EL TENIENTE PORPHYRY COPPER-MOLYBDENUM DEPOSIT, CENTRAL CHILE

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ABSTRACT

El Teniente occurs in the late Miocene-early Pliocene metallogenic belt of central Chile. It is the world's largest known copper resource, containing 94.4Mt of fine copper, and 2.5Mt of fine molybdenum. The ore deposits formed during the final stages of a period of compression and crustal thickening initiated approximately 15 m.y. ago due to subduction of the Juan Fernandez Ridge.

El Teniente is hosted by the Miocene Farellones Formation and is located at the intersection of two major faults. The NNW trending Codegua Fault is interpreted to have formed from reactivation of a basement Triassic rift and has localised late Miocene volcanism. The NNE-trending Teniente Fault Zone controlled the emplacement of the 8.9 to 7 Ma Sewell Diorite complex. The Teniente host sequence is a strongly altered package of mafic to intermediate sills, stocks, extrusives and volcaniclastic rock. Early, widespread, barren magnetite-Ca-plagioclase alteration of the host sequence occurred, prior to emplacement of the late Miocene – early Pliocene calc-alkaline Teniente intrusive complex.

Copper-molybdenum ore at El Teniente is hosted in veins and subordinate breccias, and is associated with extensive zones of hydrothermal alteration. Sulfide minerals are zoned from bornite (core) through chalcopyrite to pyrite (deposit periphery). The 0.5 % copper contour defines a 2.6 km long and up to 2.0 km wide wedge shape, broadly centred on the Teniente intrusive complex. The timing of vein and breccia formation has been constrained temporally by nine new Re-Os dates (5.9 to 4.7 Ma) obtained from molybdenite. The grey porphyry (diorite), dacite pipes, and NNW-trending, multiphase dacite porphyry dyke intruded the host sequence during the Late Magmatic (LM) stage (5.9 to 4.95 Ma). Multiple generations of quartz-anhydrite-chalcopyrite-bornite veins and anhydrite-sulfide-biotite breccias formed at this time. These structures host approximately 60% of the copper at El Teniente. Na-K-feldspar alteration occurred within and around some of the dacite intrusions, grading out to intense, texturally destructive biotite alteration and distal chlorite-stable propylitic alteration assemblages.

Chalcopyrite-rich veins with phyllic (sericitic) alteration halos formed in the Principal Hydrothermal (PH) stage (4.95 to 4.85 Ma). Despite the short duration of this stage and the low vein densities, these veins host approximately 30% of the total copper resource at El Teniente. No coeval intrusive phase has been identified.

The Late Hydrothermal (LH) stage (4.85 to 4.40 Ma) is a second stage of phyllic alteration and veining, which is related to intrusion of the 1200 m wide, funnel-shaped Braden pipe and also to the emplacement of late dacite dykes (4.8 Ma). The pipe is composed of an inner, unmineralised, rock flour matrix breccia facies, and an outer, tourmaline-chalcopyrite-anhydrite-cemented marginal facies. LH stage veins have a diverse ore and gangue mineralogy, including base metal sulfides, sulfosalts, tourmaline, and carbonates. Late post-mineralisation and alteration hornblende dykes (3.8 – 2.8 Ma) are the youngest rocks in the deposit.

LM and PH veins are orientated mostly concentrically and radially around a postulated deep-seated magma chamber, interpreted to have sourced the upper crustal intrusions, stresses, heat, metals, and fluids for the Teniente deposit. In contrast, the LH veins are orientated steeply-inward dipping, concentric to the magma chamber, implying that they formed during a stage of magma withdrawal. Other paragenetically late veins and faults are NE trending, which formed when far field stresses associated with the TFZ exceeded the stresses localised around the magma chamber.

Abundant liquid-rich (± opaque) low to moderate salinity fluid inclusions occur in LM veins, which are interpreted to have trapped a one-phase magmatic-hydrothermal fluid at 500°C ± 100°C. Sporadic decompression of this fluid resulted in generation of brine and vapour phases. The brine phase cooled and was diluted as it migrated laterally away from the dacites. Proton induced X-ray emission (PIXE) analyses detected several weight percent copper in both high and low salinity fluids in the centre of the deposit. One fluid inclusion analysed from the propylitic zone contains only 0.01 wt % copper. During the PH and LH stages the hydrothermal fluids were boiling at temperatures between 450 – 300°C. Hydrostatic pressure estimates indicate a depth below the palaeowater table of less than ~2,500m for the PH stage and less than ~1,700m for the LH stage. Salinity arrays provide support for fluid mixing as a potential depositional mechanism at El Teniente.

Oxygen and deuterium isotopic analysis indicates the predominance of magmatic-hydrothermal fluids ($\delta^{18}O_{fluid}$ = +5.7‰ to +8.2‰) in most stages at El Teniente, even at the deposit periphery. The exception is LH carbonates ($\delta^{18}O_{fluid}$ = +2.4‰ to +9.1‰)

which have a significant meteoric water component. δD_{fluid} values for LM stage (-39‰ to –56‰) overlap with the felsic magmatic fluid values, whereas deuterium enrichment in PH and LH stage fluids (-38‰ to –6‰) imply the involvement of volcanic vapours. Sulfur isotope values for sulfides at El Teniente are between –5.9‰ and +2.4‰ and for sulfates are +10.0‰ to +13.4‰. These values are consistent with a bulk sulfur isotopic composition of 6‰. The most negative values from LM stage sulfides occur close to and within the dacites, grading out to values around zero on the deposit periphery. This zonation can be explained by an oxidized fluid (SO_2/H_2S = 6) being progressive reduced as it migrated outwards from the dacites. The vertical zonation of sulfur isotope values from the PH and LH stages can be modelled by cooling an oxidised fluid (SO_2/H_2S = 2-3) from approximately 475°C to 325°C over 1,000m elevation, indicating a vertical temperature gradient of 15°C/100m. This gradient is too large to be explained simply by conductive cooling or phase separation and requires either fluid mixing or thermal disequilibrium in the system.

Strontium and neodynium isotopes for anhydrite from all the vein stages are from 0.70396 to 0.70404 and 0.51276 to 0.51281, respectively. These values overlap with the local wall rock compositions from which they were most likely sourced. In contrast, lead isotopic values for the same anhydrites vary widely, for example $^{206}Pb/^{204}Pb$ values are between 17.490 and 18.559. These values are depleted compared to the sulfide ores, which have the same lead isotopic composition as the host rocks. Lead isotopic values in anhydrite are zoned, with most enriched values occurring in the centre of the deposit to most depleted values at the deposit periphery, which may have been derived from an unidentified exotic source of lead.

Ore deposition during the LM stage at El Teniente is believed to have occurred mainly due to sulfate reduction and cooling of lithostatically-pressured, magmatic-hydrothermal fluids. Secondary magnetite has been altered to biotite, implying that a very effective reductant interacted with both the mineralising fluid and the wallrock. The transition to the PH stage involved a change to brittle conditions and hydrostatic pressures, possibly due to rupturing of a lithostatic seal as the deposit was exhumed to depths shallower than 2,500m. High uplift rates (~2.4mm/yr) have been calculated for the short-lived PH and LH stages. Eventually magmatic and fluid pressures exceeded the confining lithostatic pressures (possibly facilitated by phreatomagmatic explosion), and explosive brecciation and fluidization of the rock mass occurred. This resulted in the emplacement of the Braden Pipe. Ore deposition in the PH and LH stages was most likely related to phase seperation-induced cooling, coupled with meteoric fluid mixing, at least during the LH stage.

Apart from its anomalous size, El Teniente is a typical porphyry copper-molybdenum deposit, in terms of its alteration and sulfide assemblage, zonation, association with felsic intrusions, and predominance of quartz vein-hosted copper mineralization. Mineralogical, isotopic, and fluid inclusion datasets at El Teniente indicate that a complex interplay of processes occurred during ore formation, including fluid mixing, cooling, oxidation-reduction, phase separation, and water-rock interaction. The combination of these processes resulted in the formation of this giant porphyry copper deposit.

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