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Geology of the Ministro Hales Mine (MMH), Chuquicamata District, Chile

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Introduction

Previously known as Mansa Mina or MM, the mine was renamed Mina Ministro Hales (MMH), in 2004 after former Minister of Mines Alejandro Hales. It is centered at 22° 22'45"Lat. S 68°54'50", at an elevation of 2400 m.a.s.l., 7 km south of Chuquicamata and 7 km north of Calama (Fig. 1). The concealed MMH copper deposit was discovered in 1989 under a blanket of gravels, west of the West Fault that truncates Chuquicamata [1, 2, 3]. MMH extends 7 Km NS, 200 to 320 m EW and more than 1200 in depth (Fig. 2). Estimates suggest the deposit contains resources of ca. 1,310 Mt @ 0.96% Cu as sulfide ore, 26 Mt @ 0.54% Cu as (supergene and exotic) oxides, with a total resource of 12.6 Mt of Cu metal, qualifying MMH as another supergiant porphyry type Cu deposit within the renowned Chuquicamata district [4]. The richest upper central zone of the deposit, containing 227 Mt sulfide reserves @ 1.06 % Cu is presently being developed for open pit mining to start in 2013,. Remaining deeper resources with Cu and Mo mineralization are to be exploited later by underground methods. The geology of MMH is based on the mapping of 170,000 m of drillcore, 7.3 km of underground workings and detailed microscopic and geochronological studies [5,6,7]. The present summary is an update of the geological model of MMH established by Müller and Quiroga in 2003 [3].

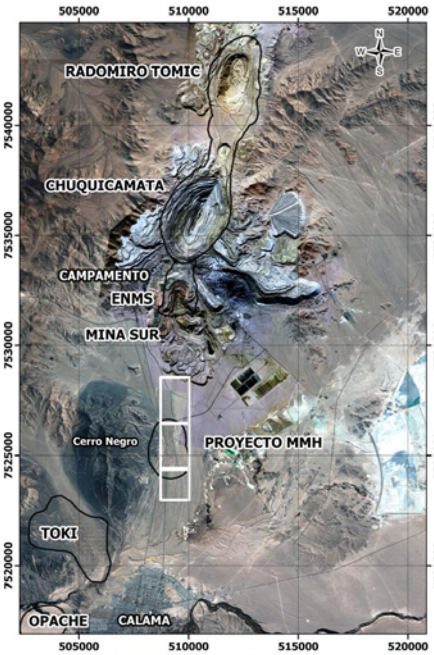

Fig. 1 Location of the MMH deposit.

Geology

MMH is a mega porphyry Cu-(Mo) deposit with the superposition of hydrothermal breccias/stockwork bodies containing Cu-(Ag-As) in its upper part [2, 3]. The porphyry and mineralization make up an elongated body resembling a large dike (Figs. 2a, 2b). It is situated west of a major strand of the West Fault system, an arc-parallel set of (early dextral, later sinistral) transcurrent fault active in Cenozoic times [1, 8]. East of the fault, Paleozoic metamorphic, intrusive and volcanic basement rocks dominate, covered by ca. 1000 m of Cenozoic gravels. West of the fault volcanic rocks are intruded by Eocene intrusive bodies. Hypogene mineralization is distributed within a fanning, subparallel array of subvertical hydrothermal breccia bodies with a NS to N15^{o}W elongation, parallel to the West Fault (Fig. 2a). Supergene enrichment and oxidation are minor west of the fault, and an exotic oxide blanket occurs in the gravels to the east (Fig. 2b). Within the deposit (Fig. 2), the older rocks are undifferentiated green **andesitic** flows and breccias with chlorite, epidote and pyrite, assigned to the Triassic Collahuasi Fm., although zircon dates indicate some rocks may be Paleozoic in age [5, 6]. As seen in Fig. 2b, the bulk of the hypogene ore is hosted by the pervasively altered, equigranular **MM Granodiorite.** It has a Triassic zircon U/Pb LAM-ICPMS age [Bertens in 6], and is presently considered to be the equivalent to the Este Granodiorite of Chuquicamata. The dike-like **MM Porphyry** appears deep in the deposit and adjacent to the West Fault (Fig. 2); its U/Pb LAM-ICPMS age in zircon is 38.9 ± 0.4 Ma [Bertens in 6]. It has an aplitic groundmass and scarce quartz *eyes*; it displays potassic alteration with K-feldspar (as veinlets and rims on plagioclase), biotite and green-grey sericite, cut by *A type* quartz veinlets. MM Porphyry is cut by early *B type* veinlets (with axial molybdenite and chalcopyrite). It is mineralized with bornite-chalcopyrite-(digenite). The **Quartz Porphyry** was intersected in one deep drillhole. It is characterized by abundant quartz *eyes*. It has been affected by potassic alteration with green-grey sericite, K-feldspar and anhydrite, and contains disseminated bornite and chalcopyrite in fine stockworks. This porphyry cuts mineralized and altered veins of the MM Porphyry. Its U/Pb LAM-ICPMS age in zircon is 35.5 ± 0.6 Ma [Bertens in 6]. **Dacite dikes** belonging to more than one generation intrude all the above units along faults but are cut by hydrothermal breccias; some are Triassic [6]. They are aphanitic with crystals of hornblende, plagioclase and scarce quartz. **Hydrothermal breccia bodies** rooted in the MM Porphyry (Figs. 2a, 2b) host the highest Cu grades, as well as elevated values of As and Ag. These consist of isolated angular (dacitic) rock fragments within a matrix of sulfides (chalcocite, enargite and pyrite), rock powder, silica and alunite; laterally these bodies grade into mineralized random stockworks. Where the breccias show evidence of rotation of clasts, and banding, Cu grades are highest. Advanced argillic alteration (silica, alunite, pyrophyllite, sericite and dickite) accompanies these breccias bodies. At depth they contain assemblages with bornite-chalcocite-pyrite, at medium depths chalcopyrite-tennantite-pyrite, and closer to the surface chalcocite-enargite-pyrite-(bornite)-(covellite). High-grade Cu zones (>2 %) contain high As, Ag, and Zn values [2]. Minor gold is present in some bodies. This assemblage represents a transition between a typical Cu-Mo porphyry and "epithermal" high-sulfidation mineralization [2]. **Pebble dikes**: post-ore dike-like bodies of breccia occur within the NS fault and vein system; some are up to 30 m wide. Clasts are angular to rounded in a clastic matrix, barren of mineralization; they are interpreted to be products of fluidized beds during venting of highly pressurized steam. **Sedimentary rocks and exotic ores.** Eocene and younger gravels are present east of the West Fault. A 10 to 50 m thick blanket of exotic copper mineralization is found in the lower MM Gravel unit below the contact with an upper thin brown unit. The unit contains chrysocolla, Cu-bearing cryptomelane, malachite, azurite, conichalcite and smectite.

Geologic History

The MMH ore system developed in several episodes, starting with the intrusion of the MM Porphyry at ca. 39 Ma (similar to the Fortuna Complex, Chuquicamata [4]) and the Quartz Porphyry at ca. 36 Ma (from reliable U/P dates on zircon, thus older than the Este Porphyry of Chuquicamata ca. 35 Ma [4]). Three phases of hypogene mineralization are recognized: 1) Cu-(Mo) Porphyry, with potassic alteration forming a bornite-chalcopyrite nucleus and a chalcopyrite-pyrite halo; 2) Phyllic alteration with sericite and abundant pyrite; and 3) Late stage high-sulfidation Cu (Ag-As) with advanced argillic alteration and introduction of hydrothermal breccias (with pyrite, enargite, chalcocite, bornite and tennantite). The oldest Re/Os date on molybdenite associated with copper sulfides is 37.3 Ma [Bertens in 6], suggesting a possible temporal and genetic association with the MM Porphyry. However other Re/Os dates in molybdenite range from 35.2 to 32.7 Ma (mean 34.7 Ma) hence mineralization is: a) younger than the MM Porphyry (related to the Quartz Porphyry?); b) it occurred in several pulses, or c) older ages were rejuvenated by younger thermal events. $^{40}Ar/^{39}Ar$ dates probably reflect the time of cooling to argon retention temperatures for various minerals (ca. 34.3 Ma for biotite in MM Porphyry, 34 Ma for sericite, 32 Ma for K-feldspar) [6,7]. Hypogene alunite from the high-sulfidation stage yields $^{40}Ar/^{39}Ar$ ages of ca. 31.4 to 32.2 Ma [6,7], slightly older than the Quartz-sericite mineralization phase of Chuquicamata (ca. 31 Ma [4]). Post-ore pebble dykes indicate continuing geothermal activity in the system. After exhumation of at least 1 km of cover, in situ oxidation and weak supergene enrichment occurred during early Miocene times (supergene alunite has $^{40}Ar/^{39}Ar$ age of 22.7-23.2 Ma [Bertens in 6]). Exotic Cu ores formed within the Cenozoic gravels, from outflow of supergene processes in Chuquicamata. A single apatite fission track age of 4.5 Ma in the sheared and sericitized MM Granodiorite [7], if confirmed, may suggest that the fault system continued to be a conduit for warm fluids into the Pliocene.

Conclusion

The giant MMH deposit formed by the superposition of different pulses of mineralization related to the intrusion of Eocene porphyry stocks controlled by and parallel to an evolving West Fault. MMH is an interesting example of the transition between porphyry and epithermal, high-sulfidation systems. MMH mineralization is relatively older than that at Chuquicamata and RT and contemporaneous with Cluster Toki orebodies (Fig. 1). The position of MMH with respect to Chuquicamata before the postulated >35 km sinistral displacement of the West Fault [e.g. 8] remains unresolved.

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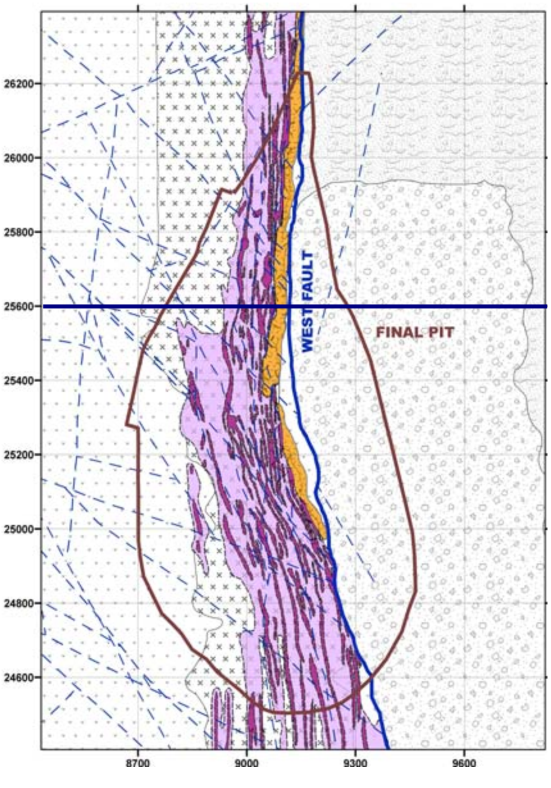

Fig. 2a. Geological Map of MMH (Level 2200)

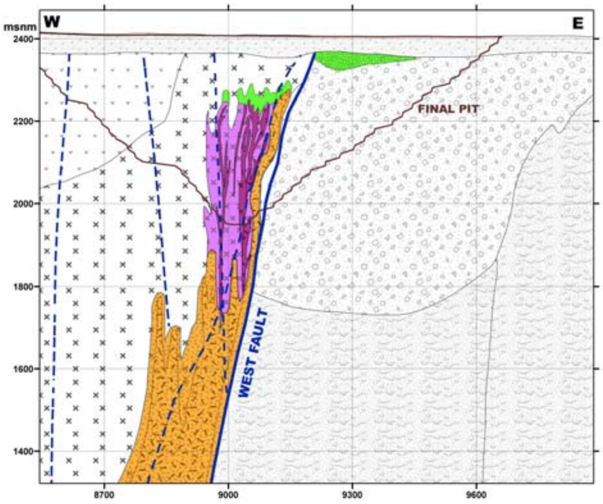

Fig. 2b. Geological Cross Section of MMH 25600N

LEGEND

MINERALIZATION
- 🟩 Exotic Cu Oxide
- 🟩 Cu Oxide
- 🟪 High Sulfidation Cu (Ag). Hydrothermal Breccias
- 🟪 High Sulfidation Cu (Ag) Stockworks
- 🟧 Porphyry Copper Cu (Mo)

LITHOLOGY
- ▨ Gravels. Upper Miocene - Pleistocene
- ▨ MM Porphyry. Eocene
- ▨ Calama Fm. Continental sedimentary breccias. Eocene
- ▨ MM Granodiorite: Triassic
- ▨ Collahuasi Fm. Andesites, tuffs. Carboniferous - Permian
- ▨ Meta-Plutonic Cerros de Chuquicamata Complex: Carboniferous- Permian