Hydrothermal Fluid Evolution and Controls of Hypogene Mineralization at the Escondida Porphyry Copper Deposit Revealed by Quartz Cathodoluminescence and Fluid Inclusion Microthermometry

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The aim of this contribution is to present new insights into the evolution of hydrothermal fluids and related mineralization processes at the Escondida porphyry copper deposit. For this purpose, we combined a high resolution microtextural study of representative quartz veins by scanning electron microscopy-cathodoluminescence (SEM-CL) with microthermometric analyses on more than 140 fluid inclusions hosted by different quartz generations and vein types.

Three types of hydrothermal quartz veins—early, transitional, and late—were classified based on morphology, mineralogical composition, and crosscutting relationships. Early veins are sinuous, occasionally showing a thin K-feldspar alteration halo and containing variable amounts of bornite, chalcopyrite, and pyrite. Transitional veins are molybdenite rich and mainly located in deeper zones. Late veins show a typical destructive hydrothermal alteration selvage and a sulfide-rich central suture containing variable amounts of chalcopyrite and pyrite.

SEM-CL imaging reveals that at least three generations of quartz compose the hydrothermal veins (Fig. 1). The first generation (Q1) is characterized by anhedral quartz crystals that show a homogeneous CL-bright signal and are mainly located on the walls of early and transitional quartz veins (Fig. 1A). Occasionally, relics of Q1 were identified in late quartz veins (Fig. 1C). Most Q1 crystals show irregular and rounded, corroded shapes, suggesting that they were disturbed by hydrothermal dissolution processes. The second generation (Q2) is represented by euhedral and strongly zoned quartz crystals that overgrow Q1 crystals (Fig. 1B). SEM-CL zoning in Q2 crystals shows alternation of bright and dark bands that gradually decrease in luminescence toward the center of veins. Q2 is the most abundant quartz type in all hydrothermal vein types, especially inside late veins, where it represents more than 90 vol % of the quartz (Fig. 1C). This suggests that Q2 precipitation represents a widespread deposition event related to the late vein stage that overprinted many earlier veins. The third quartz generation (Q3) corresponds to CL-dark crystals filling microfractures that crosscut both Q1 and Q2 (Fig. 1A, B). Q3 also infills interstitial spaces previously formed by Q1 and Q2 dissolution; in this case, Q3 can show a weak zoning in CL. Sulfide minerals (including Fe, Cu-Fe, and Mo sulfides) are always spatially related to Q3 quartz and often display euhedral crystal boundaries with Q3, suggesting coprecipitation (Fig. 1A, B, and C).

Fluid inclusion petrography and microthermometry were strictly linked to the different quartz generations previously recognized by SEM-CL. Four fluid inclusion types hosted by these quartz phases were identified: intermediate density (volume fraction of vapor,

F, F35-85), halite bearing (F20H), vapor rich (F90), and liquid rich (F20). The F35-85 inclusions are mostly hosted by Q1, coexisting F20H and F90 inclusions are mainly hosted by Q1 but occasionally occur also in Q2 in shallow early veins, and F20 inclusions invariably occur in Q3 quartz in all vein types.

Coexistence of F20H and F90 fluid inclusions hosted by Q1 and Q2 inside sulfide-rich stockwork indicates that boiling occurred before sulfide precipitation within these veins. However, in deep quartz-molybdenite veins, both Q1 and Q2 only trapped intermediate-density fluid inclusions, suggesting that a previous boiling was not necessary to precipitate molybdenite. The temporal relationship between F35-85 inclusions and boiling assemblages is uncertain, although it is possible that single-phase fluids represented by the former inclusions entered the two-phase field and underwent phase separation during ascent, depressurization, and cooling.

Observations indicate that hypogene sulfide minerals precipitated late in all quartz vein types from low-salinity (1.3–7.2% NaCl equiv), single-phase, liquid-like fluids. Homogenization temperatures are relatively low (266°–319°C) and are probably fairly close to fluid trapping temperatures. These hydrothermal fluids were channeled through microfractures and secondary porosity generated during hydrothermal dissolution processes that affected Q1 and Q2 crystals in all vein types.
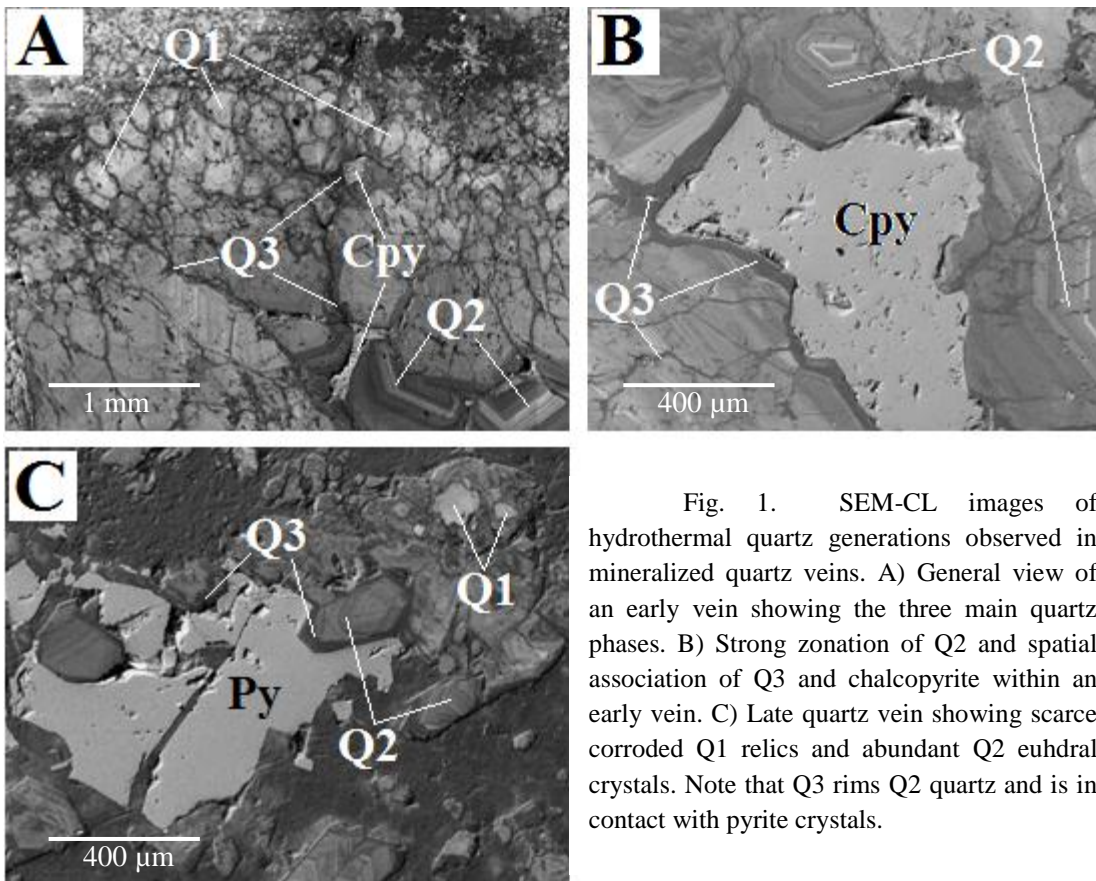
Fig. 1. SEM-CL images of hydrothermal quartz generations observed in mineralized quartz veins. A) General view of an early vein showing the three main quartz phases. B) Strong zonation of Q2 and spatial association of Q3 and chalcopyrite within an early vein. C) Late quartz vein showing scarce corroded Q1 relics and abundant Q2 euhdral crystals. Note that Q3 rims Q2 quartz and is in contact with pyrite crystals.