

RAÚL-CONDESTABLE: A 115 MA OLD SUBVOLCANIC INTRUSION-CENTERED IOCG DEPOSIT

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The Raúl-Condestable is a >32 Mt copper-gold deposit located on the Peruvian coast, 90 km south of Lima. Early studies include Ripley et Ohmoto (1977 and 1979), Cardozo (1983), Injoque (1985), Atkin et al. (1985), and Vidal et al. (1990). Recently, the deposit has been interpreted to belong to the iron oxide copper-gold class (IOCG), based on its alteration and ore mineralogy (Barton and Johnson, 1996 and 2000; De Haller, 2000 and 2006; De Haller et al., 2001, 2002, and 2006; Injoque, 2002; Sillitoe, 2003; Williams et al., 2005). The results and interpretations presented hereafter can be found in more detail in De Haller (2006) and De Haller et al. (2006).

The ore consists of chalcopyrite, pyrite, pyrrhotite, and magnetite, and is found as dissemination, pore infill, replacement, and veins in amphibolitized rocks which are part of a basaltic to dacitic volcanosedimentary sequence. The geology of the studied area comprises a series of superposed volcanic edifices of Late Jurassic to Early Cretaceous age, which are part of a larger volcanic/seashore island to continental arc system. Particularly good exposures of the tilted host sequence allow the mapping of the Raúl-Condestable IOCG deposit in a nearly complete oblique cross section, from its associated volcanic edifice down to a paleodepth of about 6 km (Fig. 1). Two hydrothermal events are defined, corresponding to a Main ore stage (the IOCG mineralization itself) and late stage calcite-sulfide veins (with no economic significance). A regional dolerite dyke swarm cuts all the geologic units present in the area, including the Main ore stage copper mineralization. Late stage calcite-sulfide veins are later and cut the dolerite dykes.

U-Pb zircon ages indicate that in the deposit area felsic magmatic activity took place between 116.7 ± 0.4 and 114.5 ± 1 Ma, defining a new Raúl-Condestable superunit, the oldest so far, of the Peruvian Coastal Batholith (Atherton and Sanderson, 1985; de Haller et al., 2006; Mukasa, 1986a; Mukasa and Tilton, 1985a; Pitcher, 1985). This superunit is located west of the main part of the Batholith and includes a dacite-andesite volcanic dome and a subvolcanic quartz-diorite porphyry sill-dike complex that were emplaced at 116.7 ± 0.4 Ma and 116.4 ± 0.3 Ma, respectively, followed by tonalite stocks and dikes emplaced between 115.1 ± 0.4 and 114.5 ± 1 Ma. All these rocks contain hornblende and/or biotite but no pyroxene and correspond to silica- and water-rich magmas following a calcic differentiation trend. Hf isotopic data on zircons ($\epsilon_{\text{Hf}}(115 \text{ Ma}) = 5.2$ to 7.5) and Pb isotopic data on whole rock, combined with lithochemical results, suggest that magmas were generated by partial melting of the upper mantle, enriched through hydrous metasomatism and/or melting of subducted pelagic sediments. The lack of zircon inheritance suggests that there was no direct involvement of continental crust. These findings are in agreement with previous regional works (Couch et al., 1981; Jones, 1981; Beckingsale et al., 1985; Mukasa and Tilton, 1985a and 1985b; Wilson, 1985; Mukasa, 1986a and 1986b; Macfarlane et al., 1990).

The Raúl-Condestable IOCG deposit is connected in space and time with the magmatism of the Raúl-Condestable super-unit. The mineralization was emplaced in the core of the dacite-andesite volcanic dome at an estimated paleodepth of 2 to 3 km, surrounding two tonalitic intrusions emplaced at 115.1 ± 0.4 and 114.8 ± 0.4 Ma (Fig. 1). The U-Pb age of hydrothermal titanite from IOCG (Main ore stage) veins at 115.2 ± 0.3 Ma indicates that the mineralization was coeval with (or more probably just followed) the emplacement of the tonalites. Copper ore is associated with a zoned alteration pattern, which surrounds the tonalite intrusions (Fig. 1). It consists of a core of biotite alteration and quartz stockwork, grading outward to actinolite (\pm magnetite, \pm chlorite, \pm titanite, \pm scapolite, \pm albite, \pm epidote) and upwards to sericite + Fe-chlorite alteration. An upper distal alteration halo consisting of

hematite-chlorite surrounds the sericite + Fe-chlorite and actinolite alterations laterally. Most of the ore is spatially associated with the actinolite alteration and, to a lesser extent, with the sericite + Fe-chlorite alteration.

The Main ore stage ore paragenesis is characterized by two end-members, corresponding to an "oxidized" and a "reduced" mineral associations. The "oxidized" mineral association consists of the sequence hematite-magnetite-pyrite-chalcopyrite, and the "reduced" mineral association to the sequence pyrrhotite-pyrite-chalcopyrite. In the "oxidized" mineral association, early bladed hematite is almost completely transformed to magnetite. The "oxidized" mineral association is zoned from proximal (feeder veins) to distal from chalcopyrite-pyrite-(magnetite \pm hematite), to pyrite-magnetite, and then to magnetite. In contrast, in the "reduced" mineral association, zoning consists of chalcopyrite-pyrite, pyrite-pyrrhotite, and then pyrrhotite with, locally, intermediate product (pyrite-marcasite).

Four types of fluid inclusions are found in quartz from stockwork and IOCG veins. They consist of 4 phase (liquid-vapor-halite-iron chloride), 3 phase (liquid-vapor-halite), and 2 phase (liquid-vapor) inclusions, of which most are liquid-dominated. Vapor homogenization temperatures are similar for the three liquid-dominated inclusion types, and range from 137.2 to 231.7 °C (n = 34) with a mean at 172 °C. For most hypersaline inclusions (probably up to >50-60 wt. % NaCl equ.), final homogenization would occur through daughter salts dissolution at temperatures higher than 300°C, where fluid inclusions start to leak. Salinity of 2 phase liquid-dominated inclusions range from 11.7 to 19.0 wt. % NaCl equ. (n = 4), with eutectic between -34.6 and -58 °C indicating complex polysaline fluids.

The Main ore stage sulfides yield $\delta^{34}\text{S}$ values of +1.0 to +26.3 ‰, with a median at 6.6 ‰ (n = 51), consistent with data by previous authors (-9.3 to +23.3 ‰, n = 198; Ripley and Ohmoto, 1977). The $\delta^{34}\text{S}$ values of Main ore stage sulfides are dependent on the stratigraphic position, with deep seated vein samples corresponding to $\delta^{34}\text{S}$ of 1.0 to 6.3 ‰ (average around 3.5 ‰, n = 13), and shallower samples to $\delta^{34}\text{S}$ of +2.7 to +26.3 ‰ (median around +7.5 ‰, n = 39). Increased dispersion of the data at shallower levels coincides with an abrupt increase of the permeability of the volcanosedimentary sequence, related to the presence of volcanic breccias and tuffs. Similar patterns are observed for pyrrhotite, pyrite, and chalcopyrite. The positive $\delta^{34}\text{S}$ values are best explained through thermochemical Rayleigh fractionation of seawater sulfate. Sulfides found in Late stage calcite-sulfide veins show strongly negative $\delta^{34}\text{S}$ values ranging between -32.7 and -22.9 ‰ (n = 6), which contrast with the positive values obtained for Main ore stage sulfides, and might indicate a different source, probably biogenic.

All the results for the Main ore stage point to the participation of two different fluids: (1) a deep-sourced, oxidized, hot, saline, and metal-rich magmatic fluid channeled through feeder veins; and (2) a seawater-derived, reduced, cooler, saline, and metal-poor fluid, circulating in a predominantly basaltic to basaltic-andesitic aquifer. Biotite alteration and quartz stockwork are interpreted to occur in the magmatic dominated core of the system, with the low Th(v) recorded in stockwork and Main ore stage vein quartz being compatible with boiling magmatic fluids originally trapped in amorphous silica (Fournier, 1985 et 1999). The upper distal hematite-chlorite alteration is thought to represent a seawater recharge zone. Actinolite and sericite + Fe-chlorite alterations would represent a mixing zone, where most of the ore precipitated. The "oxidized" mineral association can be explained by precipitation from magmatic fluids following the $\text{SO}_2\text{-H}_2\text{S}$ gas buffer line (Einaudi, 2003; Giggenbach, 1987 and 1997) at high temperature (>350 °C) and water/rock ratio, then progressively reduced and cooled through interaction with the wall rock, with or without fluid mixing with the reduced seawater derived fluid. The "reduced" mineral association (pyrrhotite-pyrite-chalcopyrite) is explained through the mixing of deep magmatic fluids, already partially or totally reduced through reaction with wall rock at medium to low water/rock ratio, with evolved (reduced) seawater that was heated at about 350 °C at the margin of Tonalite 1.

Our findings support previous suggestions that the presence of external seawater-derived, evaporitic, or metamorphic brines is not a prerequisite to the formation of IOCG deposits, and that the primary contributor consists of magmatic fluids (Pollard, 2000 and 2001; Sillitoe, 2003). This is consistent with the widespread occurrence of the "oxidized" mineral association (hematite-magnetite-pyrite-chalcopyrite±bornite) observed in Andean IOCG deposits (Sillitoe, 2003; and references therein). The Raúl-Condestable deposit appears to have no genetic link with the later dolerite dykes swarm or any other mafic magmatic event, and the hydrated magmatism of the Raúl-Condestable super-unit, and in particular Tonalite 1, is considered as the most probable mineralizing magmatic fluid source.

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Note: only selected references are given in this bibliography. For complete references, see De Haller (2006).

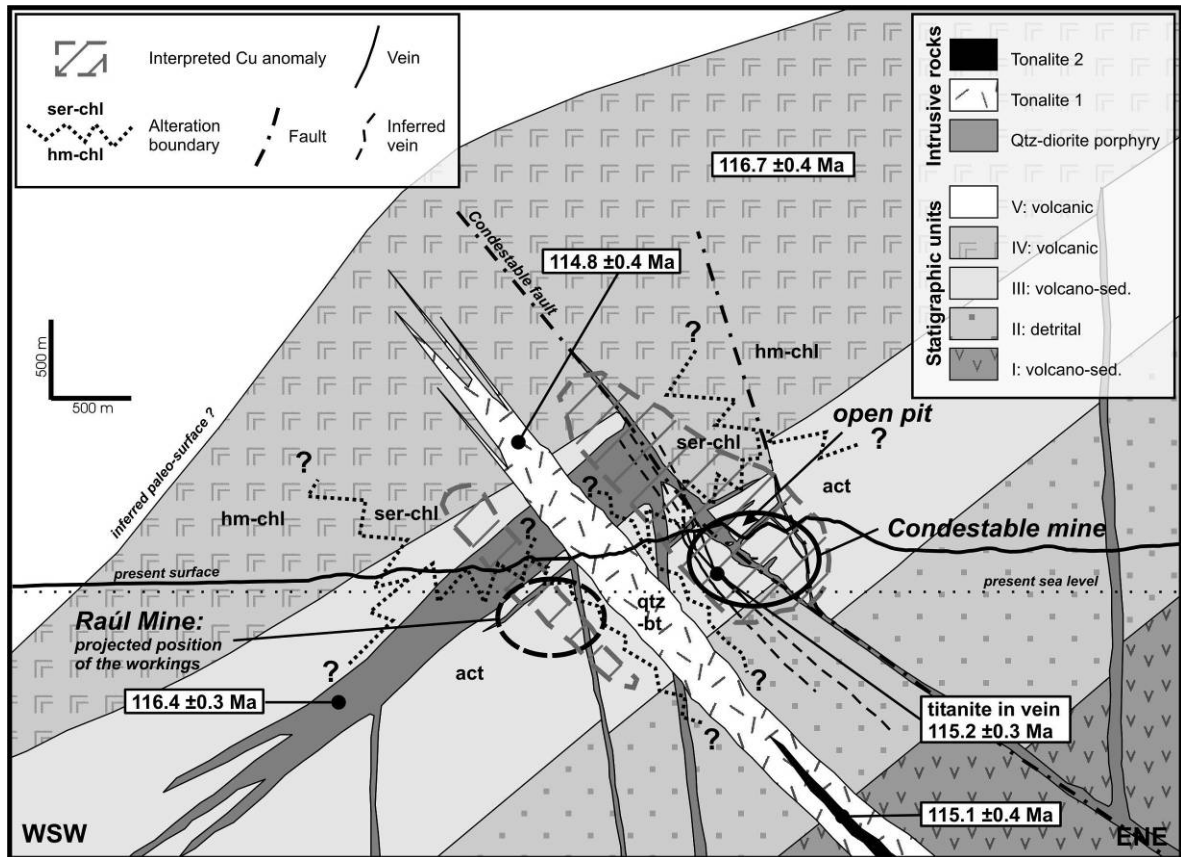


Fig. 1. Transverse section (after de Haller et al., 2006). The Tonalite 1 stock is surrounded by a biotite (bt) alteration halo, itself overprinted by a quartz stockwork (qtz). Biotite grades laterally to actinolite alteration (act), which is associated with most of the copper mineralization. The top of the system is dominated by a sericite + Fe-chlorite assemblage (ser-chl). A hematite-chlorite alteration (hm-chl) occurs in an upper lateral position. Assuming the top of Unit IV corresponds to the paleosurface at the time of mineralization, the deposit is located in a subvolcanic position at a paleo-depth of 2 to 3 km (de Haller et al., 2006). Given U-Pb ages (on magmatic zircons and hydrothermal titanite) are from de Haller et al. (2006). Dolerite dykes are not shown in this section and cut the whole sequence, including Unit V.