



THE CHUQUICAMATA PORPHYRY COPPER SYSTEM REVISITED

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INTRODUCTION

The Chuquicamata porphyry copper deposit (ca. Lat. 22°16.5'S / Long. 68°54'W; 16 km north of Calama and 240 km NE of the port of Antofagasta; 2800-3000 m.a.s.l.), was described as "the largest copper deposit in the world" in 1916 [1], as "awesome" in 1978 [2], and "behemothian" in 1993 [3]. It held more than 4243 Mt with 1.02% Cu and 0.025% Mo [3], and some compilations have suggested past production plus reserves of more than 9000 Mt. Exploitation at Chuquicamata started in pre-Hispanic times, and narrow but rich veins east of the present mine were mined before the Chile Exploration Co. consolidated the property in 1912 and started mining disseminated ore in 1915 [4]. In 1923 Anaconda Copper Mining Co. took control, and operated the open pit mine until 1972, when it became the foremost division of the present owners, Corporación del Cobre de Chile (CODELCO).

The Chuquicamata described in early studies bears little resemblance to the deposit mined today [5]. The student is puzzled by the dearth of published data on post-1940 Chuquicamata. Chuquicamata Division of CODELCO started in 1993 a concerted effort to update the database and develop an appropriate genetic model. Some highlights of pilot studies from the ongoing geological, mineralogical, geochemical and isotopic research are presented here after a

review of the geological thought on the deposit from the literature.

BACKGROUND

Historically, mining had taken place through shallow underground workings above the water table in the *llamperas*, where Cu-oxide minerals (mainly brochantite and atacamite) were easily scraped from mineral-filled fractures, then screened to obtain a fine product (*llampo*) with over 20% Cu [1;6]. Deeper rich supergene sulfides (mainly chalcocite), were too hard to mine and hence uneconomic.

In 1917 W. Lindgren [7] described the known veins of the district, but in particular the remarkable vein-like "lode" (N20°E trend; dip 60-75°W; 3400m long and 100 to 400m wide, with 1.5% Cu or more). The "lode" of variably-shattered quartz-sericite rock, was branched at both ends. Lindgren compared it with the Butte deposit in Montana. Early workers [1;7] emphasized that the primary copper sulfide was **enargite**, which occurred with pyrite, whereas bornite and chalcopyrite were "a rarity" [4;7]. At surface a mineralized granite intruded, and contained inclusions of, Mesozoic calcareous shales [4;7].

By 1930 [8], dark red iron-stained soil, fault breccias and clay gouge of the West Fissure (Falla Oeste), were recognized as the west boundary of the mineralized "Chuqui" porphyry complex. The almost glassy, aphanitic texture of dike-like bodies of dacitic "porcelain rock" (now Banco porphyry), intrusive into the Chuqui

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porphyry, attested to their shallow emplacement. There was uncertainty on whether the mineralized Chuqui porphyry itself was a porphyritic phase of a larger granite body, or a distinctly later intrusive. R.Sales [8] described the deposit as a "quartz-vein zone or belt".

As late as 1940, the mineralogy of the hypogene ores was still known only from drill cuttings and a few exposures in the open pit, and enargite was the predominant hypogene copper mineral; small amounts of molybdenite and "minute amounts of bornite and chalcopyrite" were mentioned [9;10;11]. The publications of V.M.Lopez [9;10] summarized the work by company geologists, described the West Fissure, boundary to the "mineralized, altered shear zone", and explained the pattern of veins as resulting from the development of tension fractures oblique to a dextral shear system responding to horizontal tectonic stresses. The fundamental role of oxidation in making Chuquicamata an economic deposit was explained by O.W.Jarrel in 1944 [11]. These are the last published detailed accounts of the geology and mineralogy of this notable copper deposit, a pity considering that copper sulfides began to be exploited only in 1952 and molybdenite only in 1958.

Work by company geologists has been well presented in thorough Ph.D. theses by W.J.Ambrus [12] and H.M.Soto [13] at the University of Salamanca, Spain, and R.B.Cook [2] provided a compilation of all the mineral species found at Chuquicamata. Precious information is held in company files and the oral tradition of the mine staff. Useful summaries have been published in conference proceedings [14;15], and there were valuable contributions made by student theses at Chilean universities [e.g. 16]. However, because these works are not generally available in the international scientific literature, with few exceptions [e.g.17;19;3] Chuquicamata has not been considered

appropriately in the formulation of porphyry copper models, in a way commensurate with its importance.

The generally available model for Chuquicamata appears oversimplified and static. With an off-axis quartz-sericitic core and peripheral potassic and propylitic alteration, the deposit does not fit accepted zoning patterns for porphyry copper deposits [e.g.17], and with its strong structural control and anisotropy of mineralization, it is quite different from the smaller, but much better studied, El Salvador deposit [18]. Doubts persist about almost all basic elements necessary for the formulation of a genetic model with predictive capabilities.

REVIEW OF CURRENT WORK

GEOCHRONOLOGY

Igneous rocks associated with mineralization at Chuquicamata range in age from 40 to 28 Ma, and previous authors suggested a long-lived mineralizing history [e.g.19]. The older ages belong to the unmineralized Fortuna Granodiorite, considered by most to be a precursor of the Chuqui porphyries [e.g.12]. However, significant and complicated strike-slip displacements along the Falla Oeste shear [20;21] imply that the Fortuna Granodiorite may be genetically unrelated to Chuquicamata mineralization. New $^{40}\text{Ar}/^{39}\text{Ar}$ dates on biotite, K-feldspar and alunite allow us to discern two discrete periods of alteration - mineralization: a) potassic alteration at ca. 36-34 Ma, and b) sericitic alteration at ca. 32-31 Ma. The fracture - controlled sericitic alteration has locally rejuvenated the older ages, especially close to the core of most intense alteration. Preliminary apatite fission track data suggest that the area adjacent to the Falla Oeste cooled under ca. 100°C for the last time in the Miocene-Pliocene.

RARE EARTH DATA ON ROCKS

The Fortuna and Elena Granodiorites have higher overall contents of REE, and are less depleted in HREE than the mineralized porphyries. The Banco Porphyry is indistinguishable in terms of REE from the East Porphyry, but both have higher contents of REE than the West Porphyry. Preliminary data suggest that REE have behaved as relatively immobile elements during propylitic, potassic, sericitic, and argillic hydrothermal alteration, therefore, in addition to providing petrogenetic constraints, REE are useful in characterizing the different map units.

HYPOGENE MINERALOGY

The assemblages and distribution patterns of hypogene minerals have been summarized by J.Rojas and G.Leiva [5]. Late enargite-pyrite veins are ubiquitous within sericite assemblages, but a nuisance because of their arsenic content rather than the most important copper carrier. Bornite and chalcopyrite are earliest, digenite prominent. Hypogene covellite occurs with digenite in anhydrite-rich assemblages. Electron probe microanalyses indicate that hypogene covellite contains zero to up to several mole percent Fe whereas supergene covellite is stoichiometric CuS. Digenite is rich in Fe and is seen to change through djurleite to chalcocite by losing Fe as well as gaining Cu. The Fe-rich digenite is found as remnants in supergene assemblages.

Sphalerite is always present in polished sections of hypogene ores, as plentiful as molybdenite. Zinc is also a major component (8-10 wt%) of tennantite. Chuquicamata represents a major zinc concentration in the Andes.

Hypogene anhydrite has been overlooked at Chuquicamata, but it is ubiquitous in deep samples of ores and country rock [22] and

locally abundant. Even where hydrated to gypsum, sulfur isotopes recall a hypogene anhydrite precursor.

SULPHUR ISOTOPES

Though sulfur isotope analyses completed to date do not represent the full range of assemblages, the hypogene sulfates ($\delta^{34}\text{S}$ mean +15.9; range +13.7 to +16.9) are enriched in ^{34}S relative to supergene sulfates (mean -0.8; range 2.2 to 0.2 permil), and to hypogene sulfides (mean -2.9; range -5.6 to -1.4 permil). Pyrite in Mesozoic metapelites in the SE part of the pit are relatively lighter ($\delta^{34}\text{S}$ -6.8 to -5.5 permil). It appears that earlier sulfides (pyrite, chalcopyrite, molybdenite), are isotopically heavier (-1.7 to -1.8 permil) than galena and sphalerite in relatively late veins (-5.6 to -5.3 permil). Pyrite from the RT deposit, for comparison, analyzed with a $\delta^{34}\text{S}$ of +0.1 permil. Tentatively, we interpret gypsum with relatively heavy sulfur to have an anhydrite precursor, whereas sulfates with negative values probably inherited their sulfur by supergene destruction of pre-existing sulfides.

OXYGEN AND HYDROGEN ISOTOPES

Water of hydration of gypsum was analyzed for δD and $\delta^{18}\text{O}$ in 6 of the samples also analyzed for $\delta^{34}\text{S}$. The δD values (mean -64.2; range -61 to -69 permil) and $\delta^{18}\text{O}$ values (mean -1.5; range -3.3 to +2.6 permil) place gypsum hydration waters away from the meteoric water line, in the field of strongly modified waters such as those of El Tatio [23] and other geothermal fields.

Small differences ($\text{qtz-ksp} = 0.62$ permil) between pairs of K-feldspar/quartz are compatible with high-temperature, late-magmatic crystallization, but a pair from the uppermost levels of the mine ($\text{qtz-ksp} = 1.760$) records either a much lower equilibration temperature, or the feldspar has been affected by meteoric

water which has preferentially lowered its oxygen isotope composition; the latter effect could prejudice argon geochronology.

LEAD AND STRONTIUM ISOTOPES

Pure sulfides from Chuquicamata analyzed for their lead isotope composition yield values [$^{206}\text{Pb}/^{204}\text{Pb}=18.564$; $^{207}\text{Pb}/^{204}\text{Pb}=15.602$; $^{208}\text{Pb}/^{204}\text{Pb}=38.524$), which are close to the "average Chilean porphyry copper sulphide value" [22], and sulfide concentrates from adjoining MM and RT deposits have identical lead isotope signatures. However low-grade ore samples dominated by alteration silicates produce ratios in a mixing line between that of the sulfides and an extreme value (19.063; 15.677; 38.733) obtained for a deep sample in potassic alteration. Regardless, the calculated initial $^{87}\text{Sr}/^{86}\text{Sr}$ for the rocks analyzed so far is below 0.7045. Supergene enrichment does not appear to change the ratios for hypogene sulfides, but one single sample of exotic chrysocolla from Mina Sur gave a highly anomalous value (57.549; 17.808; 38.281), which indicates that exotic mineralization has been heavily contaminated with radiogenic lead in the surficial groundwaters.

TOWARDS A DYNAMIC MODEL FOR CHUQUICAMATA

Our working hypothesis considers that Chuquicamata developed during a period of active erosion [24], at the roots of a dacitic-rhyolitic dome complex. The intrusion of the Chuqui porphyries at >34 Ma, into a relatively deep, ductile regime, was followed by potassic alteration, fracturing and low-grade (ca. 0.5% Cu) bornite-chalcopyrite mineralization dominated by magmatic fluids. Uplift and erosion ensued, removing the epithermal domains of the hydrothermal system. Probably representing a new pulse of porphyry intrusion at depth, quartz-sericite alteration and renewed

mineralization with a net input of Cu, Mo and As, occurred at ca. 31 Ma, controlled by brittle fractures at a shallower depth than the older potassic alteration, and responding to a dextral shear system. The large volumes of quartz deposited necessitate a vast input of meteoric water and a brittle regime allowing for abundant depositional space. Whereas in the peripheral areas cooling was rapid, towards the core of the deposit and particularly in the vicinity of the Falla Oeste, the system cooled at a later time. Continued exhumation in the Oligocene enhanced the wholesale supergene enrichment of the deposit into Miocene times, coinciding with a period of sinistral strike-slip movement of the Falla Oeste system. Later, spreading of copper beyond the confines of the deposit formed exotic deposits in the gravels downslope. The unaltered Fortuna granodiorite "docked" at some unknown time and is not a precursor for Chuquicamata mineralization. The multi-stage development of Chuquicamata and the protracted and complex strike-slip displacement history of the Falla Oeste imply that there could be not one but several "missing halves" of this giant deposit, one for each of the stages of development.

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