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Formation of epizonal gold mineralization within the Latimojong Metamorphic Complex, Sulawesi, Indonesia: Evidence from mineralogy, fluid inclusions and Raman spectroscopy

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ABSTRACT

The gold deposits within the Latimojong Metamorphic Complex of Sulawesi, Indonesia, including Awak Mas and Salu Bulo, are estimated to host 50 tonnes Au with an average grade of 1.41 g/t. They are located within the metamorphic basement consisting of pumpellyite- to greenschist-facies metasedimentary and metavolcanic rocks, where gold precipitated in quartz veins that fill north-south striking normal faults and extensional fractures. The mineral assemblage is dominated by pyrite, chalcopyrite, galena, minor tetrahedrite-tennantite and sphalerite; gold is electrum with a low silver content (Au:Ag ratio of 8.5 to 9.1). Albite, dolomite-ankerite, siderite, chlorite, and white mica are the main alteration minerals. Quartz, albite and carbonate veins hosting H_2O-bearing fluid inclusions with minor aqueous-carbonic phases ($CO_2 \pm N_2$) were detected (mole fraction < 0.15). Raman microspectroscopy, microthermometry, and crush leach analysis of gold-bearing quartz veins and associated host rocks provide evidence for processes resembling those described for epizonal gold mineralization. The gold bearing fluids have salinities between 1.4 and 7.3 eq. mass% NaCl and were trapped in quartz at about 180–250 °C and < 1.27 kbar, corresponding to depths less than 5 km. Trapping conditions of barren veins are about 190–390 °C and < 1.15 kbar with salinities ranging from 2.2 and 6.1 eq. mass% NaCl. Halogen and alkali ratios (Na/Cl/Br/I) from crush leach analyses correspond to deposits originating from metamorphic fluids with a strong albitization signature during ore formation. Isothermal decompression during the retrogression stage mobilized large volumes of fluids, leading to significant gold mineralization within the Awak Mas District.

1. Introduction

The Cretaceous Latimojong Metamorphic Complex (LMC) of Sulawesi, Indonesia, is host to several gold deposits. These include the Awak Mas, Salu Bullo, Tarra, and other satellite prospects (collectively referred to as the Awak Mas District, Querubin and Walters, 2012), with total indicated and inferred resources of 38.4 Mt at 1.41 g/t Au (Cube, 2017). There have been numerous models for the origin of the Awak Mas District, including orogenic gold deposit models (Hakim, 2017; Hakim et al., 2017; Hakim and Melcher, 2017b, 2016b, 2015; Harjanto, 2017; Harjanto et al., 2016a,b; Harjanto et al., 2015; Querubin and Walters, 2012; Tuakia et al., 2016). Several authors also invoked the role of intrusions and suggested a genetic model for intrusion-related gold deposits (Archibald et al., 1996; Meyer, 2016; van Leeuwen and Pieters, 2011). The most recent feasibility study also considered a high level, low-sulphidation epithermal system (Cube, 2017). Despite the fact that a number of studies have been undertaken in the Awak Mas District, many questions remain unanswered. These include the role of fluids in gold precipitation, the metamorphic history, the genetic model and timing of mineralization.

Raman spectroscopy is an effective method to calculate the evolution of carbonaceous material (CM) during regional metamorphism (Beyssac et al., 2002; Lünsdorf, 2015; Rantitsch et al., 2004). During metamorphism, CM transforms to anthracite, meta-anthracite, semi-graphite and graphite (Kwiecińska and Petersen, 2004; Rantitsch et al., 2016). Such materials are commonly associated with gold deposits in metamorphic basement, i.e. the Otago-Alpine Schists and the Macraes orogenic gold deposits, New Zealand (Craw and MacKenzie, 2016; Hu et al., 2015; Pitcairn et al., 2005) and the Suurikuusikko gold deposit-Kittilä, Northern Finland (Wyche et al., 2015). The presence of CM in

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organic-matter (OM)-rich shales can contribute to the sequestration of metals during sediment dewatering and ore deposition, because CM act as sources for metals during subsequent metamorphic processes (Hu et al., 2015; Large et al., 2011). Alternatively, CM may also form from hydrothermal fluids containing volatile organic compounds during gold deposit formation (Craw, 2002; Gu et al., 2012). However, links between Raman spectra of carbonaceous material, pressure-temperature-depth estimation and the gold mineralization processes have received less attention.

It is the aim of this paper to use a combination of Raman and petrographic analysis to document the metamorphic temperature-pressure evolution within the LMC. We present results of a detailed investigation of the ore-related mineral assemblages and the fluid inclusion data characterizing the fluids involved in ore precipitation. Crush leach analysis of quartz, carbonate and electron microprobe analysis of chlorite and mica provide an insight into the physical and chemical factors controlling the ore-forming processes. The objectives of this paper are (i) to trace the origin of ore-forming fluids, (ii) to construct a genetic model for the development of gold mineralization, and (iii) to reconstruct the metamorphic and post-metamorphic *P-T* path of the ore-hosting formation.

2. Geological setting

The Latimojong Metamorphic Complex (LMC, Fig. 1) is situated in the Western Sulawesi arc, as part of a Late Cretaceous accretionary complex (van Leeuwen and Muhardjo, 2005; Wakita, 2000; White et al., 2017). It consists of moderately to strongly folded metamorphic rocks (phyllite, chlorite schist, metasandstone), tectonically mixed with volcanic rocks (metamafic, volcaniclastic rocks) (Fig. 1b-c). Limited paleontological and radiometric data and comparison with the Bantimala and Barru metamorphic complexes (South Sulawesi) suggest that the sedimentary protoliths of the LMC formed in the Early Cretaceous and accreted to the Sundaland margin in the mid-Cretaceous (White et al., 2017), when the complex was deformed, underwent partly high-pressure metamorphism and became uplifted above sea level before the Eocene (Bergman et al., 1996; Parkinson, 1998; White et al., 2017).

Electron microprobe analyses of clinopyroxene and chromian spinel phenocrysts hosted by metamafic and metatuffite in the LMC and whole rock analyses by XRF and ICP-MS indicate a strong island-arc basalt affinity (Hakim, 2017). In multi-element spider diagrams, these mafic metavolcanic rocks show an extreme enrichment of Pb, Large Ion Lithophile Elements (LILE, i.e. Cs, Rb, Ba) with respect to High Field Strength Elements (HFSE, including Nb, Ta, Ti, P), Light REE (LREE, i.e. La, Ce, …) and Heavy REE (HREE, i.e., Yb, Lu, …). The protolith of these rocks appears to be equivalent to eclogites and blueschists of Bantimala, South Sulawesi, part of the thicker-crust environments (Oceanic Island Basalt-OIB or Island Arc Basalt-IAB) that were subducted under the southeast margin of Sundaland Craton (Maulana et al., 2013; Parkinson et al., 1998; Wakita et al., 1996).

The topography in the Awak Mas District is moderately to extremely rugged, ranging from 800 to 1400 m above sea level. The highest level in close proximity to the area of Awak Mas is the summit of Mount Rantemario (3478 m above sea level) on the Western margin of the project area. Slope gradients are steepest within the southern to western portions grading to moderate towards the northern and eastern sections. Dense primary forest exists in the northern region and is generally less accessible in regions of higher elevation. Major drainage systems are Salu Siwa, Salu Lombok, and Salu Tolobo. The Salu Siwa is the most dominant river and forms a north-south trending valley that appears to coincide with a major suture zone dividing the Eastern Latimojong sequence from the Lamasi Complex (Fig. 1b-c).

The Lamasi Complex, part of the East Sulawesi Ophiolite (ESO) (Bergman et al., 1996; Kadarusman et al., 2004; Parkinson, 1998; White et al., 2017), is situated east of the LMC (Fig. 1b-c). It is composed of dioritic plutons, basaltic sheeted dykes, pillow lavas, greenstones and tuff. The Lamasi Complex is intensely deformed, altered by ocean-floor metamorphism, and bounded by thrust faults. Generally, the mafic components of the Lamasi Complex have depleted Sr-Nd isotopes, MORB-like geochemistry, and possibly represent obducted MORB or back-arc oceanic crust (Bergman et al., 1996). Isotopic data (K-Ar, ^{40}Ar-^{39}Ar, Rb-Sr and Sm-Nd) suggest Cretaceous to Eocene formation ages (Bergman et al., 1996; Parkinson, 1998; Priadi et al., 1994). The ESO was obduction onto the Sundaland Craton at 30 Ma, based on an K-Ar age of the metamorphic sole (Parkinson, 1998). By contrast, White et al. (2017) suggested that the timing of ophiolite obduction was between Early to Middle Miocene, and the Lamasi Complex may represent Eocene-Oligocene arc/back-arc volcanic rocks.

The Late Cenozoic magmatism in Western Sulawesi has been the subject of much debate. The hypotheses proposed can be divided into two groups: (i) a collision event caused crustal/lithospheric thickening, followed by melting in the lower crust to give rise to magmatism (Bergman et al., 1996; Polve et al., 2001; Polvé et al., 1997; Priadi et al., 1994), and (ii) an extensional tectonic regime in the mid-Miocene causing astenospheric mantle uprising, resulting in shoshonitic to ultrapotassic magmatism and CAK magmatism in Central West and North Western Sulawesi, underlain by a Cretaceous continental fragment and subjected to strong uplift in the Pliocene (Hall and Wilson, 2000; Maulana et al., 2016; van Leeuwen et al., 2010; White et al., 2017). Based on our fieldwork campaign and drill hole observations in the Awak Mas District, intrusive rocks within this complex are rare. Most of the rocks are metamorphosed and none of the above scenarios are supported by the outcrop evidence. Pumpellyite, epidote and actinolite observed in clinopyroxene-phyric metamafic and metatuffite from the Salu Bullo deposit are indicator minerals for high-pressure low-temperature metamorphism, and most likely represent subduction-related metamorphism processes during the Cretaceous (Hakim and Melcher, 2017a).

Soesilo (1998) distinguished three deformational phases in the Latimojong Mountains. (i) Initial deformation and metamorphism of siliciclastic, volcanic and carbonate rocks. Metamorphism in the zeolite to pumpellyite – actinolite facies reached temperatures of 310–350 °C and pressures of 3–4.5 kbar, corresponding to a depth of > 9 km. (ii) Ductile deformation, blueschist- to greenschist-facies metamorphism of metasedimentary and metavolcanic rocks, characterized by pumpellyite-actinolite and glaucophane in metavolcanic rocks. The estimated temperature and pressure of > 350° C and > 6 kbar and further increased up to 550 °C in the low amphibolite facies (Soesilo, 1998). Final stage (iii) brittle deformation comprised the formation of chlorite and calcite as crack fillings.

During exploration work since the early 1990s in the LMC, more than a thousand drill-holes with a total aggregated length of 118,081 m yielded estimated total resources of 38.4 Mt (cut-off grade of 0.5 g/t) (One Asia Resources, 2017). Total gold contents of 50 tonnes at 1.41 g/t Au exceed the gold exploited in several historic gold mines in Indonesia (Garwin et al., 2005). Gold in the Awak Mas and Salu Bullo deposits (Fig. 1c) precipitated as laminated veins or lenses within oblique normal faults, extensional shears and fractures as well as in the host metasediments and metavolcanic rocks (Fig. 2). Early and late-mineral faulting dominates within the structures, with late-mineralization faults as host to the main veins.

The Awak Mas deposit (average grade 1.4 g/t) consists of five ore bodies dipping between 15° and 50° towards the north and dissected by three major N-S-trending faults. The ore bodies at Awak Mas can be traced along strike for up to 800 m and range from several meter up to 70 m thick (One Asia Resources, 2017). The mineralized zone cuts a metasedimentary sequence (phyllite, carbonaceous phyllite, chlorite schist; Fig. 3a-b) with associated brecciation and stockwork quartz vein development.

The Salu Bullo deposit, situated 2 km to the southeast of the Awak Mas deposit, is considered to be analogous to the Awak Mas deposit, but with a more dominant sub-vertical structural control. Accretion of