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**Geology, geochemistry, and genesis of the El Peñón epithermal Au-Ag deposit, northern
Chile: Characteristics of a bonanza-grade deposit and techniques for exploration**

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Abstract

The El Peñón gold-silver deposit comprises six epithermal veins, which contain a geologic resource (measured + indicated + inferred) of 3.8 million oz Au and 63 million oz Ag. The deposit is hosted in Paleocene and Eocene mafic to felsic volcanic rocks and is located in the central portion of the Paleocene metallogenic belt, 165 km southeast of Antofagasta. Older and younger igneous rocks occur in the district; Late Cretaceous and Eocene intermediate composition rocks record the effects of hydrothermal activity not related to precious metal mineralisation of the El Peñón deposit.

Rocks in the district display two distinct types of hydrothermal alteration: widespread alteration associated with near-neutral pH, reduced fluid and localised alteration associated with acidic pH, oxidised fluid. Near-neutral pH, reduced fluid produced widespread replacement of phenocrysts and groundmass by quartz, adularia, albite, illite, chlorite, smectite, calcite, and pyrite; quartz-adularia alteration (replacement of primary phases, vein fillings, and hydrothermal breccia matrices) intensifies in the vicinity of precious metal-bearing veins. Acidic pH, oxidised fluid produced lithocaps of massive quartz-alunite alteration, quartz-alunite cemented breccia, and, locally, weak Cu mineralisation above inferred Late Cretaceous and Eocene intrusions.

Adularia from the two largest veins is dated at 52 to 53 Ma ($^{40}\text{Ar}/^{39}\text{Ar}$), indicating formation 1 to 3 m.y. later than host rhyolite domes. Quartz-alunite alteration spatially associated with Late Cretaceous and Eocene intermediate composition intrusive rocks is dated at 70-69 Ma and 50-49 Ma, respectively. Dating of supergene alunite indicates that weathering within a semi-arid to arid climate occurred from 23-17 Ma, prior to the onset of hyperaridity.

The veins that comprise the El Peñón deposit range from <0.5 m to 22 m wide; the bonanza-grade Quebrada Colorada vein has a strike length of ~2 km, vertical extent of ~500 m (1377-1877 m asl), and varies in width from 0.5 m to 4.5 m. Pervasive supergene oxidation

extends to 400 m below surface. Limited drill intercepts at deeper levels consist of banded and brecciated quartz, adularia, and massive, bladed, and acicular, Ca-, Fe-, Mn-, and Mg-bearing carbonate minerals, with minor amounts of pyrite, chalcopyrite, sphalerite, and galena. Veins exhibit a wide range of crustiform textures, including comb, colloform, and lattice quartz, rhombic adularia, and abundant massive and bladed Fe- and Mn-oxide minerals. Recrystallization textures suggest amorphous silica and chalcedony precursors for some quartz. Coexisting liquid- and vapor-rich inclusions, lattice textures, and vein adularia are evidence for boiling conditions that were likely responsible for Au-Ag deposition. Ore minerals observed in oxidised veins consist of electrum (mostly 40-60 wt % Au), acanthite, gold, silver, silver sulfosalts, silver halides, and rarely pyrite, chalcopyrite, and galena. High ore grades are generally associated with massive bands of fine-grained quartz and adularia, breccias composed of vein clasts in a matrix of fine-grained quartz and adularia, and, less commonly, colloform quartz bands. Supergene processes resulted in local remobilisation of Au and Ag, leaving nearly pure gold (up to 98 wt % Au) along fractures and associated with oxide masses.

Fluid inclusion data from the El Peñón deposit indicate vein formation from low salinity (<2 eq. wt % NaCl), boiling hydrothermal fluid at temperatures mostly from 230 to 260°C. $\delta^{18}\text{O}$ values of quartz range from 5 to 8 per mil, which can be explained by boiling and cooling of a single parent liquid of probable meteoric origin. Comparison of the amount of Au and quartz contained in the Quebrada Colorada vein to mass fluxes in the Broadlands-Ohaaki geothermal system indicates that the vein could have formed in as little as a few thousand years.

Abundant geochemical analyses (>7000 surface samples and >4000 drill hole samples) provide ample data with which to evaluate vectors to ore. Geochemical gradients in altered rocks surrounding veins in the El Peñón district indicate that Au, Ag, As, and Sb concentrations increase toward mineralised quartz veins. Geochemical analyses of altered

rocks from drill holes surrounding the Quebrada Colorada vein show enrichment of Au and Ag and depletion of Ca, Na, and Sr toward the vein; As and Sb increase with elevation. Mass changes calculated using whole-rock geochemical data also show gradients that are centred on mineralised veins; K is typically enriched toward veins, whereas Na and Ca are depleted. Whole-rock geochemical data are used to evaluate hydrothermal alteration mineralogy so that gradients of mass change can be related to associated zoning of hydrothermal minerals.

For Lucy

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