The Kulumadau Epithermal Breccia-hosted Gold Deposit, Woodlark Island, Papua New Guinea

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ABSTRACT

The Kulumadau deposit represents an intermediate-sulfidation epithermal gold deposit (3.8 Mt at 2.3 g/t, Ag:Au = 1). Mineralisation is primarily confined to hydrothermal breccias within pre-existing fault zones, where it is disseminated throughout a hydrothermal matrix comprising chlorite-quartz-adularia-illite-I/S clays-calcite-pyrite. The host sequence represents numerous mid-Miocene pyroclastic flow eruptions within a tectonically active emergent shallow marine to subaerial depositional setting. Subsequent growth faulting was responsible for debris avalanches, which were subsequently cut by reverse faults. Faults were exploited by hydrothermal fluids, with the heightened porosity at the juncture between faults and debris material facilitating boiling of the ore constituents. Fluid inclusion studies suggest that fluid mixing between meteoric fluids and magmatic fluids, accompanied by boiling, were the primary mechanisms for gold deposition. The occurrence of anhydrite/gypsum as late-stage veins and their sulfur and oxygen isotopic values indicate post-mineralisation mixing of sea water with hydrothermal fluids.

INTRODUCTION

The Kulumadau deposit (3.8 Mt at 2.3 g/t, Ag:Au = 1) is an intermediate-sulfidation epithermal deposit located on Woodlark Island, which is on the Woodlark Rise, 600 km east of Port Moresby, Papua New Guinea (Figure 1). Mineralisation at Kulumadau is almost completely restricted to hydrothermal breccias contained within fault zones and is unusual in that it has an extremely low gold-silver ratio.

There have been few detailed studies to understand the host sequences or develop metallogenic models for the various epithermal deposits. For the most part, historical mapping

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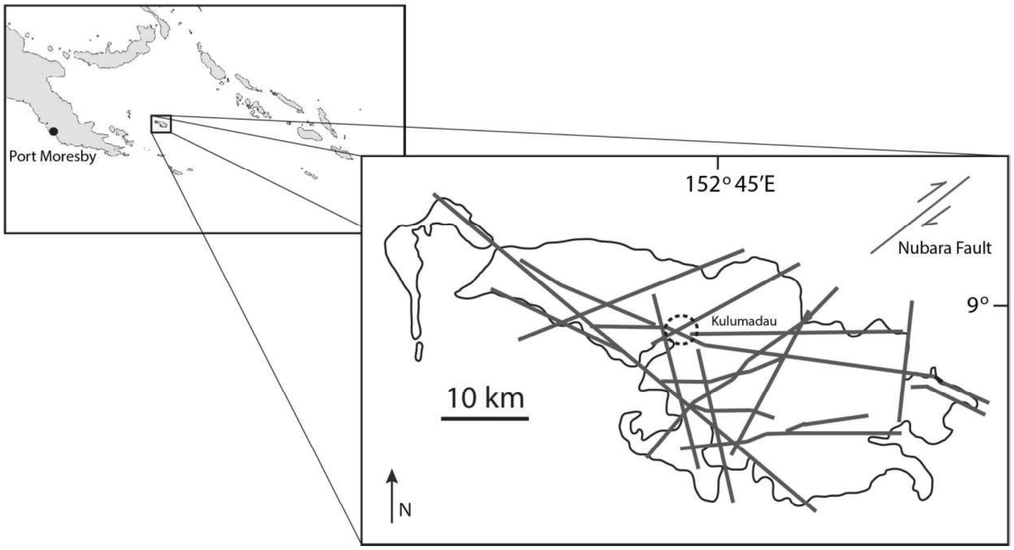


FIG 1 – Location map for the Kulumadau epithermal gold deposit and main structures on Woodlark Island, Papua New Guinea (after Lennox, 2009).

has been hindered by a lack of outcrop due to overlying younger sediments and extensive jungle cover. The regional geology has been generally mapped and classified by numerous authors (Stanley, 1912; Trail, 1967; McGee, 1978; Ashley and Flood, 1981; Russell and Finlayson, 1987; Joseph and Finlayson, 1991; Lindley, 1994).

Recently, studies were undertaken by UNSW honours students Nicholls (2009), Frey (2010) and Lau (2012) focusing on the petrology and mineralisation within the mid-Miocene Okiduse Volcanics. The current study involved detailed core-logging of over 8000 m of diamond drill core from the Kulumadau deposit in conjunction with detailed whole rock and isotope geochemical studies. This extended abstract focuses on the volcanic, structural and fluid evolution, which has been used as a basis for developing the first detailed metallogenic model for the Kulumadau deposit.

GEOLOGICAL SETTING

Regional geology

The calc-alkaline andesitic volcanic/subvolcanic rocks of the Okiduse Volcanics (13 Ma) are related to Maramuni magmatism, which is associated with the opening of the Woodlark Basin. The Okiduse Volcanics host the known primary gold mineralisation on Woodlark (Ashley and Flood, 1981). They are unconformably overlain by Quaternary-Pleistocene sediments of the Kiriwina Formation, which cover ~85 per cent of the island (Spencer, 2011).

The opening of the Woodlark Basin is also responsible for a large NE-trending dextral, strike-slip fault (Nubara Fault) to the NE of Woodlark Island (Johnson, Mackenzie and Smith, 1978; Ashley and Flood, 1981; Kington and Goodliffe, 2008). Structural analysis by Lennox (2009) and reinterpretation by this study suggests an early WNW faulting (11.6 Ma) event at Kulumadau. This is subsequently cut by a slightly younger NE-trending dextral fault, mimicking the orientation and sense of direction of the Nubara Fault. Subsequent to this, a pre-Quaternary NW-trending fault set has been dated at 11.5 Ma. Field mapping has identified a post-Quaternary NE-trending thrust faulting with >6 m of throw.

Deposit-scale geology

The host succession

The host succession comprises four primary andesitic volcaniclastic lithofacies (Units 1–4) along with two hydrothermally-cemented breccia lithofacies (Units 5–6). These include (from oldest to youngest):

- Unit 1: pyroxene-bearing, plagioclase-rich tuff
- Unit 2: lower hornblende-bearing plagioclase-rich tuff and its epiclastic equivalent
- Unit 3: upper hornblende-bearing plagioclase-rich tuff
- Unit 4: polymictic, matrix-supported breccia
- Unit 5: polymictic, chlorite-quartz-adularia-illite-I/S clays-calcite-pyrite±galena±sphalerite ±chalcopyrite cemented breccia
- Unit 6: monomictic, quartz-carbonate±base metal sulfide cemented breccia.

Table 1 provides a summary of the different units, their components, lithofacies and interpretation. A simplified plan view geological map and cross-section are provided in Figures 2 and 3 respectively.

As the primary volcanic units of the host succession are almost completely restricted to pyroclastic flow and debris avalanche deposits, Kulumadau is assumed to be situated within the ring-forming association of the palaeovolcanic environment (Davidson and De Silva, 2000). The pyroclastic units are all co-magmatic, as suggested by REE diagrams, and show a clear fractionation trend from Unit 1 up through Units 2 and 3. Regional mapping suggests that the volcanic source lies to the east of the deposit.

Drilling has identified only the western, eastern and northern boundaries of the debris avalanche deposit (Unit 4), all of which are separated from adjacent tuffs by fault zones characterised by the polymictic hydrothermally-cemented breccias of Unit 5. These

TABLE 1

Petrographic descriptions of the main rock types of the Kulumadau deposit.

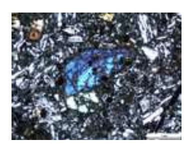
Unit	Facies	Components	Lithofacies	Interpretation	Photo
Unit 1	Pyroxene-bearing plagioclase-rich tuff	*Crystals:* 35% twinned and occasionally zoned plagioclase (0.8–1.2 mm), 5% pyroxene (0.5–1.2 mm) and <1% magnetite (1.2 mm) *Matrix:* 60% ash-sized fragments and plagioclase (100 μm)	• Massive • Poorly-sorted • Rare graded-bedding (10–30 mm) • Matrix-supported	Volcaniclastic facies: pyroclastic flow with rare ash-fall deposits evidenced by thin graded beds	
Unit 2	Lower hornblende-bearing plagioclase-rich tuff	*Crystals:* 40% twinned and commonly zoned plagioclase (1.5–3 mm), 5% basaltic hornblende (2 mm) and <1% pyroxene (1.5 mm) *Clasts:* Rare accidental lithics of Unit 1 (5 mm–7 m) *Matrix:* 55% ash-sized material and plagioclase (150 μm)	• Massive • Poorly-sorted • Matrix-supported • Individual beds within this unit often scour out pre-existing beds	Volcaniclastic facies: pyroclastic flow with new eruptions eroding the tops of prior flows	

TABLE 1 cont …

Unit 3	Upper hornblende-bearing plagioclase-rich tuff	*Crystals:* 45% twinned and commonly zoned plagioclase (1.5–3 mm), 3% basaltic hornblende and <1% pyroxene *Clasts:* Rare accidental lithics of Unit 1 (5 mm – 7 m) *Matrix:* 52% ash-sized material and plagioclase	• Massive • Poorly-sorted • Matrix-supported • Individual beds within this unit often scour out pre-existing beds • Rare low-angle cross-beds	Volcaniclastic facies: pyroclastic flow with new eruptions eroding the tops of prior flows. Rare base-surge deposits	
Unit 4	Polymictic, mud-matrix supported breccia	*Clasts:* 20% Unit 1 (20 mm–50 m) and 20% Unit 2 (3 mm–15 m) *Matrix:* 55% ash-sized fragments, 45% broken plagioclase crystals commonly zoned (1.5–3 mm) and <1% hornblende (1.5 mm)	• Clasts are rounded to well-rounded • Moderate to very poorly-sorted • Matrix-supported • Occurs adjacent to steeply dipping (~60–70°) fault	Volcanogenic sedimentary facies: debris avalanche deposit related to growth faulting. Matrix primarily composed of Unit 2 with blocks and megablocks of Units 1 and 2	
Unit 5	Polymictic chlorite-quartz-adularia-illite-I/S clays-calcite-pyritecemented breccia	*Clasts:* 70% wall rock (Units 1–3; 10–50 mm) *Matrix:* 25% chlorite, 24% quartz, 18% adularia, 12% illite, 8% intrastratified clays (corrensite), 4% calcite and 4% pyrite	• Clasts are rounded to well-rounded • Very poorly-sorted • Matrix-supported • Matrix is poorly consolidated	Hydrothermal facies: upward migrating magmatic fluids fracturing, rotating and altering country rock	
Unit 6	Monomictic quartz-carbonate ± base metal sulfide cemented breccia	*Clasts:* 70% wall rock (Units 1–3) *Matrix:* 60% quartz, 35% carbonate, 18% ± galena ± sphalerite ± chalcopyrite ± gold	• Clasts are angular to subangular • Monomictic jigsaw-fit breccia transitioning to stringer veins of the same composition	Hydrothermal facies: hydraulic brecciation grading into veinlets	

hydrothermally-cemented breccias host the bulk of mineralisation at Kulumadau. Lesser yet appreciable resources are also contained within hydrothermal jigsaw fit breccias and veins (Unit 6) that are patchy and irregular in distribution. The fault zones to the west and east both dip ~60–70° to the east and are known as the Kulumadau West and Kulumadau East lodes respectively (Figure 2). The fault zone to the north dips towards the south-west at 60° and is referred to as the Adelaide Lode (Figure 2). The fault zones to the west and north (Adelaide Lode) appear to be normal faults, while the fault to the east shows evidence of reverse faulting.

Blocks and megablocks of Units 1 and 3 are abundant within the breccias of Unit 4. Petrographic and geochemical analyses indicate that the matrix of polymictic breccias from Unit 4 is of the same composition as the upper hornblende-bearing tuff (Unit 3).

Alteration and mineralisation

Due to the poorly consolidated nature of the polymictic cemented breccia facies (Unit 5), the determination of a paragenetic sequence for the ore constituents has been limited to

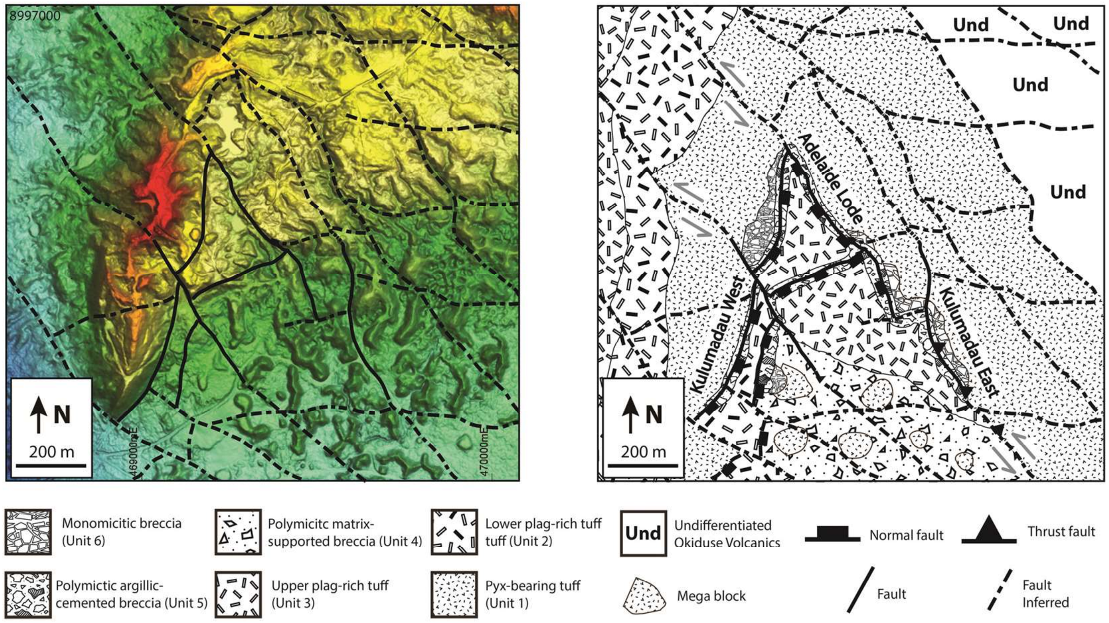


FIG 2 – Maps of the Kulumadau deposit: (A) structural interpretation of LiDAR data after core-logging and field mapping, and (B) geology, with the Kiriwina Formation removed. Key: plag – plagioclase; pyx – pyroxene.

petrographic studies of the monomictic breccias (Unit 6). The paragenetic sequence appears to be: pyrite → chalcopyrite-sphalerite-pyrite → galena-gold → gold.

Alteration zones vary both vertically and laterally throughout the deposit. Petrographic studies, detailed diamond drill core logging and whole-rock X-ray diffraction (XRD) were used to identify alteration assemblages, and Siroquant software was used to quantify mineral assemblages from XRD traces. X-ray fluorescence (XRF) was used to quantify changes in major element geochemistry and verify mineral percentage estimates from Siroquant. Sulfur and oxygen isotopes were used to help constrain the fluid origin for the sulfates.

The distribution of alteration assemblages throughout the Kulumadau deposit are illustrated in Figure 3b. With the exception of the chlorite±hematite assemblage, all alteration zones contain chlorite and quartz in similar quantities and therefore, for simplicity, they have been omitted from Figure 3b. Patchy zones of gypsum-anhydrite flooding (veins up to 1 m wide) occur at the margins of the Kulumadau West and East lodes. The range in sulfur and oxygen isotope values suggest that their origin is due to mixing of hydrothermal fluids and sea water ($\delta^{34}S$ 9.8–20.2 and $\delta^{18}O$ 10.6–13.9). Gypsum appears to be pseudomorphous after anhydrite, suggesting subsequent hydration in the volcanic pile.

Siroquant analysis shows increasing calcite in the footwall with proximity to ore-bearing faults and exhibits a sharp decrease in the hanging wall with distance from ore. Monomictic breccias of Unit 6 exhibit the highest gold grades at the juncture of hematite-bearing and adularia±illite-bearing assemblages, suggesting fluid mixing could be a potentially important mechanism for gold deposition. This mechanism is supported by preliminary fluid inclusion studies, which show that salinities are indicative of mixing between hydrothermal and meteoric fluids.

VOLCANIC AND HYDROTHERMAL EVOLUTION OF THE KULUMADAU DEPOSIT

Pyroclastic eruptions to the east of Kulumadau at ca 13 Ma resulted in the deposition of pyroxene-bearing, plagioclase-rich pyroclastic flows. These appear to have been deposited

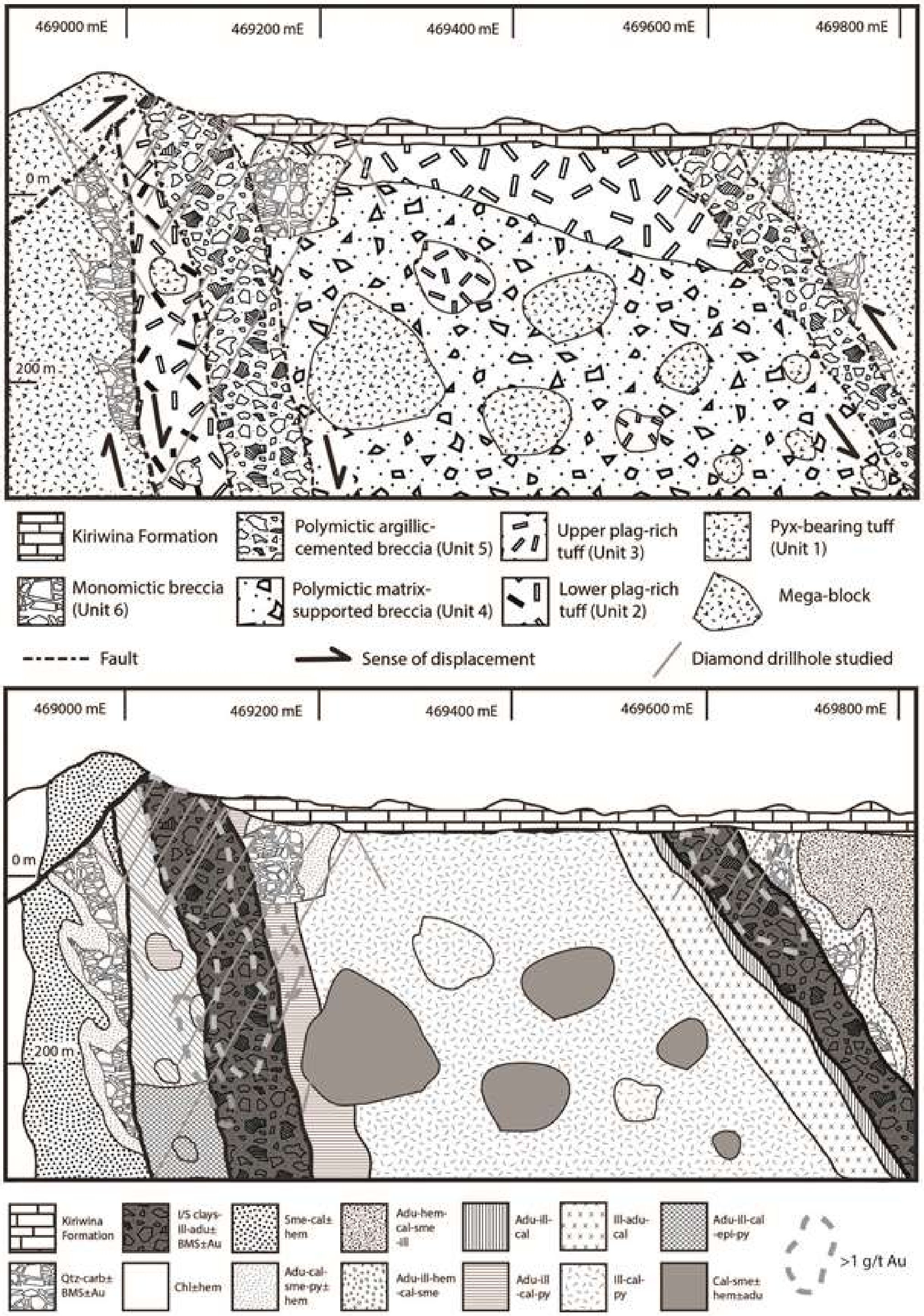


FIG 3 – Cross-section 8995875 through the Kulumadau deposit: (A) geology and (B) alteration model. All alteration zones contain chlorite and quartz in similar quantities and therefore, for simplicity, they have been omitted from Figure 3b. Key to alteration minerals: adu – adularia; BMS – base-metal sulfides (ie sphalerite-galena-chalcopyrite); cal – calcite; carb – carbonate; chl – chlorite; epi – epidote; hem – hematite; ill – illite; I/S – illite-smectite; py – pyrite; qtz – quartz; sme – smectite.

in a shallow marine to emergent setting. As the magma chamber evolved, more fractionated hornblende-bearing, plagioclase-rich tuffs were erupted (Figure 4a). Shortly after, with further opening of the Woodlark Basin to the south, NE-trending dextral faults cut the stratigraphy, resulting in debris avalanches (approximately 11.5 Ma; Figure 4b).

Subsequent reverse faulting pushed pyroxene-bearing tuffs in the east of the deposit over debris avalanche deposits (Figure 4c). This was followed by a phase of relaxation relatively soon afterwards (<1 Ma) in which hydrothermal fluids exploited and deposited ore constituents within pre-existing fault zones (Figure 4d). Fluid flow was greatest along faults adjacent to debris avalanches due to their inherent porosity. This heightened porosity facilitated boiling of the ore-forming fluid within fault zones (as evidenced by bladed adularia). Mineralising fluids also hydraulically fractured less porous, pyroxene-bearing, plagioclase-rich tuffs in the wall rocks and in megablocks within the debris avalanches.

Later sea water infiltration into the hydrothermal system resulted in deposition of anhydrite at the margins due to mixing of sea water with hydrothermal fluids. As hydrothermal activity waned, sea water infiltrated to deeper portions of the deposit resulting in more $\delta^{34}S$- and $\delta^{16}O$-enriched anhydrite.

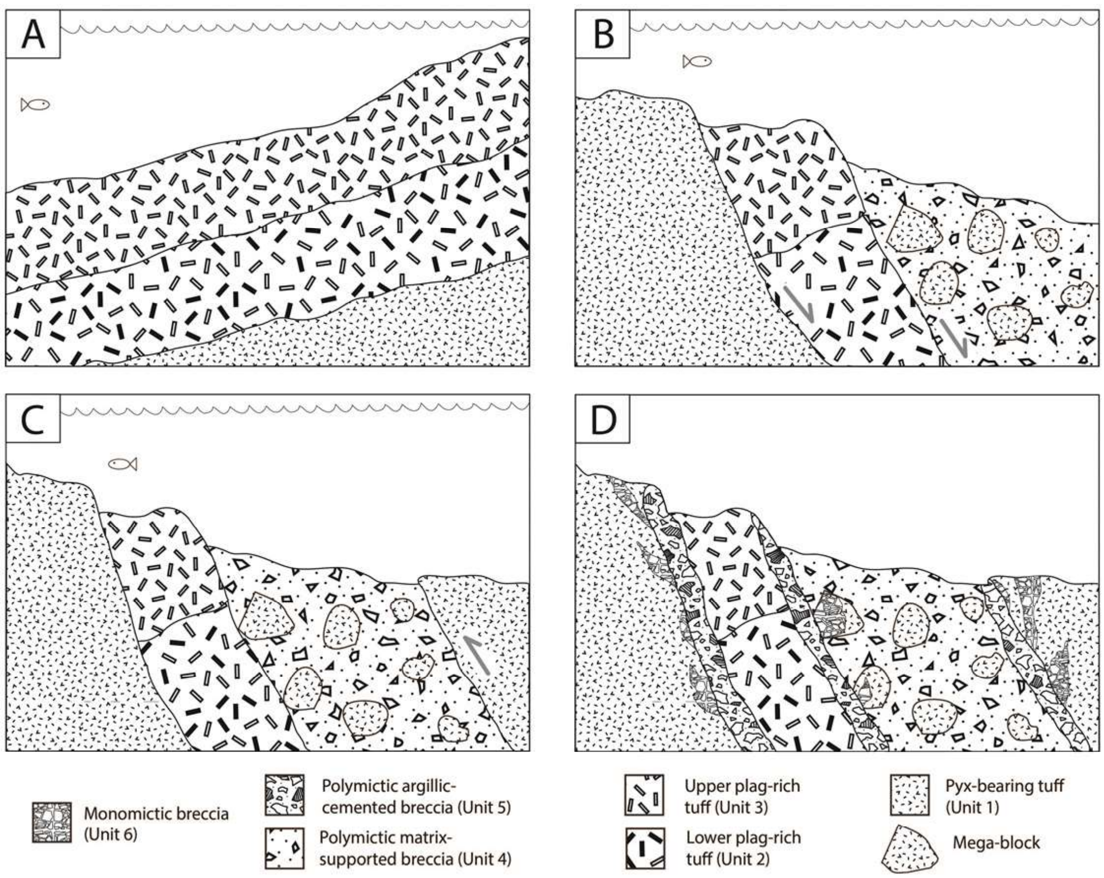


FIG 4 – Ore genesis model for the Kulumadau gold deposit: (A) pyroclastic flows deposited in a submarine to emergent setting; (B) normal faulting responsible for debris avalanches; (C) reverse faulting in the west, which pushed the pyroxene-bearing tuffs over the debris avalanche deposits; and (D) period of relaxation that allowed hydrothermal fluids to exploit pre-existing fault zones and deposit ore constituents in a subaerial environment.

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