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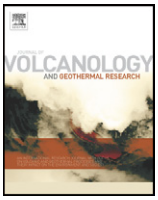

The Lepanto Cu–Au deposit, Philippines: A fossil hyperacidic volcanic lake complex

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ABSTRACT

Hyperacidic lakes and associated solfatara in active volcanoes are the expression of magmatic gas expansion from source to surface. Here we show for the first time, that the vein system that comprises the ~ 2 Ma high-sulfidation, Lepanto copper–gold deposit in the Mankayan district (Philippines) was associated with a contemporary hyperacidic volcanic lake complex—possibly the first such lake recognized in the geological record. A 15–20‰ difference in sulfur isotopic composition between barite and sulfides and sulfosalts in the vent fumarole encrustations supports the interpretation that SO_2-rich volcanic gas vented into the base of the lake and marginal to it and ties the mineralization directly to magmatic gas expansion, fracture propagation, and mineralization that occurred through a series of decompression steps within the feeder fracture network. These data confirm that crater lake environments such as Kawah Ijen (Java, Indonesia) provide modern day analogs of the Lepanto and other high sulfidation Cu–Au depositing environments.

We also provide extensive analysis of sulfosalt–sulfide reactions during vein formation within the hyperacidic lake complex. Pyrite ± silica deposited first at high temperature followed by enargite that preserves the vapor–solid diffusion of, for example, antimony, tin, and tellurium into the vapor from the crystallizing solid. Subsolidus, intra-crystalline diffusion continued as temperature declined. Pyrite and enargite are replaced by Fe-tennantite in the lodes which initially has low Sb/(Sb + As) atomic ratios around 13.5% close to the ideal tennantite formula, but evolves to higher ratios as crystallization proceeds. Fumarole encrustation clasts and sulfosalts in the lake sediment are more highly evolved with a larger range of trace element substitutions, including antimony. Substitution of especially Zn, Te, Ag, and Sn into tennantite records metal and semi-metal fractionation between the expanding magmatic gas and deposited sulfide sublimates provides a rare insight into the fate of metals and semi-metals in the shallower parts of fracture arrays that feed modern hyperacidic lakes.

These data support a growing understanding of the formation of high-sulfidation gold deposits as the consequence of single-phase expansion of gas from magmatic-gas reservoirs beneath the surface of active volcanoes without the intervention of a later aqueous fluid including groundwater. Aggressive sulfide–sulfosalt reactions, including pitting and the almost complete dissolution of earlier minerals, are persistent characteristics of the vein assemblages and precious metals typically occur late in pits or along brittle fractures. These characteristics support a hypothesis of mineral deposition at temperatures of the order of 600 °C in contrast to available fluid inclusion data from enargite that record temperatures following phase transitions in the sulfosalt during the retrograde devolution of the deposit in the presence of groundwater.

1. Introduction

The Lepanto mine in Luzon, Philippines, is one of the classic “high-sulfidation” type copper–gold deposits (cf. Arribas, 1995). Stable isotope (e.g., Rye, 1993) and mineral chemistry (e.g., Henley and Berger, 2012) along with geologic data have established that such deposits are fossil fumarole–solfatara systems associated with then active volcanic systems as originally proposed by Cross (1891) and Ransome (1909). This volcanic context is often preserved as extensive blankets of intense advanced argillic – sensu lato – alteration typified by abundant silica with alunite, kaolinite and other aluminosilicates (Fig. 1) within which discrete bodies of sulfosalt mineralization – typically enargite-pyrite rich assemblages with economic trace concentrations of silver and gold – are localized by syn-hydrothermal fracture arrays. The mineralogy and isotope geochemistry show that paleo-solfatara, their underlying alteration and the sulfide mineralization in these deposits resulted directly from an expanding magmatic gas released into a continually-evolving fracture array from some underlying magmatic-gas reservoir associated with an assembly of sub-volcanic intrusions (e.g., Rye, 1993; Arribas, 1995; Berger and Henley, 2011; Henley and Berger, 2011, 2013).

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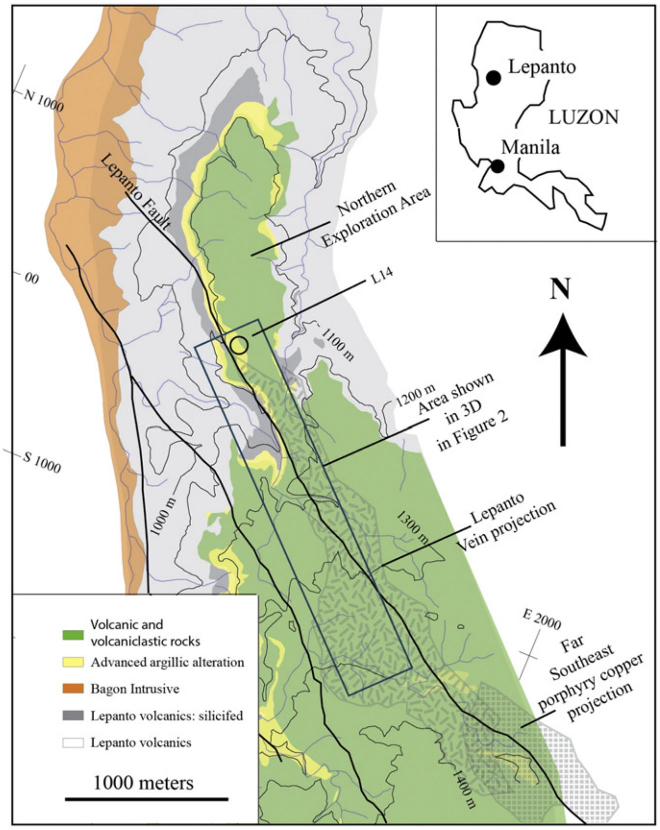

Fig. 1. Lithologic map of the Lepanto area based on Gonzalez (1959) showing the distribution of advanced argillic alteration in relation to sub-surface Cu–Au mining, the subadjacent Far South–East porphyry copper deposit, and the Northern Exploration Area.

In active volcanoes today, exotic sublimate assemblages characterize high-temperature fumarole vents including a wide range of metallic elements (e.g., Au, Bi, Pb, V); however, curiously very little copper or arsenic is observed (Henley and Berger, 2013). Henley et al. (2012) and Henley and Berger (2012) proposed that the arsenic-rich sulfosalt assemblages exposed at depths up to 1 km in high-sulfidation vein deposits account for the missing copper and arsenic in modern fumaroles due to the rapid sub-surface deposition of pyrite and enargite–tennantite in response to the extreme pressure gradient from quasi-lithostatic conditions to gas-pressured conditions in the fracture arrays that feed fumarole discharges at the surface (Henley and Berger, 2013). These vein assemblages preserve a record of aggressive sulfosalt reactions with paragenetically earlier sulfides, sequences of microcrystalline and amorphous sublimate assemblages interpretable as directly sublimated by a high temperature gas phase. Post-depositional phase changes and sub-solidus reactions are inevitable as these non-equilibrium assemblages cool and age resulting in complex intermediate mineral parageneses, stable isotope systematics and low, post-phase change, fluid inclusion homogenization temperatures that obscure the primary origin of the sulfosalts and silica in high-temperature paleo-fumaroles.

In this paper, drawing on detailed microanalyses of samples from across the Lepanto copper–gold deposit, we document the preservation of a previously unrecognized paleo-hyperacidic lake-fumarole complex from the lake through to the deepest levels of mining. These data and field-emission scanning electron microscope (FESEM) images reveal the details of sequential precipitation–dissolution–replacement reactions, diffusive metal and semi-metal fractionation, syn- and post-crystallization transformations, and the role of local stress in mineralization processes within the array of fractures that fed expanding magmatic gas through into the hyperacidic lake-fumarole complex, just as is seen in hyperacidic volcanic lake environments today. In turn these data provide a unique view of the otherwise inaccessible regions beneath such modern crater lakes.

2. Geology of the Mankayan District and the Lepanto copper–gold deposit

Based on the published geological maps by Gonzalez (1959), Sillitoe and Angeles (1985) and Garcia (1991), Hedenquist et al. (1998) summarized the geology of the Mankayan district which hosts the Lepanto copper–gold deposit, one of the most prominent mining areas in the Philippine archipelago. Within an area of less than 25 km^2, the district contains several porphyry Cu–Au (Far Southeast (FSE), Guinaoang, Palidan) and epithermal precious- and base-metal deposits, both high-sulfidation (Lepanto) and low-sulfidation (Nayac, Suyoc, Victoria) types. The Lepanto deposit is in the northern part of the district and is spatially related to porphyry Cu–Au mineralization of the FSE deposit that occurs at $<$800 m elevation, below and about 3 km to the southeast of the Lepanto enargite-Au ore body (Fig. 1). The geology of the Mankayan district can be divided into four main lithologic groups: (1) a metavolcanic and epiclastic basement consisting of Late Cretaceous to Middle Miocene units, (2) a large Miocene tonalitic to gabbroic intrusion; (3) a Pliocene dacitic pyroclastic and porphyry unit that predates mineralization in the Lepanto and FSE deposits; and (4) an unaltered Pleistocene dacitic pyroclastic and porphyry unit. The Pliocene dacite pyroclastic rocks form a district-wide blanket of interlayered volcaniclastic and pyroclastic rocks and porphyritic lava flows. Near the FSE deposit, numerous dikes and two large (0.3 m in diameter) volcanic vents filled with Pliocene dacite porphyry and pyroclastic rock were delineated through exploration drilling. The scale and geologic assembly of the district may be readily interpreted as a now eroded composite volcano that dominated the Pliocene–Pleistocene landscape between 2.2 and 1.2 Ma (Arribas et al., 1995).

The Lepanto deposit is a typical 'high-sulfidation' copper gold deposit (Arribas, 1995; Berger and Henley, 2011; Henley and Berger, 2011) and Claveria (1997); Claveria and Hedenquist (1994); Hedenquist et al. (1998) and Imai (1999) have described key aspects of its alteration and the sulfide and sulfosalt paragenesis. As summarized by Berger and Henley (2011) the silica–alunite Sulfate Stage alteration in the main part of the Lepanto mine forms a pervasive, but asymmetric, zone of silicification along and in both walls of the Lepanto fault. At the surface, it is broader to the southeast and mostly in the southwest wall of the Lepanto fault zone, narrows to the northwest and crosses over to be predominantly in the northeast wall of the fault zone. Where the silicification is broadest, Gonzalez (1959) mapped pre-mineralization east–northeast-striking faults. In cross section, the silica–alunite alteration narrows downward to give a distinct triangular cross-sectional shape (Gonzalez, 1959). Although the zone is along the Lepanto fault zone, its width is controlled by the density and length of generally east–west tensile fractures in both walls of the fault. It is evident from the fracture and alteration relationships that high-sulfidation mineralization post-dates all transtensional deformation in the Mankayan district.

The Sulfide Stage ore mineralization penetrates the silica–alunite alteration and occurs along narrow, generally east–west-striking, discontinuous extensional fractures ("branch veins" or "splits"), often occurring in swarms along the whole of the main Lepanto mine fault zone (Gonzalez, 1959). The sulfide-sulfosalt ore occurs in zones that expand upward and have distinct roots at depth indicating that fluid flow was predominantly vertical (Fig. 2). There are two stages of brecciation and accompanying ore mineralization along the Lepanto fault (cf. Gonzalez, 1959). The earliest ore consists of brecciated and silicified, micro-veined sulfide-bearing rock. This stage is most readily observable in the northwest of the mine. The early brecciation stage was re-broken creating open spaces between early stage breccia ore that were partially filled by dense, fine-grained masses of quartz and sulfosalts. Anecdotally open spaces between early stage fragments were greatest to the