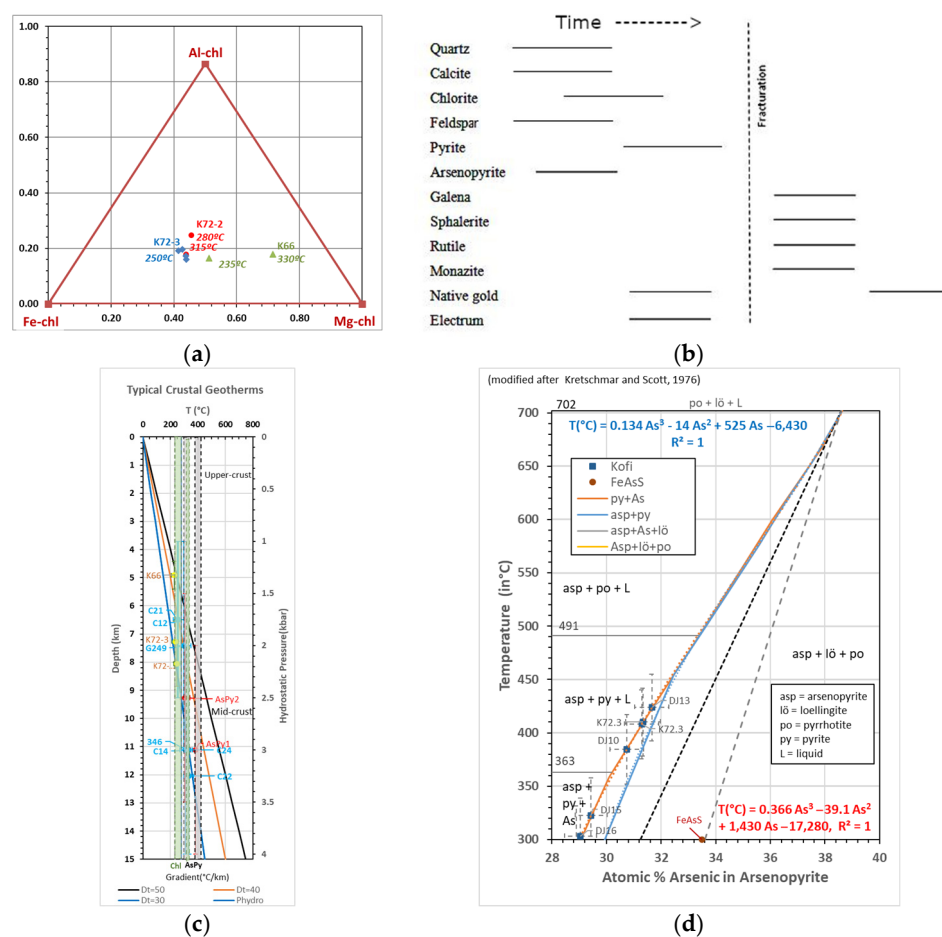


Figure 6. (a) Ternary diagram of Al-, Fe-, and Mg-chlorite showing end-member compositions and temperatures (using the Jowett thermometer); (b) Relative paragenetic sequence for Zone C based on thin-section observations; (c) Representative crustal geotherm with temperature and pressure estimates derived from microprobe analyses of arsenopyrite, chlorite, and carbonate, including calculated chlorite and arsenopyrite temperatures; (d) Simplified T-X diagram along the pyrite–loellingite join, showing arsenopyrite composition versus temperature, with selected samples from the Kofi area (after [38,39]). Compositional data are provided in Appendix A, Tables A2–A10.

(i) *High-T group* (~355–425 °C): Samples n° K72-3 DJ-9, DJ-12, and K72-3 reflect conditions consistent with the greenschist–amphibolite transition, likely corresponding to the peak metamorphic stage and the main gold mineralization event, associated with deformation-driven hydrothermal activity.

(ii) *Low-T group* (~225–325 °C): Samples n° DJ-13, DJ-14, and DJ-15 show cooler conditions, possibly related to retrograde alteration or late-stage fluid pulses during post-orogenic uplift.

Assuming typical depths of ~9–15 km and pressures of 1–3 kbar for orogenic gold systems, high-T arsenopyrite likely formed at deeper crustal levels, while low-T arsenopyrite suggests exhumation-related pressure drops. Arsenopyrite stability necessitates reducing conditions near or below the FMQ buffer.

The As/S ratio in arsenopyrite is a geochemical indicator of oxygen fugacity (fO_2) and sulfur activity during mineralization in orogenic gold deposits [40,41]. Higher As/S ratios in high-temperature arsenopyrite (~31% As vs. ~29% in low-T) indicate moderately reduced fO_2 and elevated sulfur activity, favoring sulfide precipitation. In contrast, lower As in low-T arsenopyrite may indicate more reducing conditions or dilution of sulfur-bearing fluids during cooling.

High-T fluids were likely CO_2 -rich and moderately saline metamorphic fluids derived from devolatilization processes, transporting Au as bisulfide complexes (HS^-/H_2S). Trace osmium (Os) concentrations suggest minor mantle or metasomatic fluid interaction and support the use of Re-Os dating of arsenopyrite to constrain mineralization age.

This thermal evolution is consistent with global orogenic gold systems, where early high-temperature fluid activity transitions to lower-temperature retrograde regimes during uplift.

Biotite Geothermobarometers: Compositions of two selected biotite samples are presented in Table A6. Tetrahedral occupancy, defined by Si (~6.5 apfu) and Al^{iv} (~1.4–1.5 apfu), totals ~8 apfu, consistent with the ideal biotite structure. Octahedral sites are dominated by Al^{vi} (~3.4 apfu), Fe^{2+} (~0.32 apfu), and Mg^{2+} (~0.27 apfu). The total slightly exceeds the ideal trioctahedral value (~3 apfu), likely due to solid-solution effects common in natural systems. These compositions correspond to biotite from the annite-phlogopite series. High K content ($K \sim 1.7$ – 1.76 apfu) confirms interlayer site occupancy, while moderate X_{Mg} (~0.45–0.46) reflects Fe^{2+} - Mg^{2+} mixing in octahedral sites. These values constrain late-stage hydrothermal conditions, likely associated with late cross-faulting and observed gold paragenesis.

Using geothermometers [36] and geobarometers [37] based on the Ti and Al occupancy in biotite: Sample 1 (19.267-C2-4): $Ti = 0.013$ apfu $\rightarrow$ 400–500 °C; Sample 2 (S44 346-C1-2): $Ti = 0.045$ apfu $\rightarrow$ 500–550 °C. These temperatures correspond to greenschist–amphibolite facies metamorphism. Total Al content ($Al^{iv} + Al^{vi}$) correlates positively with pressure: Sample 1: $Al_{total} = 4.83$ apfu; Sample 2: $Al_{total} = 4.91$ apfu. Empirical calibrations [37] indicate moderate pressures (~5–8 kbar), corresponding to mid-crustal depths (~15–25 km). Although Fe^{3+}/Fe^{2+} ratios were not measured, the presence of hematite in sample S44 284-C1-3 (with negligible impurities) suggests oxidizing conditions, with fO_2 well above the FMQ buffer ($\Delta \log fO_2 \geq +2$), in line with the hematite stability field typical of oxidized hydrothermal systems at these depths.

Feldspar Geothermobarometry: Feldspar compositions are presented in Table A7 and correspond to sodic, albite-rich plagioclase ($Na/(Na + Ca) > 90\%$) with minor anorthite ($An = 0.08\%$ – 3.35%) and trace orthoclase ($Or = 0.01\%$ – 3.93%). This composition reflects interaction with late-stage Na-rich fluids under greenschist–facies metamorphic conditions. Minimal Fe^{3+} (<0.01 apfu) suggests limited redox-sensitive substitutions. Low Ti content (<0.001 apfu) indicates low to moderate temperatures (~300–450 °C) [36], while pressures (~5–8 kbar) correspond to mid-crustal depths (~15–25 km) typical of orogenic gold sys-

tems [37]. As inferred from low Fe^{+2} and the absence of hematite or magnetite, the redox state is moderately reducing, suggesting $f\text{O}_2$ conditions near the FMQ buffer. Retrograde albitization is associated with gold deposition, likely triggered by redox changes or fluid cooling [7], within the context of syntectonic magmatism in collisional belts [42].

Carbonate Geothermometer: Hydrothermal conditions associated with carbonate mineral assemblages comprising rhodochrosite (MnCO_3), magnesite (MgCO_3), siderite (FeCO_3), and calcite (CaCO_3) were evaluated using the methodology described in [10,43–47] (Table A8). Based on the carbonate mineralogical compositions from Kofi, Zone C, temperature, pressure, pH, X_{CO_2} , and $f\text{O}_2$ conditions were estimated and are presented in Table A9. The data indicate deep, CO_2 -rich, reducing hydrothermal fluids with neutral to slightly alkaline pH (~6.5–7.5). These fluids suggest interaction with highly reactive ultramafic rocks (e.g., basalts or peridotites), which contributed significant Mg^{2+} and Fe^{2+} , but limited Mn. Conceptually, deep-sourced fluids ascended through fractures and underwent intense water–rock interaction, stripping large amounts of Mg^{2+} and some Fe^{2+} into solution.

The stability fields of carbonates rhodochrosite (Rho), magnesite (Mag), siderite (Sid), and calcite (Cal) were calculated under varying physico-chemical conditions, including CO_2 mole fraction in fluids (X_{CO_2}), fluid pH, and lithostatic pressure [43–47], and are shown in Figure 7 alongside carbonate assemblages identified by electron microprobe (Table A9). Combined with other geothermometers, this diagram helps constrain the possible pressure–temperature (P–T) conditions of gold mineralization at Kofi.

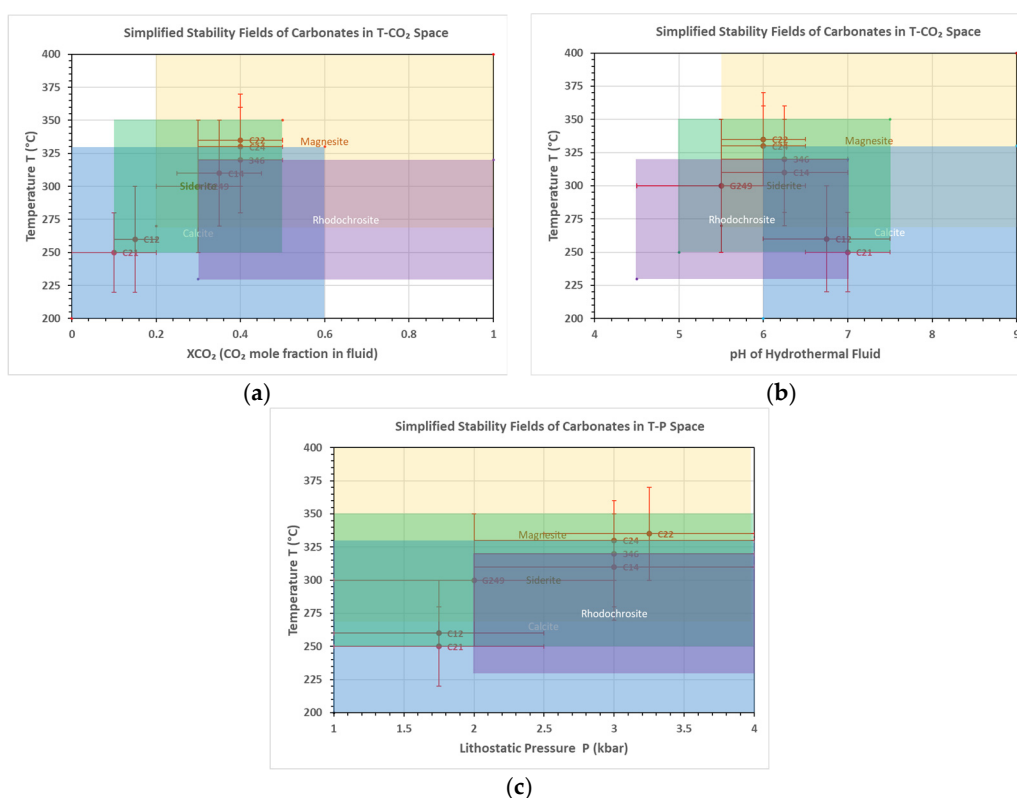


Figure 7. Simplified stability field diagrams showing conditions under which calcite, magnesite, siderite, and rhodochrosite are likely to precipitate or remain stable in hydrothermal environments typical of gold-bearing systems. (a) T- X_{CO_2} space: illustrates how temperature and CO_2 content control carbonate deposition. (b) T-pH space: calcite dominates at higher pH and lower temperatures; siderite and magnesite are stable at moderate pH and elevated temperatures; rhodochrosite favors near-neutral to slightly acidic pH at intermediate temperatures. (c) T-P space: pressure has minimal influence on most carbonates, except rhodochrosite, whose solubility at ~220 °C and 2 kbar is moderate; cooling, pressure drops, or shifts in CO_2 or pH promote its precipitation.

Comparative Mineralogy and Gold Deposition Mechanisms—Zone C, Kofi Area: This zone shares mineralogical similarities with Djambaye [48], Yaléa Gara [49] (south of Kofi), and Gara and Yaléa in Kofi Nétékéto, all within comparable tectonic settings. However, alteration styles differ across zones: Zone C and Djambaye exhibit pervasive silicification and epidotization with minor tourmaline, whereas Yaléa and Gara are dominated by tourmalinization and lack of epidotization.

Petrographic evidence indicates that gold-bearing fluids in Zone C originated from greenschist-facies metamorphic devolatilization, transporting gold primarily as bisulfide complexes ($\text{Au}(\text{HS})_2^-$) stable under moderate $f\text{O}_2$ near the Nickel–Nickel Oxide (NNO) buffer (A redox buffer used in geochemistry and mineralogy to define oxygen fugacity). Additionally, alternative ligands, such as trisulfur (S_3), may have also contributed. S_3 forms highly stable and soluble Au^+ complexes in aqueous fluids at $>250^\circ\text{C}$ and >100 bar, potentially enhancing gold transport and deposition by 10–100 times compared to sulfide or chloride-dominated systems [50].

Early interaction with Fe^{2+} -rich host rocks destabilized bisulfide complexes, precipitating quartz (Qz) and arsenopyrite (AsPy). These hot, reduced, CO_2 -rich fluids carried significant As and S, precipitating *invisible* gold within arsenopyrite at $\sim 320\text{--}450^\circ\text{C}$ under reducing conditions. As the system cooled to $\sim 300\text{--}350^\circ\text{C}$ during fault-valve cycling and depressurization, chlorite formed, which produced classic green alteration halos. Simultaneously, CO_2 loss and fluid phase separation (boiling) further destabilized bisulfide complexes, triggering free gold precipitation.

Subsequent mixing with oxidized fluids (e.g., hematite-/anhydrite-bearing) induced redox shifts, elevated $f\text{O}_2$, and oxidized sulfides. This breakdown of pyrite and arsenopyrite released structurally bound gold as Au^- , further reducing to native Au^0 . During the waning late stages ($\sim 200\text{--}300^\circ\text{C}$), continued cooling and degassing under more neutral to alkaline and sulfur-depleted conditions promoted carbonate precipitation (e.g., calcite, ankerite, magnesite, rhodochrosite) within fractures and late-stage overprinting veins. Figure 8 schematically summarizes the gold deposition process.

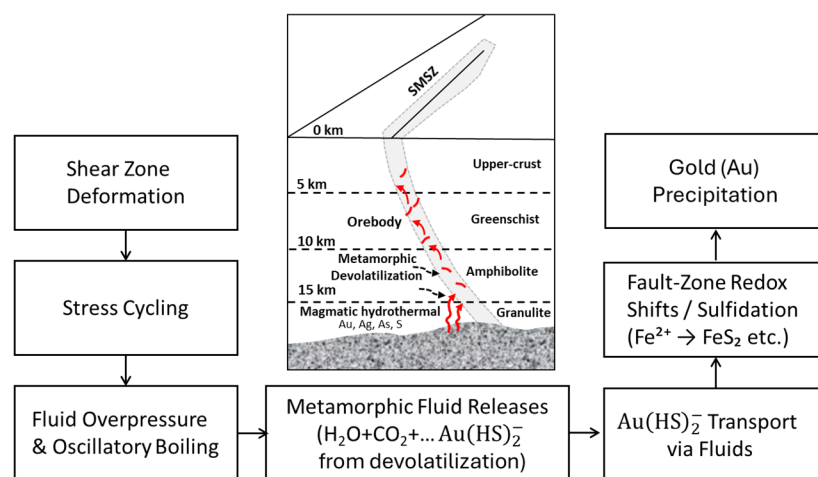


Figure 8. Scheme for gold deposition (picture modified after [51]).

Pathfinder exploration indicators include the following: (i) chlorite and carbonate minerals, especially those with high Mg/Fe ratios or elevated Sr, marking cooler, distal halos around or above main gold zones; (ii) arsenian pyrite, indicative of proximal, hotter, gold-rich cores typical of orogenic systems [52].

2.2.4. Concluding Overview

Geothermometric and mineralogical analyses at Zone C in Kofi reveal a complex, multi-phase hydrothermal evolution characteristic of orogenic gold systems. Thermobarometry of chlorite, arsenopyrite, biotite, feldspar, and carbonates indicates greenschist to amphibolite facies conditions (250–550 °C, 3–8 kbar), suggesting mid- to deep-crustal fluid sources with variable metamorphic overprints. Early high-temperature, reduced, CO₂-rich fluids transported gold as bisulfide complexes, with precipitation driven by cooling, pressure drops, wall-rock interaction, and redox changes. Later-stage alteration, marked by chlorite halos and carbonate veining, reflects progressive fluid evolution and mineral overprinting. Pathfinder indicators such as Mg-rich chlorite and arsenian pyrite provide vectors toward mineralized zones, supporting targeted exploration and deeper resource modeling.

3. Spatial Analysis

Endeavour Mining (Mali) conducted whole-rock geochemical analyses on core samples from 76 boreholes drilled during pit operations. Statistical methods, including univariate (histograms), bivariate (cross-plots), and multivariate analyses like Principal Component Analysis (PCA), were applied to characterize lithologies and support 3D deposit modeling.

3.1. Available Data

Geochemical analyses were performed by SGS (<https://www.sgs.com/en-us/industry/mining/mineral-and-metal-commodities>, 27 July 2025), a North American laboratory specializing in mining and petroleum exploration. Core samples (SGS C10, C11, C12, and CRC11) were collected at approximately 2 m intervals (Figure 9a), yielding 11,980 samples. Analyses included 10 major elements (Al, Ca, Fe, K, Mg, Mn, Na, P, S, and Ti) and 29 trace elements (Ag, As, B, Be, Bi, Cd, Co, Cr, Cu, Ga, Hg, La, Li, Mo, Nb, Sb, Sc, Se, Sr, Sn, Te, Th, Tl, U, V, W, Y, Zn, and Zr). Values below the detection limits were replaced with half the detection limit. Further details on analytical errors and quality control protocols can be found in [17].

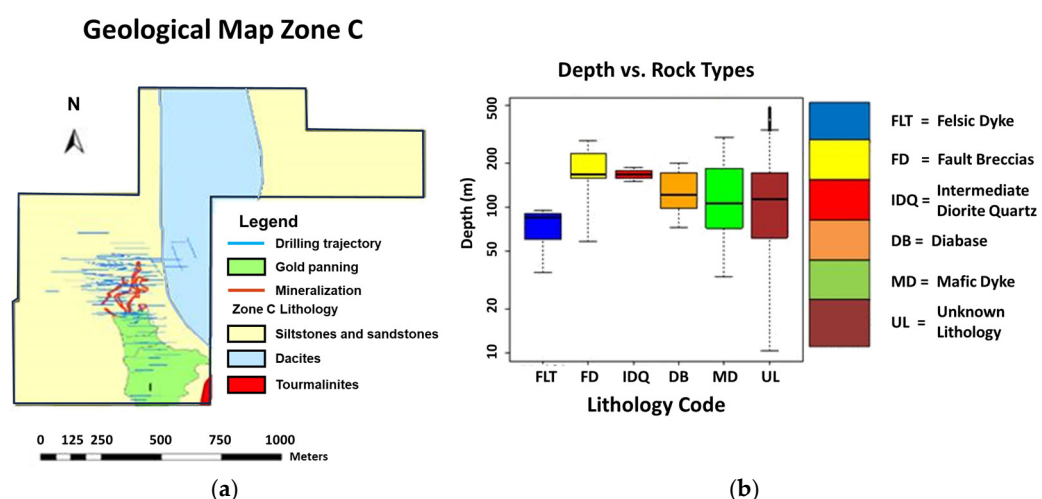


Figure 9. (a) Geological map of the study area. (b) Lithologies distribution with depth.

Characterizing Rock Types: Five lithological units were identified, with their vertical distribution shown in Figure 9b. From surface to depth, the sequence includes felsic dykes (0–90 m), mafic dykes (0–100 m), unknown lithologies (0–130 m), and diabase (0–150 m). Diorite quartz appears around 180 m, while fault breccias are scattered throughout the 0–180 m interval.

Comparative statistical diagrams show vertical distribution of rock types (Figure 9b) and differentiate barren from mineralized rocks, and also show enrichment in Mn, As, Pb, Cr, V, B, Ca, Mo, Cd, Na, S, P, Ti, and Au (Figures 10 and 11). High-grade gold zones ($\text{Au} > 5 \text{ g/t}$), relative to low-grade zones ($0.5 < \text{Au} < 5 \text{ g/t}$), show further enrichment in Zr, Fe, Li, Bi, Mn, Ni, Zn, Sb, Mg, Na, Co, Be, Pb, Mo, Cu, Cd, Sr, and As, and depletion in La, K, Ba, P, and Ti. These trends reflect the influence of sulfur, rutile, and hydrothermal alteration products (e.g., albitization) within mineralized facies.

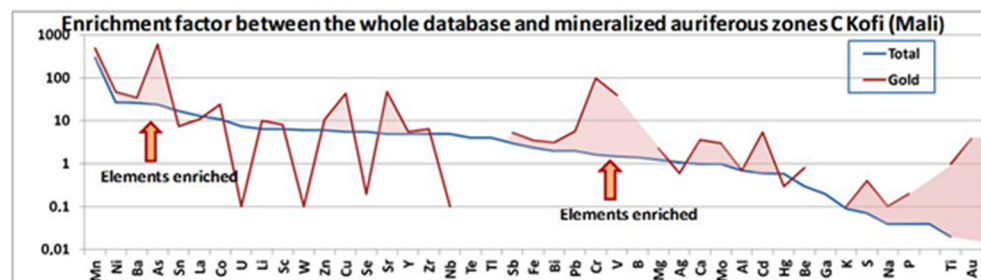


Figure 10. Log-scale plots comparing average element concentrations in the full dataset (11,980 samples) and in mineralized gold zones (780 samples).

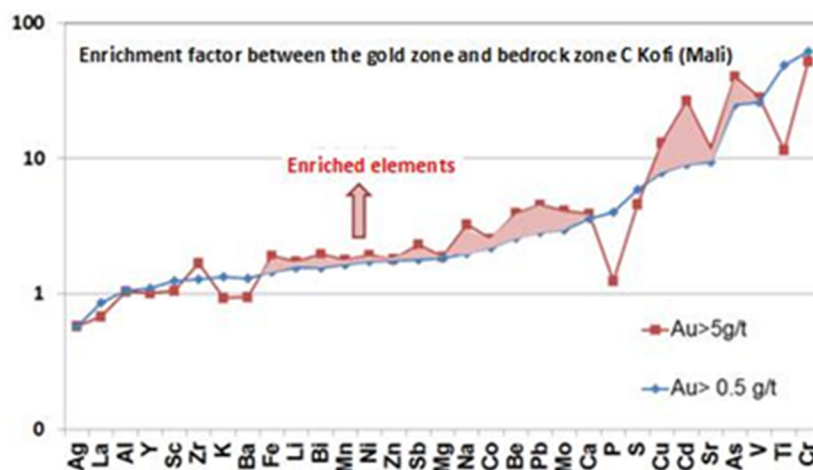


Figure 11. Log-scale plots comparing average element concentrations for the entire prospect and mineralized zones at two gold cut-offs (0.5 g/t and 5 g/t Au), showing enrichment in Fe, Li, Bi, Mn, Ni, Sb, Mg, Na, Co, Be, Pb, Mo, Ca, Cu, Cd, Sr, As, and V (780 samples).

Such geochemical patterns are consistent with known lithogeochemical haloes, both distal and proximal, such as Au-W-Te-Ag anomalies extending along structural fabrics up to 10 km long and 2 km wide in the Malartic district, Québec [52]. These anomalies serve as effective pathfinders for identifying gold-rich zones and guiding exploration in similar geological settings.

3.2. Univariable and Multivariable Statistical Analysis

Univariate Statistical Analysis: Histograms (Figure 12a) show that most elements such as Cu, Fe, Zr follow log-normal distributions with a single population (see Q-Q plots in Appendix B), while others like Au, As, and Mn exhibit multimodal distributions with slight right or left tails, or both (Sr), likely reflecting multiple hydrothermal pulses or paragenetic events.

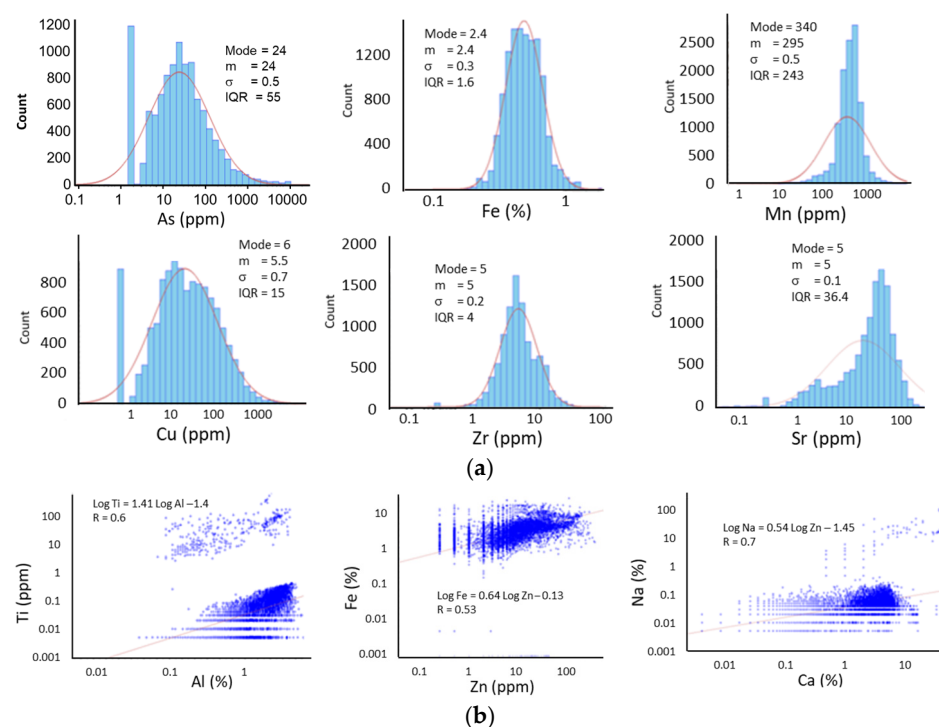


Figure 12. (a) Histogram: As, Fe, and Mn follow log-normal distributions with a single population; Cu, Zr, and Sr exhibit bimodal distributions. (b) Correlation diagrams of selected elements.

Element concentrations in the Earth's crust commonly follow the log-normal distribution due to multiplicative processes such as chemical reactions. These reactions are governed by the law of mass action, which states that reaction rates are proportional to the product of reactant activities or concentrations. According to the Van't Hoff equation, the equilibrium constant K , defined as the ratio of forward to reverse reaction products, is temperature dependent [53]:

$$\ln K = -D_r G^0 / RT$$

where $-D_r G^0$ is the standard Gibbs free energy of reaction, R is the gas constant, and T is the absolute temperature. The effect of pressure P is generally negligible.

Temperature variations induce linear changes in the logarithm of equilibrium constants and, consequently, in the logarithm of element concentration, assuming linear reaction behavior. Thus, normally distributed temperature fluctuations yield log-normal distributions of equilibrium constants and, by extension, of element concentrations. Examples of log-normal distributions are shown in Appendix B.

Since elements often participate in multiple geochemical reactions and transport processes, their concentrations tend to be log-normally distributed. Therefore, it is a standard practice to analyze logarithmic values rather than raw concentrations when constructing log-log plots, performing PCA to identify linear geochemical trends, and when calculating variograms.

Bivariate Analysis: Correlation diagrams (Figure 12b) illustrate elemental relationships and mobility during alteration. Two populations with strong correlations, for example, Al-Ti, where $r \approx 1$, and moderate correlations ($r \approx 0.6$) suggest common sources or mineral hosts. Sodium (Na) shows a moderate correlation with calcium (Ca) ($r = 0.7$), indicating the presence of plagioclase (albite). In contrast, low Na levels uncorrelated with Ca may indicate carbonate phases or Na leaching by hydrothermal fluids. Na concentrations $> 1\%$ suggest two distinct populations, consistent with albite and other Na-bearing minerals identified in the mineralogical studies, such as jadeite and anorthoclase.

Principal Component Analysis (PCA): PCA is a multivariate statistical method that reduces p initial variables to $f \leq p$ principal components (eigenvectors or *factors*) derived from the correlation matrix. These components are linear combinations summarizing inter-element relationships [54]. PCA projects samples into an f -dimensional chemical space, approximating n individuals in a lower-dimensional subspace [55], and revealing correlations or anti-correlations among variables.

PCA was applied to logarithmic values of 20 elements from the Kofi dataset using the Gocad/SKUA PCA plug-in [56] (Figure 13a,b). Three principal components explain ~62% of total variance, indicating strong inter-variable associations:

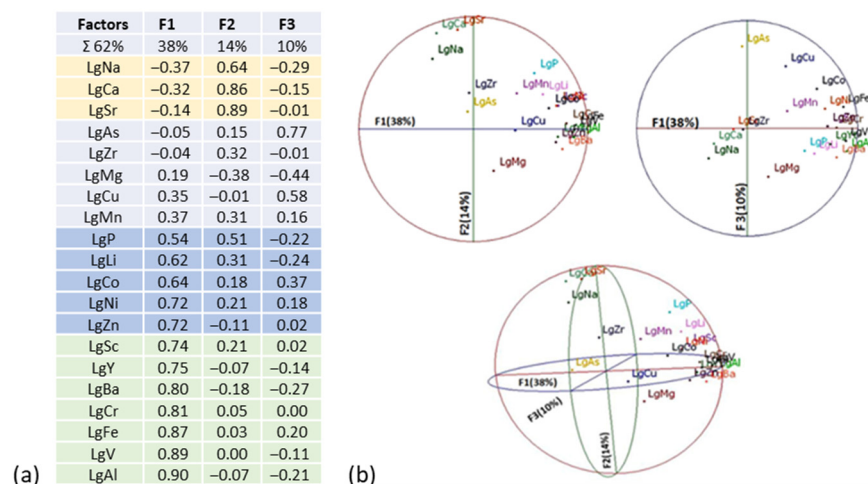


Figure 13. (a) Linear correlations between principal components and original variables. (b) PCA correlation diagrams. Top: 2D circular; bottom: 3D spherical, where variables are correlated when close, anti-correlated when opposite about the center, and uncorrelated when orthogonal.

Factor 1 (F_1 , 38%, ~7–8 variables) associated with *mafic-ultramafic rocks*, strongly correlates with Li, Co, Ni, Zn, Sc, Y, Ba, Cr, Fe, V, and Al; moderately with P.

Factor 2 (F_2 , 14%, approximately three variables) correlates with Na, Ca, and Sr, likely indicating plagioclase (albite), calcite, and weakly with P. This correlation represents *hydrothermal alteration*, particularly carbonatization. Sr shows the highest correlation coefficient with F_2 ($r \approx 0.9$) and will be used to characterize the spatial variation in *carbonatization*.

Factor 3 (F_3 , 10%, approximately two variables) linked to mineralization indicators (As, Cu, Zn), representing arsenopyrite, sphalerite, chalcopyrite, and pyrite, minerals commonly associated with gold.

3.3. Variography

Geostatistical analysis identifies spatial structures using statistical tools such as the mean, median, mode, variance, standard deviation, interquartile range, coefficient of variation, and variograms. In mining, these tools support mineral resource and reserve estimation along with their associated uncertainties.

Experimental variograms are fitted to theoretical models to optimize interpolation methods such as kriging [57,58] and are computed in multiple directions to assess isotropy or anisotropy. Three main variogram models are commonly used: (i) models with a sill—spherical, exponential, Gaussian; (ii) models without a sill—linear, logarithmic; (iii) hole-effect models—oscillating variograms around a sill. Variograms are defined by three key parameters. (i) *Range* (a): the distance beyond which spatial correlation ceases. *Anisotropy* occurs when the range varies by direction; otherwise, the structure is *isotropic*. (ii) *Sill* (C): typically equivalent to the variance (σ^2), representing the distance at which the

variogram reaches a constant value. (iii) *Nugget effect* (C_0): a discontinuity at the origin, indicating local variability or sampling error.

Experimental variograms were computed on all elements using samples from drill holes inclined 55–60° westward. Log-transformed values of Sr, Ag, and PCA-derived factors are shown in Figure 14 to illustrate spatial variability. As SEM analyses reveal electrum in pyrite, the Ag variogram is presented alongside that of Au. The results indicate (i) all variables exhibit *stationarity* (presence of a sill) and *isotropic* spherical structures with no significant anisotropy. Therefore, isotropic variograms were computed for each element to improve estimation accuracy. (ii) Some variograms (e.g., F_1 , F_2 , F_3) show *nugget effects* accounting for 20%–33% of total variance, indicating significant local variability (Figure 14). (iii) Ranges vary from 35 m (Ag, Sr, F_2 , F_1 -linked to mafic/ultramafic rocks and hydrothermal alteration) to 75 m (F_3), reflecting the spatial continuity of mineralized zones. The average continuity is estimated at ~75 m.

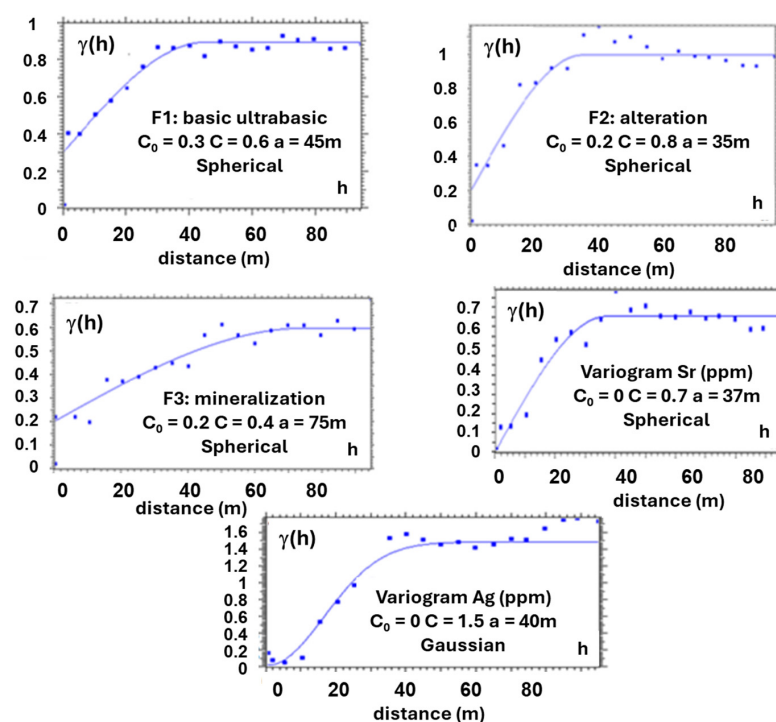


Figure 14. Variograms calculated on the $\log_{10}$ scale for Sr, Ag, and PCA-derived factors. Sr, Ag, and F_2 (alteration) show isotropic spatial ranges of approximately $a \approx 40$ m; F_1 (lithology), $a \approx 45$ m; and F_3 (mineralization) $a \approx 75$ m. F_1 , F_2 , and F_3 variograms exhibit a nugget effect at the origin.

A log-normal cumulative distribution was fitted to the Au data (Figure 15a). Notably, the gold variogram shows no nugget effect, an unusual feature likely caused by the sampling method, which involved crushing 2 m (or longer) core segments, thereby homogenizing grade fluctuations over a larger volume than point sampling. The variogram follows a spherical model with a 60 m range (Figure 15b), suggesting that gold zones of similar grade typically extend ~60 m, likely due to fault recurrences or thickness variation.

Ranges, sills, and nugget effects (in log scale) derived from element variograms at the Kofi prospects are summarized in circular diagrams (Figure 16). Spatial continuity varies significantly, with ranges nearly doubling from less continuous elements like cobalt (Co, $a \approx 35$ m) to more continuous ones like gallium (Ga, $a \approx 80$ m). Elements such as Ag, Ti, Cr, Te, and Au exhibit a negligible or no nugget effect, while B and Ga show the lowest, and Cu and F_1 the highest local variability.

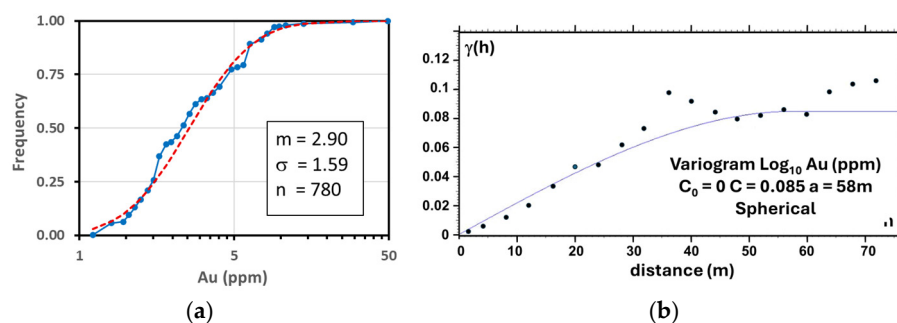


Figure 15. (a) Log-normal cumulative distribution (red) was fitted to Au data (blue). (b) Spherical variogram of Log_{10} -transformed gold (Au). Gold mineralization is isotropic, with a range of approximately $a \approx 60$ m and no nugget effect at the origin.

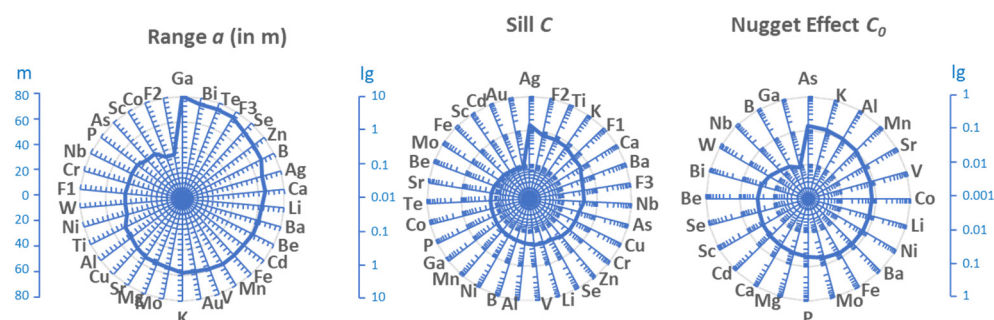


Figure 16. Left to right: Circular diagrams comparing ranges (in meters), sills (C), and nugget effects (C_0) in log scale for geochemical variograms at the Kofi prospect.

These fitted variograms were used to construct the 3D grade block model of the Kofi prospect.

3.4. Three-Dimensional Block Model

A Gocad regular S-grid (An S-grid (or structured grid) is a regularly spaced, lattice-like grid used in geostatistics and modeling, where cells are aligned along consistent X, Y, and Z deformed axes to better fit geological bodies, forming a 3D matrix) block model was built using SKUA Gocad [59], consisting of $65 \times 65 \times 54$ cells (each $10 \times 10 \times 5$ m), totaling approximately 230,000 blocks. Grades were interpolated at block centers using Discrete Smooth Interpolation (DSI is a spatial interpolator that fits a smooth, continuous estimate through discrete samples while honoring known values and optional inequality constraints. Its minimizes the second derivative (Laplacian or curvature) to enforce smoothness. Unlike kriging, which requires a variogram, DSI is deterministic and supports constraints such as positivity or upper bounds. It is used here as a complementary method to validate the results. Additional details can be found in references [59,60]) (DSI) [60] and ordinary kriging [57] based on fitted variograms. Kriging estimation variances were also calculated. Grade cut-offs were applied for elements such as B, Cu, Na, Hg, Pb, Sb, and Zn (see Table A11) to delineate mineralized zones for resource estimation (Figures 17 and 18). Additional targets were also defined by intersecting anomalous Na-B-Hg zones, highlighting alteration-related associations.

The cutoff values used to define geochemical targets are listed in Table A12. Several samples represent barren rocks for common elements (e.g., Ba, Na) or elements analyzed in low numbers (e.g., B, Hg), making classical statistical techniques (e.g., quantile or mean + 2 s cutoffs) less applicable. Therefore, cut-offs were primarily based on results shown in Figure 10 and geological break points. For Ag, Sb, and Zn, cutoffs were defined using quantiles. For Cu and Pb, they were determined on both geological break points and

statistical considerations. The resulting target volumes are visualized in Figures 17–19. B and Sb define the largest anomalies, with total volumes of 0.651 and 0.855 Mm³, respectively. B anomalies near Ag mineralization (outlined in red) suggest intense tourmalinization linked to Ag-Au mineralization, as supported by the geological map (Figure 2b) and petrographic analysis.

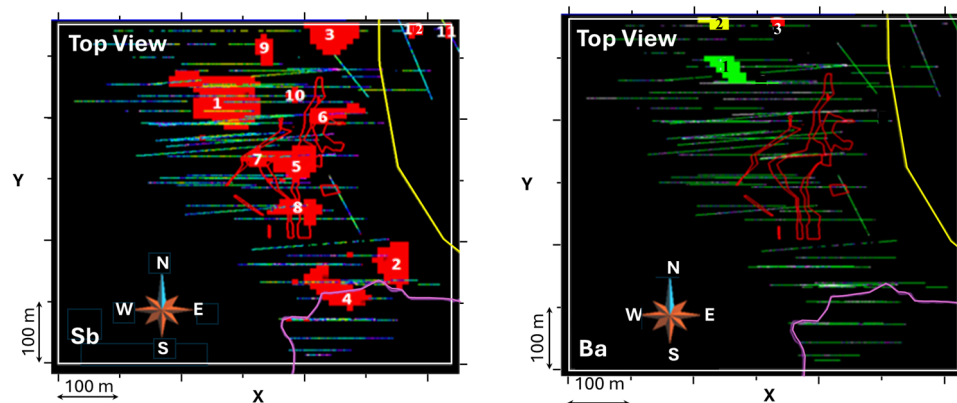


Figure 17. (Left): 3D block model (top view) for antimony (Sb). Numbers indicate target in descending order. Bluish-green horizontal lines represent drillholes; red contours indicate outcropping mineralization. (Right): Same representation for barium (Ba).

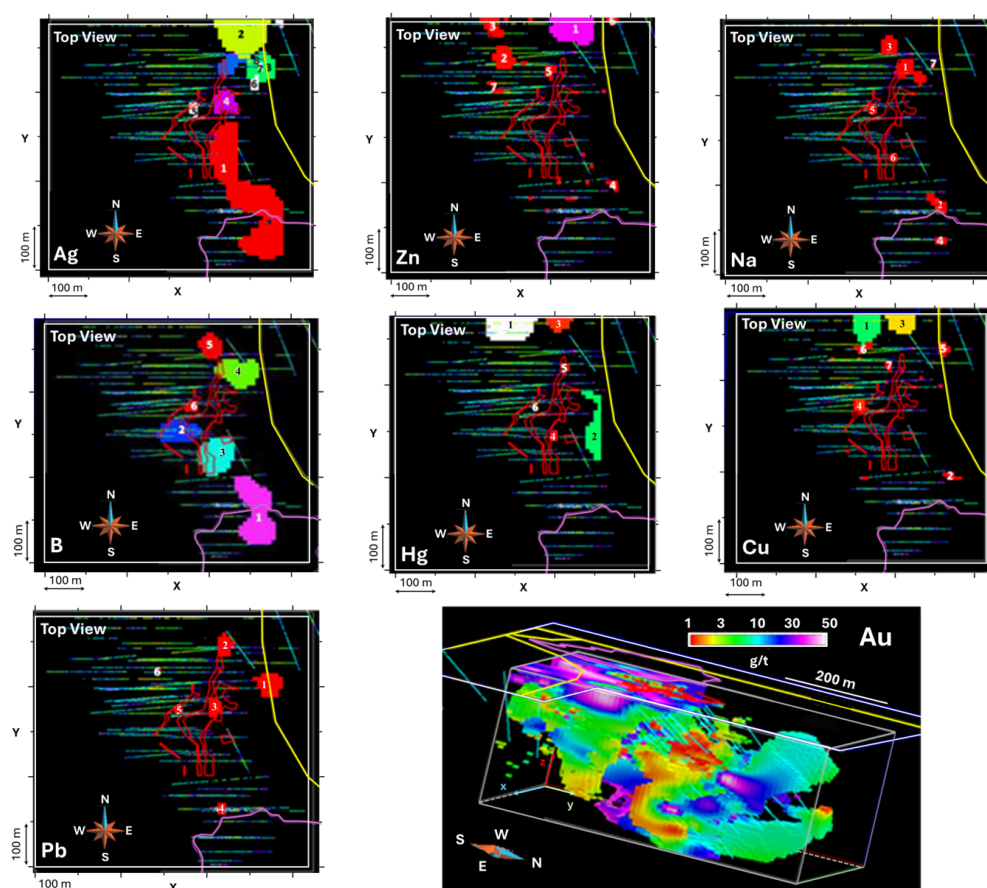


Figure 18. Three-dimensional block model for Ag, Zn, Na, B, Hg, Cu, Pb, and Au. Numbers indicate target volumes in descending order. Bluish-green horizontal lines represent boreholes; red contours indicate surface mineralization. Bottom-right view shows gold mineralization from a southern perspective.

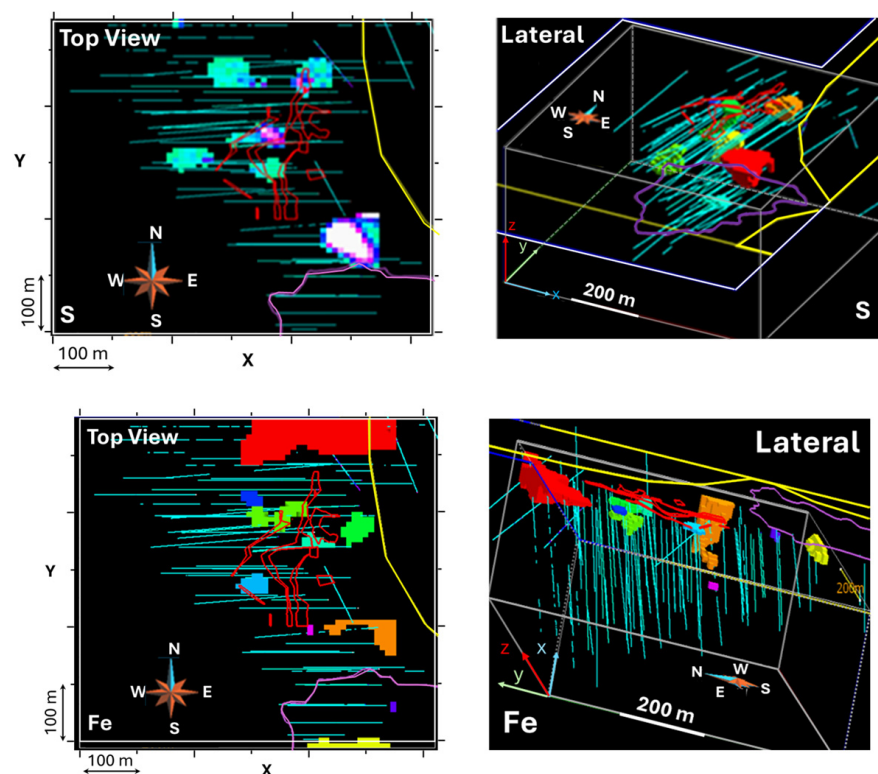


Figure 19. Top view (1st column) and 3D block model (2nd column) for sulfur (S) and iron (Fe) indicating the presence of pyrite or arsenopyrite; bluish-greenish horizontal lines represent drillholes; red contours indicate surface mineralization.

Smaller anomalies in Pb, Zn, and Na reflect the presence of galena, sphalerite, and secondary phases associated with albitization or tourmalinization. A minor Cu anomaly ($\sim 7000 \text{ m}^3$), spatially linked to mineralization, may indicate trace amounts of chalcopyrite, bornite, or hydrothermal minerals such as chalcocite and covellite.

The 3D spatial distributions of sulfur (S) and iron (Fe) are shown in Figure 19. Sulfur anomalies partly coincide with tourmaline zones (B) in the eastern area and with Au mineralization. However, two large anomalies in the west appear unrelated to other mineralization (e.g., Pb, Zn, Cu) and may indicate the presence of pyrite or arsenopyrite.

Discussion: Geostatistical analysis at the Kofi prospect reveals predominantly isotropic, spherical spatial structures with well-defined ranges and low nugget effects for most elements, including gold. Variogram modeling indicates spatial continuity ranging from 35 m (for elements linked to localized alteration) to 80 m (for more uniformly distributed elements), supporting reliable 3D grade block modeling. The absence of the nugget effect in gold further confirms its spatial consistency and enhances confidence in reserve estimation. Spatial variability estimates derived from mineralization and pathfinder element ranges provide valuable guidance for ongoing exploration efforts.

4. Geostatistical Resource Estimation

Silver (Ag) and gold (Au) contents (log-scaled) were estimated at each grid node using Discrete Smooth Interpolation (DSI) [60] and ordinary kriging [57,58] in SKUA Gocad [56], via a mining estimation script [61]. Grades were then back-transformed from $\log_{10}$ values to ppm (g/t). The results in Table 3 indicate an overall estimated kriging standard deviation of approximately 5% in gold reserve calculations, consistent with the *Indicated Resources* category under the JORC guidelines. This may translate to *Probable*

Mineral Reserves, depending on technical and economic modifying factors (e.g., mining methods, metallurgical recovery, economic viability).

Table 3. Reserves inferred using various estimation methods, where Q_{ore} and Q_{met} are the ore and metal quantities, σ_{es} is the kriging-estimated standard deviation, SGS denotes Sequential Gaussian Simulation, and Avon refers to company-reported reserves.

Method	Q_{ore}	Q_{met}	Q_{met}	Grade	Grade	Gain ¹	
	(Mt)	(t)	(Moz)	(g/t)	(oz/t)	2022	2025
Kriging	1.29	8.20	0.289	6.36	0.22	110.2	501.8
$\pm \sigma_{\text{es}}$	0.06	0.41	0.01	0.32	0.01	5.5	25.1
SGS	0.71	5.24	0.168	7.38	0.26	70.4	320.7
Avon	2.47	8.6	0.303	3.50	0.12		

¹ In MUSD, calculated as in situ metal value minus operational costs for a cut-off Au at 4 g/t.

Kriging results for various gold cut-off grades (4–15 g/t) are presented in Table A13. A parallel estimation using a Sequential Gaussian Simulation (SGS) is provided in Table A14 with an ore density of 2.7 g/cm³ assumed.

Conversion factors included the following: 1 oz = 28.349 g; gold price as of 08/03/2022 = USD 1750/oz; production cost (PC) = USD 1369/oz (2018, [62]). Updated values as of 25/04/2025 account for 5% annual inflation, with operating costs at USD 1585/oz and gold priced at USD 3320/oz.

Given the economic context at the time of the study (with gold prices at half their current value) and processing costs related to risk management, a high cut-off grade of 4 g/t Au was chosen. In situ reserves at the Kofi prospect are estimated at 0.289 Moz (~8.2 t Au), with an average grade of 0.22 oz/t (~6.36 g/t), corresponding to 1.29 Mt of ore (Tables 3 and A13–A15). Gold grade (g/t) and ore tonnage (t) versus cut-off grade for both methods are shown in Figure 20a, alongside expected gains under 2022 and 2025 scenarios (Figure 20b). A sixth-order polynomial fits the cut-off vs. grade curve:

$$Q_{\text{Au}}(t) = \sum_{i=0}^6 a_i c_{\text{Au}}^i$$

where c_{Au} is the cut-off grade, and a_i are coefficients listed in Table A16. The relationship shows that increasing the cut-off grade raises average ore grade but reduces total recoverable metal.

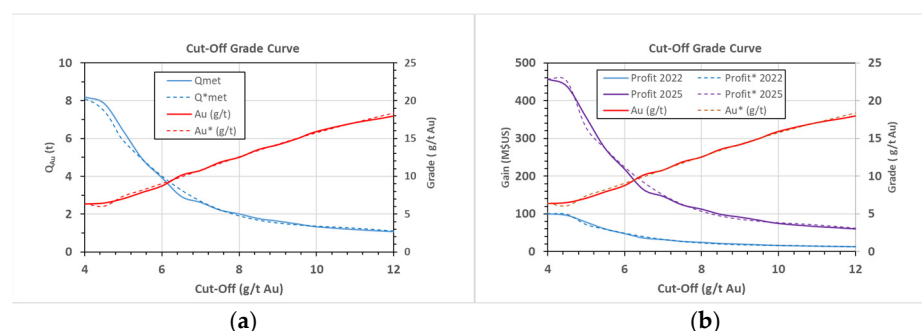


Figure 20. Gold cut-off grade diagrams: (a) Average production grade (g/t, red) and in situ gold tonnage (t, blue) vs. cut-off grade; (b) Expected gains (blue) at gold prices of 1750 USD/oz (08/03/2022) and 3320 USD/oz (04/28/2025). Dotted lines represent sixth-order polynomial fits to the cut-off grade and cut-off metal curves (see coefficients in Appendix A, Table A16).

In Zone C of the Kofi area, kriging-based in situ reserves are estimated at ~8.2 t Au@ 6.36 g/t, totaling 1.287 Mt of ore. The estimated gold value is approximately USD

506 million, with expected gains of USD ~110 million at 2022 prices, rising to USD 960 million in value and USD 502 million in gains under 2025 assumptions (Tables 3 and A15). These estimates (indicated and inferred) align closely with figures reported by Avion Gold Corp. (2012, Report No. 235 [17]) for the Kofi C zone:

Indicated: 2.476 Mt @ 3.5 g/t Au, totaling 0.2784 Moz (8.67 t) at a 1.0 g/t cut-off.

Inferred: 1.254 Mt @ 2.78 g/t Au, totaling 0.1122 Moz (3.49 t).

Discussion: The cut-off grade analysis highlights the trade-off between ore grade, tonnage, and economic return—higher cut-offs yield higher-grade ore but lower volumes. While profitability is positive at the 2022 gold price (1750 USD/oz), returns increase significantly under 2025 conditions (3320 USD/oz), illustrating the project's strong sensitivity to gold price fluctuations—an uncertainty often greater than resource estimation variance. These results underscore the importance of flexible, market-responsive cut-off strategies, supported by polynomial modeling to enhance long-term planning and project resilience.

5. Conclusions

The main conclusions of the study include the following:

1. *Gold Mineralization:* Petrographic analysis reveals two phases of gold mineralization: (a) native gold and electrum as inclusions in pyrite (40–50 μm), and (b) disseminated native gold in pyrite-hosted fractures (~100 μm). As pyrite consistently hosts arsenopyrite, the latter is interpreted as the earlier phase. No gold was observed in quartz veins under SEM.
2. *Hydrothermal Alteration:* Four alteration types were identified: epidotization, chloritization, carbonation, and dominant albitization, often linked with regional tourmalinization. The matrix comprises carbonates and silicates, with variable sulfide mineralization.
3. *Thermobarometry:* Data from chlorite, arsenopyrite, biotite, feldspar, and carbonates indicate greenschist to amphibolite facies conditions (250–550 $^{\circ}\text{C}$, 3–8 kbar), suggesting mid- to deep-crustal fluid origins with varying metamorphic overprints.
4. *Hydrothermal Evolution:* Geothermometric and mineralogical evidence confirms a complex, multi-phase hydrothermal evolution typical of orogenic gold systems. Gold was transported by reduced, CO_2 -rich fluids and precipitated through cooling, pressure drops, and redox changes. Pathfinder minerals such as Mg-rich chlorite and arsenian pyrite help direct the gold towards mineralized zones.
5. *Multivariate Analysis:* PCA identified three key factors: F_1 lithology (mafic/ultra-mafic rocks and quartz vein breccias), F_2 hydrothermal alteration (mainly carbonatization), and F_3 mineralization. F_2 shows the strongest correlation with gold content.
6. *Spatial Modeling:* A 3D block model delineated potential mineralized zones. Variogram analysis of log-transformed gold values indicates a stationary, isotropic spatial structure with no nugget effect and a 60 m range.
7. *Resource Estimation:* In situ gold resources were estimated using ordinary kriging on a regular structured grid. Gold grades follow a log-normal distribution. Mineralization is associated with mafic intrusions and occurs in dolomitized and albitized zones. Despite the presence of electrum, no significant gold-silver correlation was observed across 780 mineralized samples.
8. *Structural Controls:* Subsurface mineralization aligns with surface structural trends. In situ resource total 1.295 Mt of ore, with an average of 6.36 g/t for Au (at a 4 g/t cut-off), yielding ~8.2 t Au, confirming strong exploration potential in Zone C, Kofi, Mali.

This multidisciplinary approach—integrating petrology, mineralogy, and geochemistry, and 3D geostatistical modeling—provides a robust framework for resource estima-

tion in orogenic gold systems. It demonstrates how combining advanced analytical techniques with solid geological understanding can effectively identify high-potential exploration targets.

Author Contributions: Conceptualization, J.-J.R.; methodology, J.-J.R.; software, J.-J.R. and N.C.; validation, J.-J.R. and N.C.; petrographic analysis, N.C.; investigation, N.C.; resources, J.-J.R. and N.C.; data curation, N.C.; writing—original draft preparation, J.-J.R. and N.C.; writing—review and editing, J.-J.R.; visualization, J.-J.R. and N.C.; supervision, J.-J.R.; funding acquisition, J.-J.R. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Restrictions apply to the availability of this data. The data was obtained from Endeavor Mining Inc. and can be requested with the company’s permission.

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Appendix A

Table A1. Sample description with depth and geological context (Py = pyrite, Qz = quartz, Chlr = chlorite).

Borehole	Sample ID	From (m)	To (m)	Comments
C-11-14	K66	127.9	128	Poly conglomerate with disseminated Py
C-11-14	K67	146.1	146.25	Dark rock. Few Py + Qz carbonate veins with big Py
C-10-05	K70	96.75	96.9	Strongly altered silt with veinlets filled by Chlr and Py
C-10-14	K72	112.5	112.6	Strongly altered fault breccia zone Qz stockwork

Table A2. Chemical composition (in %) of chlorites analyzed by electron microprobe.

Oxide	K72-3a	K72-3b	K72-3c	K72-3d	K66a	K66b	K72-2a	K72-2b
Na ₂ O	0.04	0.03	0.01	0.07	0.04	0.06	0.05	0.05
MgO	11.55	12.73	12.46	10.98	24.2	15.61	11.27	12.24
Al ₂ O ₃	20.11	15.88	17.58	17.72	20.5	16.3	21.62	18.51
SiO ₂	26.05	28.63	27.51	28.23	27.36	29.55	28.31	26.28
P ₂ O ₅	0	0.04	0	0	0	0.01	0.02	0
K ₂ O	0.04	0.01	0.05	0.09	0.02	0.06	0.07	0
CaO	0.06	0.18	0.2	0.32	0	0.2	0.17	0.08
TiO ₂	0.06	0.03	0	0.02	0.07	0	0.27	0.02
MnO	0	0.14	0.1	0.02	0	0.08	0	0.07
FeO	30.23	30.41	30.24	30.48	12.79	26.18	25.88	29.85

Table A3. Structural formulas and estimated formation temperatures of selected chlorite samples.

	K72-3	K72-3	K72-3	K72-3	K66	K66	K72-2	K72-2
<i>Fe/(Fe + Mg)</i>								
Fe/(Fe + Mg)	0.59	0.57	0.58	0.61	0.23	0.48	0.56	0.58
<i>Structural formula (half-cell)</i> ¹								
Si ^{iv}	2.80	3.08	2.96	3.04	2.78	3.10	2.96	2.86
Al ^{iv}	1.20	0.92	1.04	0.96	1.22	0.90	1.04	1.14
Al ^{vi}	1.34	1.09	1.18	1.28	1.23	1.11	1.62	1.23
Fe ^{vi}	2.71	2.73	2.72	2.74	1.09	2.30	2.26	2.72
Mg ^{vi}	1.85	2.04	2.00	1.76	3.66	2.44	1.75	1.98
Mn ^{vi}	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.01
Σ ^{vi}	5.91	5.88	5.90	5.79	5.98	5.86	5.64	5.94
<i>End-member proportions</i>								
Al-chl	0.23	0.19	0.20	0.22	0.21	0.19	0.29	0.21
Fe-chl	0.46	0.47	0.46	0.47	0.18	0.39	0.40	0.46
Mg-chl	0.31	0.35	0.34	0.30	0.61	0.42	0.31	0.33
<i>Al_c^{iv} = Al^{iv} + 0.1 [Fe/(Fe + Mg)]</i> ²								
Al ^{iv} _c	1.26	0.98	1.10	1.02	1.24	0.95	1.10	1.20
<i>Geothermometers</i> ³								
MC88 T (°C)	325	235	275	250	330	230	275	305
WJ91 T (°C)	335	245	280	260	330	235	280	315
<i>Geobarometer</i> ⁴								
P (kbar)	3.1–3.2	2.2–2.3	2.6–2.6	2.3–2.4	3.2	2.1–2.2	2.6–2.7	2.9–3
Depth (km)	8.3–8.6	5.7–6.0	6.9–7.0	6.1–6.4	8.4	5.6–5.7	6.9–7.0	7.7–8.0

¹ Structural formula calculated assuming 14 oxygen atoms per half-cell, ~88% total anhydrous oxides, and no ferric iron, using chlorite compositions from Table A1. ² Tetrahedral Al_c^{iv} determined using Jowett's correction [31]. ³ Chlorite formation temperatures estimated using geothermometers from [30] (MC88) and [31] (WJ91), with an error margin of ±5 °C. Calculations assume relative EPMA analytical errors of ~2% using the following equations: MC88: T(°C) = 321.98 Al^{iv} – 61.92 (Cathelineau, 1988) [30]. WJ91: T(°C) = 319 Al_c^{iv} – 69 (with Al_c^{iv} = Al^{iv} + 0.1[Fe/(Fe + Mg)] (Jowett, 1991) [31]. ⁴ Pressure estimated based on an assumed thermal gradient of 35 °C/km and average surface temperatures of ~20–30 °C during the Proterozoic.

Table A4. Chemical composition (in atomic %) of selected chlorites analyzed by electron microprobe¹.

Chlorites	Si	Ti	Al/Al ^{IV}	Al ^{VI}	Cr	Fe ²⁺	Mg ²⁺	Mg	Ca	Na	K	Ni	OH	Sum Cat#	X _{Mg}	Al _{tot} apfu
267-C1.4	6.04	0.03	1.96	2.84	0.00	3.30	0.00	5.28	0.01	0.00	0.13	0.01	16	35.59	0.62	4.80
267-C2.1	5.28	0.00	2.72	2.90	0.01	4.11	0.01	4.88	0.00	0.00	0.00	0.00	16	35.91	0.54	5.62
267-C2.3	5.29	0.02	2.71	2.79	0.00	3.98	0.00	5.16	0.00	0.00	0.01	0.00	16	35.95	0.57	5.50
284-C1.1	5.48	0.00	2.53	2.60	0.00	5.77	0.02	3.54	0.01	0.02	0.02	0.00	16	35.98	0.38	5.12
346-C3.2	5.59	0.03	2.41	2.46	0.00	4.04	0.01	5.38	0.01	0.00	0.00	0.01	16	35.95	0.57	4.87
346-C1.3	5.56	0.01	2.44	2.78	0.01	4.23	0.00	4.75	0.03	0.00	0.03	0.01	16	35.84	0.53	5.22
249-C2.1	5.31	0.00	2.69	2.87	0.01	4.75	0.00	4.22	0.03	0.00	0.00	0.02	16	35.90	0.47	5.56
249-C2.3	5.30	0.01	2.71	2.80	0.02	4.55	0.01	4.48	0.01	0.00	0.00	0.05	16	35.93	0.50	5.51

Table A4. Cont.

	T (°C) ²	P ³ (kbar)	Depth ⁴ (km)	P ⁵ (kbar) ($\sigma = \pm 0.1$)	Depth ⁴ (km) ($\sigma = \pm 0.2$)	$\Delta \log$ fO ₂ ⁶
267-C1.4	245–255	2.25–2.35	6.0–6.2	4.2	11	~FMQ
267-C2.1	365–375	3.55–3.67	9.4–9.7	4.8	13	~FMQ–1
267-C2.3	365–375	3.54–3.66	9.4–9.7	4.7	13	~FMQ
284-C1.1	335–345	3.22–3.34	8.5–8.8	4.4	12	~FMQ + 1
346-C3.2	315–325	3.02–3.13	8.0–8.3	4.1	11	~FMQ
346-C1.3	320–330	3.07–3.18	8.1–8.4	4.5	12	~FMQ–0.5
249-C2.3	360–370	3.49–3.61	9.3–9.6	4.8	13	~FMQ
284-C1–3	360–370	3.51–3.63	9.3–9.6	4.7	13	~FMQ

¹ Elements below detection limits were excluded. ² Chlorite formation temperatures estimated using geothermometers from [30] (MC88) and [31] (WJ91), with an error margin of ± 5 °C, assuming a relative EPMA analytical error of ~2%. ³ Pressure derived from an assumed thermal gradient of 35 °C/km and average surface temperatures of ~20–30 °C during the Proterozoic. ⁴ Density is assumed to be 2.7 g/cm³. ⁵ Pressure is also estimated using the geobarometer equation [37]: $P(\text{kbar}) = 0.3 \times \text{Al}^{\text{VI}} + 0.7 \times \text{Al}^{\text{total}}$. Discrepancies between this estimate and the thermal gradient-based pressure may reflect an underestimated gradient or limitations of single-mineral thermobarometry. ⁶ Oxygen fugacity (fO₂) assumed near the FMQ buffer due to the absence of Fe³⁺ data.

Table A5. Chemical composition (in atomic %) of selected arsenopyrites analyzed by electron microprobe ¹.

AsPy	K72-3-2	K72-3-4	DJ-9	DJ-12	DJ-13	DJ-14	DJ-15
S	35.79	35.23	36.29	34.73	37.36	37.37	37.57
Fe	32.7	33.27	32.73	33.49	33.59	33.11	33.21
As	31.29	31.34	30.75	31.66	28.9	29.44	29.05
Os	0.11	0.13	0.16	0.08	0.04	0.03	0.1
Geothermometers ²							
asp + py + As T (°C)	410 $\pm$ 30	410 $\pm$ 30	385 $\pm$ 30	425 $\pm$ 30	295 $\pm$ 35	325 $\pm$ 35	300 $\pm$ 35
py + asp T (°C)	390 $\pm$ 45	390 $\pm$ 40	355 $\pm$ 45	410 $\pm$ 40	215 $\pm$ 60	260 $\pm$ 55	230 $\pm$ 60

¹ Element contents below 0.1 at % was excluded. Analytical precision is approximately 2%. ² Arsenopyrite formation temperatures were estimated using geothermometers based on the asp + py + As X-T curve [38] and the py + asp equilibrium X-T curve [39].

Table A6. Chemical composition (in atomic %) of selected biotites and hematite analyzed by electron microprobe ¹.

Biotites	Si	Ti	Al/Al ^{IV}	Al ^{VI}	Fe ²⁺	Mg	Mg	Ca	Na	F	OH	Sum Cat#	X _{Mg}
267-C2-4	6.58	0.01	1.42	3.46	0.32	6.58	0.28	0.19	1.72	0.10	3.90	17.95	0.47
346-C1-2	6.50	0.05	1.50	3.41	0.33	6.50	0.27	0.08	1.77	0.01	3.99	17.92	0.46
Hematite													
284-C1-3					1.99							2.00	
	T (°C) ²		P (kbar) ³		Depth (km)								
267-C2-4	~400–500		~5–10		~5–10								
346-C1-2	~500–550												
284-C1-3													

¹ Elements below detection limits were excluded. ² Formation temperatures (T) were estimated based on Ti content (0.013–0.045 apfu) in biotite [36]. ³ Total Al content ($\text{Al}^{\text{total}} = \text{Al}^{\text{IV}} + \text{Al}^{\text{VI}} = 4.83\text{--}4.91$ apfu) shows a positive correlation with pressure (P) [39].

Table A7. Chemical composition (in atomic %) of selected feldspars analyzed by electron microprobe ¹.

Feldspars	Si	Al/Al ^{IV}	Ca	Na	K	Sum Cat#	Ab%	An%	Or%
267-C1.1	2.93	1.08	0.03	0.95	0.04	5.03	92.72	3.35	3.93
267-C1.3	2.99	0.98	0.01	1.03	0.00	5.03	98.85	0.97	0.17
G249-C2	3.01	0.98	0.00	1.02	0.00	5.01	99.83	0.08	0.10
	T (°C) ²		P (kbar) ³		Depth (km)		$\Delta\log fO_2$ ⁴		
	~300–450		~5–8		~15–25		FMQ Buffer		

¹ Elements below detection limits were excluded. ² Formation temperatures (T) were estimated based on low Ti (<0.001 apfu) [36]. ³ Total Al content (Al_{total} = Al^{IV} + Al^{VI} = 4.83 – 4.91 apfu) shows positive correlation with pressure (P) [39]. ⁴ Redox-conditions from [7].

Table A8. Chemical composition (in %) of selected carbonates analyzed by electron microprobe.

Carbonate	346-	G249-	284-				346-
	C2-1	C1	C1-2	C1-4	C2-1	C2-2	C1-4a
Rhodochrosite	0.6	0.1	1.9	1.1	1.1	1.5	0.1
Magnesite	36.0	35.9	0.7	25.9	0.6	21.1	34.4
Siderite	13.0	15.6	1.4	17.9	1.1	27.4	15.2
Calcite	50.3	48.4	95.4	54.8	97.0	50.0	50.2
	<i>Geothermometers</i> ¹						
T (°C)	320 ± 40	300 ± 50	260 ± 40	310 ± 40	250 ± 30	335 ± 35	330 ± 30
P (kbar)	3.0 ± 1.0	2.0 ± 1.0	1.75 ± 0.75	3.0 ± 1.0	1.75 ± 0.75	3.25 ± 0.75	3.0 ± 1.0
pH	6.3 ± 0.75	5.5 ± 1.0	6.8 ± 0.75	6.3 ± 0.75	7.0 ± 0.5	6.0 ± 0.5	6.0 ± 0.5
X _{CO2}	0.4 ± 0.1	0.3 ± 0.1	0.2 ± 0.05	0.4 ± 0.1	0.1 ± 0.1	0.4 ± 0.1	0.4 ± 0.1

¹ Carbonate T-P formation conditions were estimated using carbonate-based geothermometers and geobarometers [38] and the py + asp equilibrium X-T curve [39].

Table A9. Carbonate assemblages in the Kofi orogenic gold systems.

N°	Mineral ¹ Composition (in %)				T (°C)	P (kbar)	pH	fO ₂	X _{CO2}	Key Observations
	Rho.	Mag.	Sid.	Cal.						
C1	0.1	35.9	15.6	48.4	280–340	2–4	5.5–7	PMB ²	0.2–0.4	High Mg and Fe content; late stage calcite formation under reducing conditions
C1.4	1.1	25.9	17.9	54.8	270–350	2–4	5.5–67	reducing	0.25–0.45	High Mg and Fe content; late-stage calcite formation under reducing conditions with H ₂ O–CO ₂ dominant fluids.
C1.4a	0.1	34.4	15.2	50.2	300–360	2–4	5.5–6.5	PPMB ³	0.3–0.5	High magnesite and siderite content, indicating Fe–Mg-rich fluid interaction with CO ₂ .
C2.2	1.5	21.1	27.4	50.0	300–370	2.5–4	5.5–6.5	PPMB	0.3–0.5	Siderite and magnesite suggest Mg–Fe-rich fluids under moderate to high CO ₂ activity.
C2.1	0.6	36.0	13.0	50.3	280–360	2–4	5.5–7	QFMB ⁴	0.3–0.5	High magnesite and siderite content, indicating interaction with CO ₂ rich, Fe–Mg-bearing fluids.
C1.2	1.9	0.75	1.4	95.4	220–300	1–2.5	6–7.5	PMB	0.1–0.2	Calcite-dominated assemblage suggests fluid cooling; high CO ₂ activity is required for siderite and magnetite formation.
C2.1	1.1	0.6	1.1	97.0	220–280	1–2.5	6.5–7.5	mildly reducing	0.1–0.2	Predominantly calcite with trace Fe and Mn carbonates, indicating late-stage fluid neutralization.

¹ Abbrev.: Rho. = Rhodochrosite; Mag. = Magnesite; Sid. = Siderite; Cal. = Calcite. ² PMB = near the pyrite-magnetite buffer, indicating moderately reducing conditions. ³ PPMB = near the pyrite-pyrrhotite-magnetite buffer, indicating reducing conditions. ⁴ QFMB = near the quartz-fayalite-magnetite buffer, representing mildly reduced conditions that promote stable transport of gold as bisulfide complexes (AuHS⁰) and sulfur, creating favorable conditions for gold deposition during interaction with Fe-bearing rocks.

Table A10. Carbonate and sulfide assemblages in the Kofi orogenic gold systems.

N°	Carbonate ¹ (in %)				AsPy ²	Alteration Minerals	Dominant Features	T (°C)	Gold Association	Interpretation
	Rod. (MnCO ₃)	Mag. (MgCO ₃)	Sid. (FeCO ₃)	Cal. (CaCO ₃)						
C1	0.1	35.9	15.6	48.4	Arsenopyrite present	Chlorite + minor sericite	Fe-Mg dominant	280–350	Mid-stage/Gold	Strong interaction with ultramafic/mafic rocks
C1.4	1.9	25.9	17.9	54.8	Common pyrite	Moderate chlorite	Mg-Fe rich	250–340	Mid-stage	Moderate fluid-rock interaction in a proximal zone
C1.4a	0.1	34.4	15.2	50.2	Pyrite + arsenopyrite	Strong chlorite	Mg-Fe rich	260–350	Mid-stage	Mafic host interaction in a proximal setting
C2.2	1.5	21.1	27.4	50.0	Pyrite + arsenopyrite	Chlorite-dominant	Mg-Fe rich	300–370	Mid-stage	Fluid-rock interaction in a proximal zone
C2.1	0.6	36.0	13.0	50.3	Abundant arsenopyrite	Chlorite-dominant	Mg-Fe dominant	280–360	Likely coeval	Shear-hosted proximal alteration with gold potential
C1.2	1.9	0.75	1.4	95.4	Trace sulfides	Weak sericite	Ca-dominant	200–280	Late/Post	Weak fluid-rock interaction in a distal zone
C2.1	1.1	0.6	1.1	97.0	Trace sulfides	None to weak	Ca-dominant	180–260	Late/Post	Distal alteration halo with minimal Mg-Fe input

¹ Abbrev.: Rho. = Rhodochrosite, Mag. = Magnesite, Sid. = Siderite, Cal. = Calcite. ² AsPy = arsenopyrite. Notes: Assemblages with >30% magnesite + siderite indicate significant Mg-Fe mobility and proximal alteration. Rhodochrosite remains low in all samples, indicating Mn-poor systems or limited late-stage Mn availability. Sulfide presence correlates with Fe-Mg carbonate abundance and proximity to gold mineralization. Chlorite and sericite alteration trends reflect fluid temperature and wall-rock chemistry. Late-stage, calcite-dominant samples likely represent distal or post-mineralization fluids. This extended table integrates carbonate mineralogy with sulfide and alteration phases, providing a more comprehensive paragenetic framework for orogenic gold systems.

Table A11. Descriptive statistics of geochemical elements.

Elements	Units	n	med	m	σ	IQR	σ ²	25th	75th
LgAg	ppm	9612	1	1.07	0.2	0	0.03	1	1
LgAl	%	11,835	1	0.7	0.5	0	0.2	1	1
LgAs	ppm	11,965	24	24	0.7	55	0.5	8	63
LgB	ppm	202	10	1.4	0.6	0	0.4	10	10
LgBa	ppm	11,968	28	26	0.7	98	0.5	7	105
LgBe	ppm	11,968	1	0.3	0.4	0	0.2	1	1
LgBi	ppm	11,968	2.5	2	0.4	0.5	0.1	2	2.5
LgCa	%	11,916	3	1	0.9	3	0.7	1	4
LgCd	ppm	11,968	1	0.6	0.3	0	0.08	1	1
LgCo	ppm	11,968	19	11	0.5	17	0.2	6	23
LgCr	ppm	11,968	42	1.6	0.7	98	0.4	13	111
LgCu	ppm	11,835	6	5.5	0.7	15	0.4	2	17
LgFe	%	11,841	2.4	2.4	0.3	1.6	0.07	2	3.6

Table A11. Cont.

Elements	Units	n	med	m	σ	IQR	σ^2	25th	75th
LgGa	ppm	202	10	0.2	1	0	1.6	10	10
LgHg	ppm	7560	1	0.58	0.2	−9	0.6	10	1
LgK	%	11,968	1	0.09	0.9	0	0.8	1	1
LgLi	ppm	11,968	7	6.42	0.6	14	0.3	3	17
LgMg	%	11,968	2.2	1.25	0.7	1.6	0.5	1.4	3
LgMn	ppm	11,966	349	295	0.5	243	0.3	235	478
LgMo	ppm	11,838	1	1	0.4	0	0.2	1	1
LgNa	%	11,968	1	0.04	0.5	0	0.2	1	1
LgNb	ppm	568	10	4.9	0.3	0	0.09	10	10
LgNi	ppm	11,968	30	27	0.5	32	0.3	19	51
LgP	%	11,884	1	0.04	0.5	0	0.2	1	1
LgPb	ppm	11,968	2	2	0.5	0	0.6	1	1
LgS	%	9386	1	0.07	0.8	−0.5	0.6	3	2.5
LgSb	ppm	11,835	2.5	3	0.3	7.7	0.06	2.5	10.2
LgSc	ppm	11,968	6.4	6.4	0.3	5.7	0.1	4.3	10
LgSe	ppm	202	10	5.5	0.2	0	0.1	10	10
LgSn	ppm	11,835	27.5	17	0.7	0	0.01	5	5
LgSr	ppm	11,835	5	5	0.1	36.4	0.1	9.6	46
LgTe	ppm	202	10	4	1.7	0	1.8	10	10
LgTi	%	11,835	1	0.02	0.8	0	0.8	1	1
LgTl	ppm	202	10	4	0.8	0	0.6	10	10
LgU	ppm	133	10	7.5	0.3	0	0.1	10	10
LgV	ppm	11,968	32	1.5	0.5	70	0.3	10	80
LgW	ppm	11,968	5	6	0.2	0	0.06	5	5
LgY	ppm	11,965	5	5	0.2	3.4	0.06	4	7.4
LgZn	ppm	11,835	6	6	0.6	12	0.3	3	15
LgZr	ppm	11,598	5	5	0.2	4	0.08	3	7

n = number of samples; med = median; m = mean; σ = standard deviation; 25th = 1^{er} quartile; 75th = 3^{eme} quartile; nb = sample numbers; σ^2 = variance.

Table A12. Volumes of geochemical anomalies identified at the Kofi prospect.

Elements ¹	Cut-Off	Volume (in m ³)											Comments
		1	2	3	4	5	6	7	8	9	10	11	
B	>0.003	220,500	171,000	139,500	92,000	24,000	4500						Tourmalinization
Cu	>100	121,500	12,000	66,500	7000	4500	4000	2500	2000				Cu Anomaly
Na(%)	>0.3%	35,500	24,000	12,500	6500	5500	3500						Albitization
Hg	>5	403,000	121,000	42,000	2500	2500							Sulfides
Pb	>35	21,000	17,000	8000	6000	2000							Galena
Sb	>10	415,500	120,000	109,500	78,000	58,000	23,000	18,000	16,500	7000	5000	5000	Antimony
Zn	>25	214,500	37,000	34,000	9500	4500	4000	3000	2000				Sphalerite
Ag	>2	938,000	125,000	51,000	21,000	14,500	12,500	12,500	12,500	9500	9000		Silver zone
Ba	>500	31,000	17,000	2000									Barium

¹ Cut-off in g/t, excepted for Na in %.

Table A13. In situ gold (Au) reserves estimated by kriging at varying cut-off grades.

	Nb	Vol	Q _{ore}	Q _{met}	Q _{met}	Grade	Grade
(g/t)	blocs	(Mm ³)	(Mt)	(t)	(Moz)	(Au g/t)	(Au oz/t)
4	956	0.48	1.29	8.20	0.289	6.36	0.22
4.5	897	0.45	1.21	7.86	0.277	6.49	0.23
5	670	0.34	0.90	6.39	0.225	7.07	0.25
5.5	457	0.23	0.62	4.89	0.172	7.92	0.28
6	332	0.17	0.45	3.92	0.138	8.75	0.31
6.5	214	0.11	0.29	2.93	0.103	10.16	0.36
7	180	0.09	0.24	2.62	0.092	10.80	0.38
7.5	138	0.07	0.19	2.21	0.078	11.88	0.42
8	119	0.06	0.16	2.01	0.071	12.54	0.44
8.5	96	0.05	0.13	1.76	0.062	13.57	0.48
9	85	0.04	0.11	1.63	0.057	14.19	0.50
9.5	73	0.04	0.10	1.48	0.052	15.00	0.53
10	62	0.03	0.08	1.33	0.047	15.94	0.56
11	51	0.03	0.07	1.18	0.042	17.11	0.60
12	44	0.02	0.06	1.07	0.038	18.00	0.63
13	35	0.02	0.05	0.92	0.032	19.39	0.68
14	26	0.01	0.04	0.75	0.026	21.41	0.76
15	23	0.01	0.03	0.69	0.024	22.34	0.79

Table A14. In situ gold (Au) reserves estimated by Sequential Gaussian Simulation (SGS).

Cut-Off	Nb	Vol	Q _{ore}	Q _{met}	Q _{met}	Grade	Grade
(g/t)	blocs	(Mm ³)	(Mt)	(t)	(Moz)	(Au g/t)	(Au oz)
4	526	0.26	0.71	5.24	0.185	7.38	0.26
4.5	507	0.25	0.68	5.13	0.181	7.50	0.26
5	406	0.20	0.55	4.48	0.158	8.16	0.29
5.5	372	0.19	0.50	4.24	0.150	8.44	0.30
6	353	0.18	0.48	4.09	0.144	8.59	0.30
6.5	173	0.09	0.23	2.60	0.092	11.13	0.39
7	171	0.09	0.23	2.58	0.091	11.18	0.39
7.5	149	0.07	0.20	2.36	0.083	11.74	0.41
8	134	0.07	0.18	2.21	0.078	12.21	0.43
8.5	75	0.04	0.10	1.55	0.055	15.28	0.54
9	61	0.03	0.08	1.38	0.049	16.75	0.59
9.5	24	0.01	0.03	0.92	0.032	28.43	1.00
10	22	0.01	0.03	0.89	0.031	30.13	1.06
11	12	0.01	0.02	0.75	0.026	46.46	1.64
12	11	0.01	0.01	0.74	0.026	49.60	1.75
13	11	0.01	0.01	0.74	0.026	49.60	1.75
14	11	0.01	0.01	0.74	0.026	49.60	1.75
15	11	0.01	0.01	0.74	0.026	49.60	1.75

Table A15. In situ gold (Au) reserves estimated by Kriging.

	Orebody N°	1	2	3	4	5	6	7	8	9	Total
	Vol (m³)	266,000	71,500	44,500	26,000	24,500	22,000	9000	7000	2500	473,000
	Q _{met} (t)	2.873	0.772	0.481	0.281	0.265	0.238	0.097	0.076	0.027	5.110
	Q _{met} (oz)	101,344	27,232	16,967	9912	9348	8395	3422	2681	952	180,253
	Q _{ore} (t)	718,200	193,050	120,150	70,200	66,150	59,400	24,300	18,900	6750	1,277,100
2022	V _{met} (MUSD)	177.352	47.656	29.692	17.346	16.359	14.692	5.988	4.692	1.519	315.296
	PC (MUSD)	138.740	37.281	23.228	13.570	12.797	11.493	4.684	3.670	1.304	246.767
	Gain (MUSD)	38.612	10.375	6.464	3.777	3.562	3.199	1.304	1.021	0.215	68.529
2025	V _{met} (MUSD)	336.413	90.397	56.323	32.904	31.030	27.869	11.358	8.899	3.162	598.354
	PC (MUSD)	160.609	43.157	26.889	15.709	14.814	13.305	5.423	4.249	1.509	285.663
	Gain (MUSD)	175.805	47.240	29.433	17.195	16.216	14.564	5.936	4.651	1.652	312.691

Rock density: d = 2.7 g/cm³; Conversion: 1 oz = 28.1349 g; 2022: Gold price ¹: 1750 USD/oz; Operational costs (PC) = 1369 USD/oz; 2025: Gold price ²: 3320 USD/oz; Operational costs (PC) = 1585 USD/oz; Cut-off = 4 g/t; V_{met} = Metal value; Vol = Volume (m³); Q_{ore} = Ore quantity (t); Q_{met} = Metal quantity. ¹ Price as of August 2022. ² Price as of April 2025.

Table A16. Sixth-order polynomial coefficients fitting reserves, grade, and gains curves as a function of cut-off estimated by kriging.

a _i , i=	0	1	2	3	4	5	6	R²
Q _{Au} (t)	−0.0002	0.0142	−0.337	4.065	−26.039	81.476	−88.426	0.996
Au (g/t)	0.0026	−0.1002	1.333	−5.667	13.188	-	-	0.998
Gain 2022 (MUSD)	−0.0035	0.2048	−4.877	59.36	−384.76	1229	−1404	0.995
Gain 2025 (MUSD)	−0.0158	0.9326	−22.206	270.3	−1752	5594	−6392	0.995

Appendix B

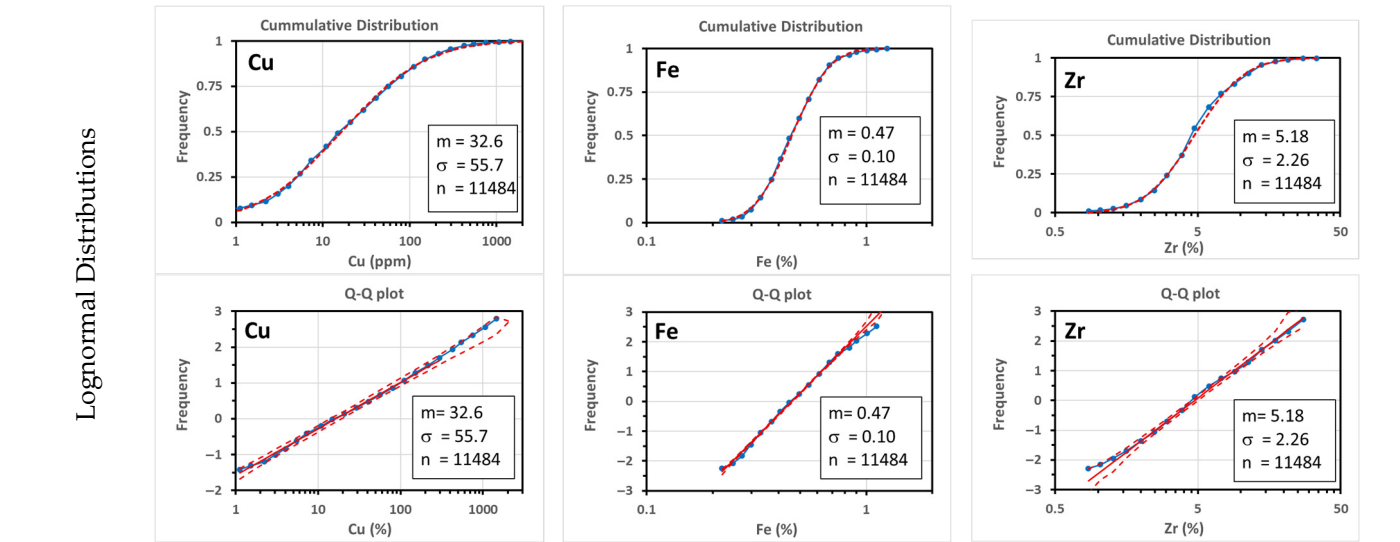


Figure A1. Cont.

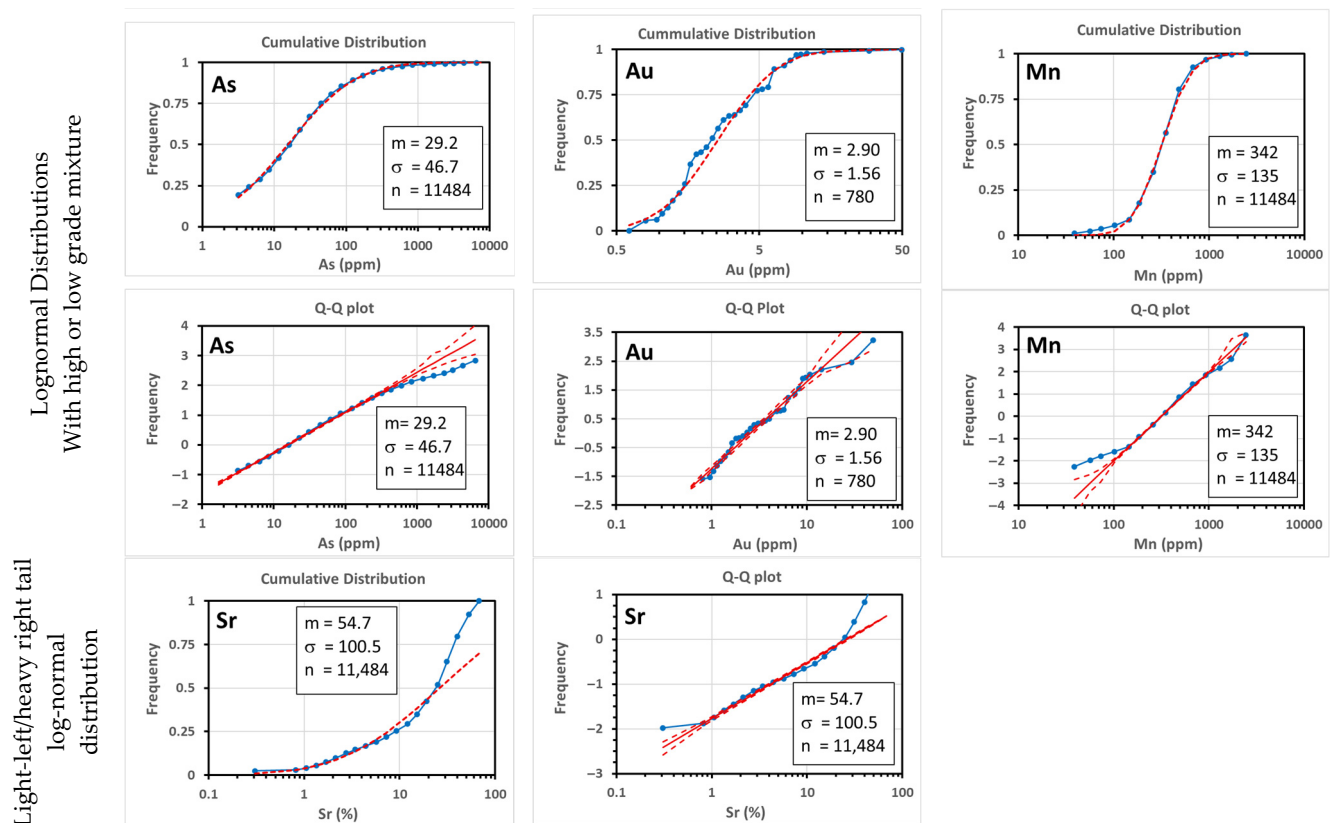


Figure A1. Cumulative and Q-Q plots of selected geochemical elements (blue dotted line) are fitted to their theoretical lognormal distributions (red solid line) with confidence bands (red dashed line). Some elements (e.g., Cu, Fe, Zr) show a near lognormal distribution, while others display a slight right tail (Au, As), a left tail (Mn), or both (Sr), suggesting mixed processes.

Appendix C

Appendix C.1 Regional Geological Settings

The West African Craton (WAC) consists of three main geological units [63]: (i) Archean (3.0–2.7 Ga) and Paleoproterozoic (2.0 Ga) terranes of the Reguibat Shield; (ii) the Kénéna–Man Archean domain and Birimian Paleoproterozoic formations of the Léo–Man Shield (named after the Birim River); and (iii) the Birimian Kédougou–Kéniéba inlier. The Precambrian Léo–Man and Reguibat Shields are separated by the Phanerozoic Taoudeni Basin [24]. In both shields, Archean terranes lie to the west and Paleoproterozoic terranes to the east [64].

Appendix C.1.1 Paleoproterozoic Domains

The WAC in the eastern Man Shield is composed of Paleoproterozoic Birimian formations [63,65,66]. This crust developed in two main geological periods [67] (Figure A2): (i) the lower Birimian (2.2–2.15 Ga), marked by the formation of greenstone belts and tonalite–trondhjemite–granodiorite (TTG) granitoids; and (ii) the Upper Birimian (2.15–1.9 Ga), characterized by the development of volcano-sedimentary basins and the emplacement of leucogranites. Previous studies [68–71] identified key features of these Paleoproterozoic domains. These features are: (i) juvenile crust with no Archean base-met; (ii) pluton emplacement under relatively low water content, with foliation resulting from detachment; (iii) limited crustal thickening, as indicated by the lack of high-grade metamorphic rock exhumation; (iv) regional metamorphism ranging from greenschist to amphibolite facies linked to intrusive events; and (v) an absence of migmatites, except in

the far southwest of West Africa. Similar features are observed in other Paleoproterozoic complexes, such as the Guyana Craton [72,73].

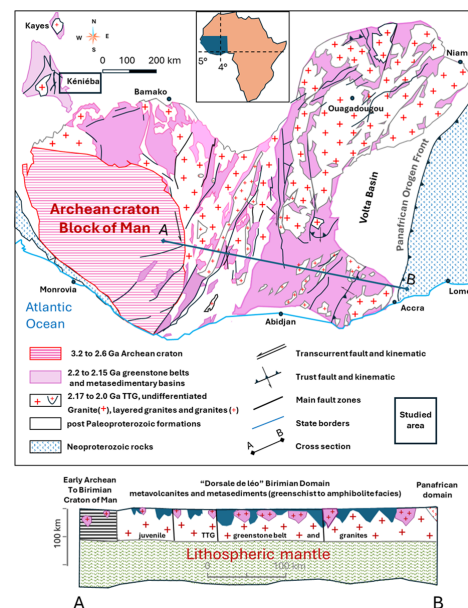


Figure A2. Map of the West African Craton with a synthetic cross-section (after [67]).

Appendix C.1.2 Geodynamic Context

The eastern Baoulé-Mossi domain, Reguibat Ridge, and the Kédougou–Kénédougou/Kayes inliers in Mali are primarily of Birimian age [63] (Figures A3 and A4). The Archean and Birimian terranes of West Africa were shaped by the Eburnean orogeny (2.13–1.98 Ga), which produced north–south oriented fault systems. Over 550 Ma ago, an intra-continental rift (the Rockelide Belt) cut across the Guyana and West African cratons, followed by a collision involving the eastern Guyana Craton, resulting in the overthrusting of Rockelide units onto the West African Craton [74]. Paleomagnetic evidence suggests the West African and Guyana cratons formed a single block around 2.02 Ga, later separating during the opening of the Atlantic Ocean [75].

The Birimian tectonic evolution involved three deformation phases: (i) D₁—a major collisional phase with west-northwest-directed thrusting and regional shortening, also observed in Guyana [68,72,73], along the margins of the Archean Man Block. D₁ reflects the progressive accretion of Paleoproterozoic rocks onto Archean crust, supported by paleomagnetic data [69]; (ii) D₂—characterized by sinistral shearing, folding, and granitic pluton emplacement. This phase shaped the structural framework of the Tarkwaian Basin [70]; (iii) D₃—a dextral shearing phase reflecting a shift to NE–SW convergence. D₂ and D₃ are often grouped [68,70]. D₂ also facilitated hydrothermal fluid circulation, resulting in stratiform gold mineralization [68,76,77]).

Two major orogenic events shaped the Precambrian West African Craton (WAC) [24]: (i) the Liberian orogeny (2.6–2.9 Ga), which affected Archean terranes in the Reguibat and Leo (Kénédougou–Man) ridges, and (ii) the Eburnean orogeny (2.2–1.6 Ga), which reactivated Birimian terranes across the Baoulé-Mossi domain including Guinea; southern Mali; Côte d’Ivoire; Ghana; Burkina Faso; Niger; and northern Togo. It also affected the Kayes and Kédougou–Kénédougou inliers and the eastern Reguibat Ridge (Yetti–Egla domain).

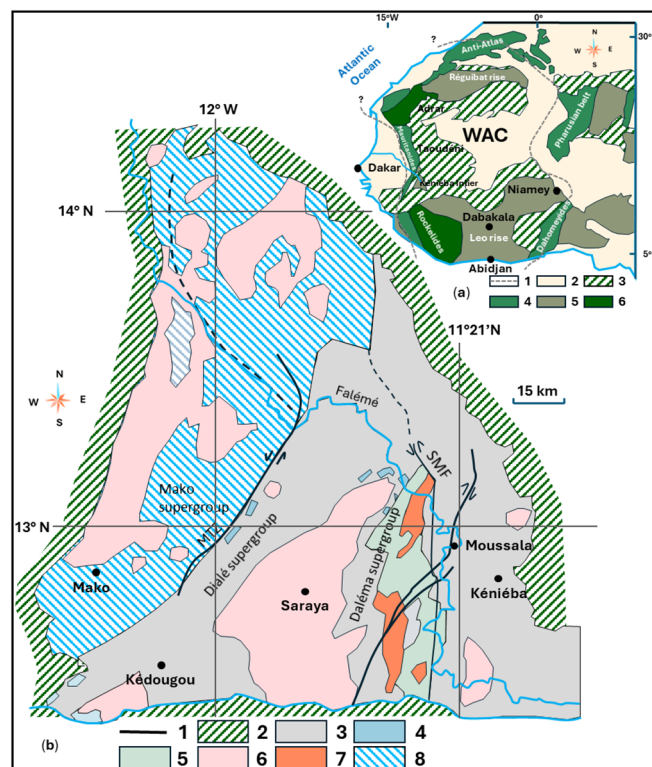


Figure A3. Location map of the Kédougou–Kéniéba Inlier within the West African Craton (upper right corner) (a) Schematic representation of major Precambrian inliers (simplified from [78]): (1) Boundaries of the West African Craton. (2) Post-Paleozoic cover. (3) Neoproterozoic and Paleozoic units. (4) Pan-African and Hercynian belts. (5) Lower Proterozoic. (6) Archean. (b) Simplified geological map of the West African Craton (modified from [23]). (main map) (1) Major D₂ shear zones. (2) Neoproterozoic and Paleozoic units. (3) Dialé and Daléma Supergroups. (4) Carbonate formations. (5) Calc-alkaline volcanic rocks. (6) Saraya and Badon-Kakadian batholiths. (7) Boboti clinopyroxene-bearing granitoid. (8) Mako Supergroup.

Appendix C.1.3 Lithostratigraphy

From bottom to top, the Birimian sequence comprises metavolcanic rocks and metasediments deposited synchronously [19,79–81]. Sm/Nd geochronology suggests the metasediments formed from the pene-contemporaneous erosion of the metavolcanic rocks [19]. Two dating methods yielded consistent ages for the metasediments: 2152 ± 6 Ma (U-Pb zircon dating) and 2155 ± 9 Ma (Sm/Nd zircon dating) [82]. Similar ages have been reported in the Kumasi Basin, northwest of the Ashanti Belt in Ghana [83].

According to Adadey et al. [90], the Birimian is subdivided into two groups: (i) the Sefwi Group (2195–2170 Ma), composed of mica schists (mainly quartz-muscovite-biotite, with rare garnet) and metavolcanic rocks; and (ii) the Kumasi Group, deposited after 2150 Ma, consisting of metasediments interbedded with andesitic layers dated at 2142 ± 24 Ma (U-Pb zircon dating) and intruded by the Suhuma granodiorites, dated at 2136 ± 19 Ma (U-Pb zircon dating) [90]. The Kumasi Group also includes metasediments, volcanic rocks, and locally graphite-rich phyllites. The formation of the Gondwana supercontinent began with the Eburnean convergence of the Guyana and West African Cratons, marking the onset of the Birimian tectonic evolution of the West African Craton.

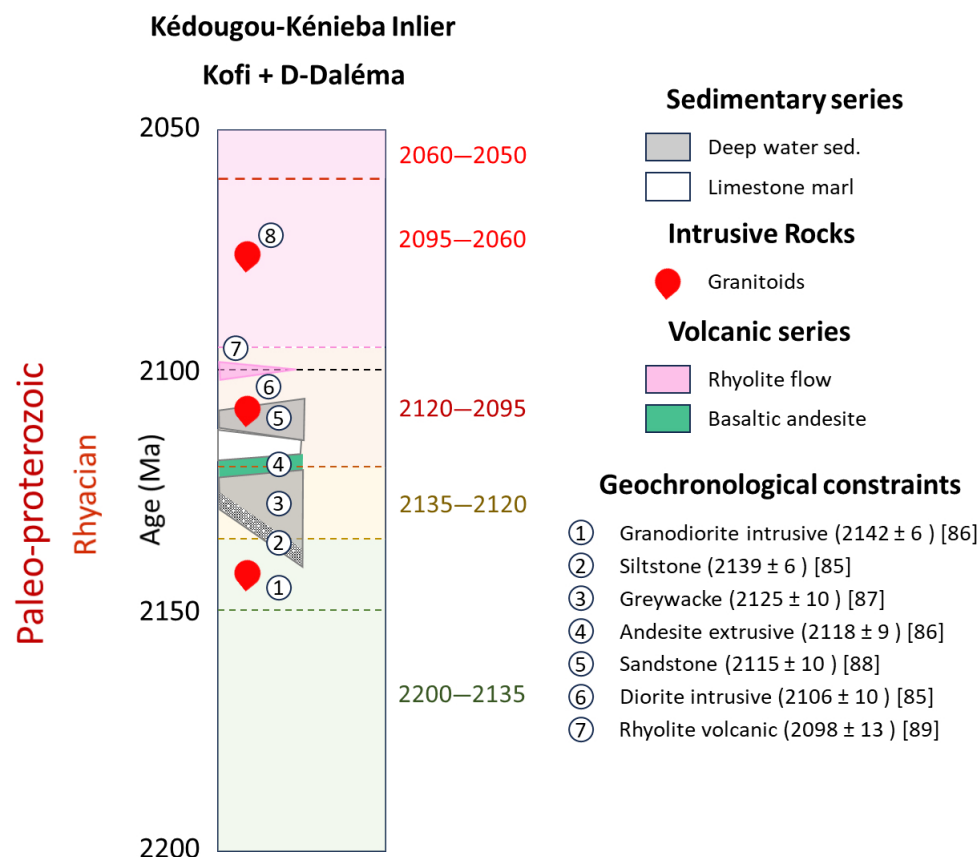


Figure A4. Schematic stratigraphic evolution (modified from [84–89]) of the Kédougou–Kénieba Inlier at Kofi (Mali) and the Dialé–Daléma Series (Senegal), illustrating geosynclinal development. The sequence begins with volcanic intrusions, followed by clastic sedimentation interbedded with volcanoclastic rocks, overlain by limestone and sandstone, and locally capped by fluvio-deltaic deposits. It ends with diorite and rhyolite intrusions [87]. Background colors represent a time-slice stratigraphic framework for Paleoproterozoic units, with age intervals shown to the right of the column.

The initial geosynclinal evolution model proposed for the Birimian formations of the WAC, particularly in Senegal [91,92] and Mali, suggested an early emplacement of volcanic rocks followed by the deposition of clastic sediments. This interpretation was primarily based on structural evidence. Milési et al. [65] and Ledru et al. [66] identified a lower Birimian flysch-type unit (B_1), the Kofi and Dialé–Daléma series, affected by three main Eburnean tectono-metamorphic phases (D_1 to D_3), overlain by an upper volcanic unit (B_2) with intercalated fluvio-deltaic deposits, affected only by the latter two phases (D_2 – D_3) [91].

However, recent geochronological data have challenged this model. U–Pb dating of detrital zircon grains from the Kofi metasedimentary series constrains the maximum depositional age to between 2115 and 2098 Ma [65,88,91] (Figure A2). In Senegal, new U–Pb ages [89], combined with magnetic and gravimetric analyses, suggest that the volcanic Mako Belt predates the Dialé–Daléma metasedimentary series, which records D_1 and D_3 structures [93–95], contradicting the model proposed by Ledru et al. [66].

Appendix C.1.4 Gold Mineralization of the West African Craton

The majority of gold deposits in West Africa are located within greenstone belts [64], which are regionally metamorphosed to greenschist and amphibolite facies around granitoid intrusions [96].

The host rocks of gold deposits vary by location and are generally classified into three main lithological series: Mako, Kéniébandi, and Kofi [97]. These series have the following characteristics: (i) The Dialé–Daléma Series (Paleoproterozoic) consists of folded sandstones, metagraywackes, siltstones (metapelites), and metacarbonates intercalated with calc-alkaline volcanic units [97,98]. They are considered the youngest series. (ii) The Mako Series comprises siliciclastic rocks containing detrital zircons [21,98]. (iii) The Falémé Series, bounded to the east by the Kédougou–Kéniéba Inlier, includes rare sedimentary rocks, basalts, and minor andesites and rhyolites [13,24,97,99].

Gold mineralization broadly coincides with major magmatic and tectonic events [13,68–70]. Goldfarb et al. [1] identified seven global peaks in gold deposit formation in the following eras: (i) Mesoarchean (15 Moz), (ii) Neorchaean (740 Moz), (iii) Paleoproterozoic (300 Moz), (iv) Meso-/Neoproterozoic (140 Moz), (v) Paleozoic (470 Moz), (vi) Mesozoic (460 Moz), and (vii) Cenozoic (380 Moz). In West Africa, most gold deposits are Paleoproterozoic in age.

Mineralization Related to Magmatic Accretion

Mineralization associated with magmatic accretion is observed at the Loulo deposit (Mali) and is attributed to the Eburnean orogeny, likely around 2072 ± 7 Ma ($^{207}\text{Pb}/^{206}\text{Pb}$ zircon age from crosscutting dolerite dikes [65]) and 2098 ± 11 Ma (minimum detrital U-Pb zircon age from tourmalinized sandstones [22]). According to previous works [13,69,99], this mineralization developed during tectonic extension of sedimentary basins, driven by hydrothermal fluid circulation through fractures and surrounding rocks. A syngenetic tourmaline-gold event likely occurred during this period.

Mineralization Related to Tectonic Accretion

Tectonic accretion-related mineralization, dated between 1945 and 2080 Ma [70], represents the most economically significant gold phase in West Africa. These gold occurrences are discordant and linked to brittle deformation during the late D₂ and D₃ orogenic phases [77]. Hydrothermal events, driven by plutonism (~2105 Ma) and metamorphism, facilitated fluid migration along faults and fractures, concentrating minerals in structural traps [64,76]. The resulting disseminated arsenopyrite-rich gold mineralization is often crosscut by quartz veins containing native gold. In the lower Birimian (B1), quartz and carbonate-hosted mineralization is also found at the Syama mine in Mali [100], typically associated with tholeiitic volcanic rocks.

Appendix C.1.5 Classification of Gold Deposits in West Africa

Numerous studies have investigated the characterization of West African gold deposits. Milési et al. [79] classified them into three types: (i) Type 1—*Pre-orogenic* deposits: stratiform types associated with extensional settings [65]; (ii) Type 2—*Syn-orogenic* deposits (combining former Types 2 and 3 of Milési et al. [65]): including disseminated gold-sulfide mineralization in metavolcanics and metadiorites, as well as paleo-placer gold in the Tarkwaian conglomerates, formed during extensional phases; (iii) Type 3—*Post-orogenic* deposits: discordant mesothermal gold mineralization, representing the most economically significant type.

This classification was later simplified in the context of Ghana into two main types [76,80]: (i) Type 1: disseminated sulfide or gold-sulfide ores; (ii) Type 2: gold-bearing quartz veins. Type 2 deposits, characterized by quartz veining, generally offer better economic prospects than Type 1 due to (i) structurally controlled hydrothermal mineralization contemporaneous with the Eburnean tectono-thermal event (~2.0 Ga) [64,76], and (ii) the

potential coexistence of both types in the same field, as observed at Loulo (Mali) and Inata (Burkina Faso).

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