Chuquicamata, the world's greatest copper orebody

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Abstract
Chuquicamata, in northern Chile, is the world's greatest orebody. It was mainly controlled by initial intrusions (probably at 36 to 33 Ma) through mineralization (last major hydrothermal event at 31 Ma) to postmineral brecciation and offset by the West Fault system. The Chuquicamata Porphyry Complex consists of the East Porphyry, West Porphyry, Banco Porphyry and Fine Texture Porphyry. Potassic alteration, the early stage of alteration, affects all porphyries. Veins of quartz-molybdenite, up to 5 m wide and cutting all porphyries, were emplaced between the early and the main stages. Main-stage veins occupy many of the same structures of the early stage and may involve massive remobilization of earlier mineralization. The late stage formed digenite with relatively coarse grained covellite from deep in the sericitic zone. A leached capping and oxide copper ore, replacing an upper chalcocite blanket, overlie a high-grade supergene chalcocite body that extends up to 800 m in depth.

Introduction
Chuquicamata lies in the Atacama Desert at about 2800 m elevation in northern Chile, approximately 15 km north of Calama and 240 km northeast of Antofagasta. It belongs to the Chuquicamata district comprising of Radomiro Tomic, MM, Mina Sur and Chuquicamata itself. At the beginning, outcropping copper oxide was worked out by the Incas and Spanish explorers. Later English and Chilean companies try to win the ore. In 1915, open-pit mining was initiated on disseminated oxide ore by Chile Exploration Co. Anaconda Copper Mining Co. purchased the property in 1923 and managed 48 yr of continually expanding operation. Within the years production increases and shifted from dominantly oxide to dominantly sulfide ores in the 1950s as the pit deepened. In 1957 Exótica (now Mina Sur) deposit was discovered. In 1970, the mine was nationalized and management and operation were taken over by the Corporación Nacional del Cobre-Chile (CODELCO). Furthermore, geologic models, ore reserve calculations grade control and mine planning were accomplished. By 1993 it was clear, that the geologic model, which was used, was long overdue. So major effort was initiated and over 2300 drill holes were relogged and/or reinterpreted. The results of these efforts were the focus of a day-long symposium sponsored by the Society of Economic Geologists at the Eighth Chilean Geological Congress in 1997. After the standings of this congress two thousand and thirty-five million metric tons (2,035 Mt) of ore, averaging 1.54 % Cu has been mined from the Chuquicamata orebody, plus 120 Mt of 1.25 % Cu from the South mine. A resource of some 6,450 Mt at 0.55 % Cu remains in the main orebody, plus 190 Mt of 1.12 % Cu in the South mine. In 1997, the combined production from the Chuquicamata and Exótica orebodies was 644,000 t of fine copper (Ossandón and Zentilli 1997). In 2006, the production rate rises to 940,613 t of fine copper and 17,781 t of molybdenite (http://www.codelco.cl).

Geologic Setting
Chuquicamata lies in the Precordillera of northern Chile, which is parallel and west of the volcanoes that form the modern continental arc of the Andean Cordillera. It is closely related to Eocene, early Oligocene porphyritic intrusions that occur within the middle to late Cenozoic, north-south striking Domeyko Fault system.
Pre-Oligocene rocks
The oldest rocks in the Chuquicamata district occur in a north-northeast trending belt of Paleozoic metasedimentary and metaplutonic rocks, which are exposed within the South mine pit and within a kilometer east of the Chuquicamata pit (Fig. 1). After Tomlinson (1999) these rocks include gneissic granite, metadiorite, quartz diorite, and minor tonalite recrystallized in varying degrees to amphibolite. The widespread pervasive chlorite-epidote-calcite alteration in the metadioritic rocks was interpreted by Ambrus (1979) as retrograde regional metamorphism rather than propylitic alteration related to the orebodies. Dioritic rocks intrude the Mesa Granite. It is a pink microcline granite with locally developed weak to moderate gneissic fabric. In Sierra Limón Verde, south of Calama, this granite is also recognized and dated at late Carboniferous (Marinovic and Lahsen, 1984). At the west edge of the metaplutonic complex East Granodiorite intrudes and extends at least 9 km northnortheast from the southeast edge of Chuquicamata pit along the crest of the Chu-

quicamata hills. It is medium to coarse equigranular texture, with plagioclase, microperthitic K-feldspar, quartz, biotite, and hornblende. Zircon dating with U-Pb shows a Middle Triassic age (Tomlinson, 1999). After Ambrus (1979) local alteration to albite-chlorite-magnetite and sericite-clay is attributed to the influence of the Chuquicamata porphyries.
In the Sierra Limón Verde, these crystalline rocks are unconformable overlain by a volcanic and sedimentary sequence of Mesozoic age. At its base this sequence consists of continental facies conglomerate, sandstone, and andesitic and dacitic lava, breccia, and tuff of presumed Late Triassic age (Lira, 1989; Mpodozis et al., 1993). A transgressive marine sequence of Jurassic shale, sandstone, and limestone overlay this sequenz gradationally. Equivalent Mesozoic rocks in the Chuquicamata Hills are often in fault contact with the basement rocks (Tomlinson, 1999). Here andesitic volcanic rocks are the dominant Mesozoic lithology, but continental sandstone units crop out on the north flank of the Chuquicamata Hills.
Along the Mesabi Fault occur marine limestone and calcareous shale as fault slivers from the north end of the hills to the east edge of the pit. The sedimentary units in the pit consist of calcareous, fine-grained sedimentary rocks that are intruded and contact metamorphosed by East Porphyry of the Chuquicamata Porphyry Complex (Lindsay, 1998).

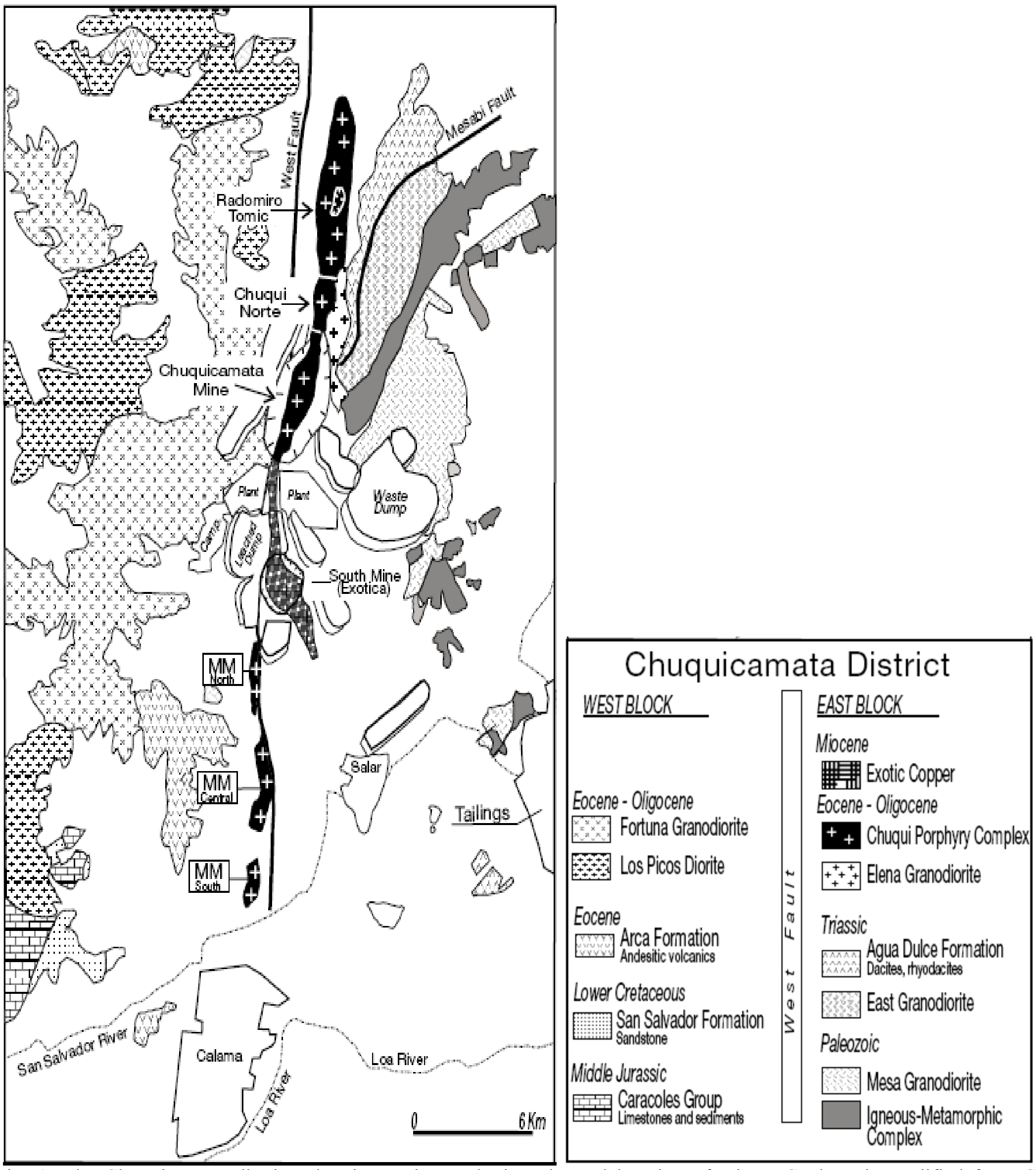

Fig: 1: The Chuquicamata district, showing major geologic units and location of mines. Geology is modified from G. Chong and R. Pardo, unpublished map (1997). The Chuquicamata mine is at 22o17.5' S, 68o54.5' W (UTM E510350, N7535600). Reference: Ossandonet al. 2001, Geology of the Chuquicamata Mine: A progress report: Economic Geology, v. 96, p. 249–270.

Eocene-Oligocene intrusions

The porphyritic rocks in the Chuquicamata pit, with the dominantly barren Fortuna Complex to the west and the intensely mineralized Chupui Porphyry Complex to the east, are separated by the major postmineral West Fault. Rocks with textures essentially identical to those of the Chuqui Porphyry Complex extend northward at least 9 km through the Radomiro Tomic mine (Cuadra et al., 1997; Cuadra and Rojas, 2001).

Structure

The West Fault, separating the two halves of the Chuquicamata pit, is a major strand of the West Fault system, as the part of the Domeyko Fault system north of Calama is now called. This structure zone extends several hundred kilometres in northern Chile. It is interpreted as a Cenozoic age, arc-parallel set of transcurrent and reversal faults. North of the Chuquicamata pit, from the Terera Fault on the west to the Mesabi Fault on the east, the zone is 5 km wide. Dilles et al. (1997) and Tomlinson and Blanco (1997) describe the evolution of the West Fault system. It has been active prior to intrusion of the Chuquicamata Porphyry Complex until after 1 Ma, changing sense of movement at least twice. Furthermore it has had a critical control on the emplacement of the host intrusions, formation of mineralized structures, and postmineral displacement of the orebodies.

Rock Types

Fortuna Intrusive Complex

The Fortuna Intrusive Complex borders to the open pit and contains only low-grade mineralization. It has been structurally juxtaposed against the intensely mineralized Chuquicamata Porphyry Complex by large-scale, postmineral movement on the Wets Fault, which is documented by Dilles et al. (1997), Tomlinson and Blanco (1997), and previous workers. The Fiesta Granodiorite phase of the Complex is volumetrically dominant and is intruded by small irregular bodies of San Lorenzo Granodioritic Porphyry and minor Tetera Aplite Porphyry. Fiesta Granodiorite is weakly mineralized with copper oxides in the uppermost northwestern benches of the pit. Sulfides occur only near contacts of the San Lorenzo porphyries.

Pre-Chuqui porphyry intrusions

The Elena and East Granodiorites are exposed on the eastern margin of the pit. They intrude metasedimentary rocks that were originally shale and sandstone with minor limestone. Whereas Elena Granodiorite is mineralogically and texturally similar to the East Porphyry, the East Granodiorite is texturally distinctive and clearly older. A radiometric dating of the Elena Granodiorite indicates a Jurassic (dating of zircon) to Early Cretaceous age (dating of biotite), published by Ambrus (1979). All of these rocks at the east edge of the pit are essentially poor of mineralization.

Chuqui Porphyry Complex

Practically the entire Chuquicamata orebody is hosted by the Chuqui Porphyry Complex, made up of East, West, Fine Texture, and Banco porphyries. Their textures vary widely, and most exposures are affected by some degree of hydrothermal alteration and pervasive cataclastic deformation. The probably oldest and largest intrusion is the East Porphyry with hypidiomorphic-granular texture. The West Porphyry is finer grained and with quartz eyes in an aplitic groundmass. Locally both porphyries are weakly foliated. Banco Porphyry is more porphyritic and finer grained than East Porphyry, which it intrudes. From West Porphyry it differs in having an abundance of small plagioclase crystals in the aplitic mass. The Fine Texture Porphyry is distinctly finer grained than normal East Porphyry but has also a hypidiomorphic-granular texture. Contacts with East Porphyry may be abrupt but usually faulted. Because of the overprinting of most dikes by quartz-sericite alteration, their identification is very difficult. Furthermore is seems, that Banco and Fine Texture porphyries have been affected by all of the same stage of alteration and mineralization as the East Porphyry.

Structural Controls

The dynamic setting within the West Fault system, described by Tomlinson and Blanco (1997), has been a critical control on events at Chuquicamata, from initial emplacement of the porphyries to metal distribution and slope stability in the present-day pit. During an early period of dextral shear developed between the Mesabi Fault on the east and a western fault, that has probably been displaced by or evolved into the younger West Fault, various vein systems were formed. Following reversal of movement to sinistral shear produced the postmineral offset on the West Fault. The evolution of the shear system from ductile to brittle and its control on mineralization in the deposit have been described by Lindsay et al. (1995), Rojas and Lindsay (1997), and Lindsay (1998).

A large part of the copper at Chuquicamata occurs in veins and veinlets filling faults and fault-related shatter zones. In the main orebody practically all of these fractures have been opened and mineralized more than once. Early-stage veinlets of quartz and quartz-K feldspar contain no or only very minor sulfide. They are cut by more continuous quartz veins, to 5 cm wide, containing minor molybdenite and traces of chalcopyrite. Large banded quartz veins, known as blue veins, are typically 1 m or more in width. They contain abundant molybdenite and truncate the previous veins. Furthermore, they are commonly surrounded by sericitic alteration, but this is due to superposition of younger pyritic veins following the same structures. Veins and veinlets of the main stage contain pyrite, chalcopyrite, bornite, and digenite, decreasing amounts of quartz and increasingly well developed sericitic alteration halos. Locally, the earliest of these veins appear to contain pyrite without Cu sulfide (Lindsay et al., 1995). Relatively late main stage veins contain enargite ± pyrite and minor sphalerite. Later on, veinlets and fractures are filled with relatively coarse grained covellite (to 1 mm) and digenite with and without pyrite.

Because of the abundance and complexity of crosscutting and offset faulting, veins and faults have hardly any continuity. In general, early north-south to northeast striking fault veins show pre- to synmineral, dextral movement, with superimposed sinistral reactivation, and contain all stages of mineralization. Northwest-striking structures are younger, show sinistral movement, and are largely barren, except for minor enargite-sphalerite and covellite-digenite mineralization.

Hypogene Alteration and Mineralization

The gross patterns of alteration and sulfide mineralization within the orebody, as exposed in the pit at the end of 1995, are shown in Figure 2A and B.

Just like El Salvador and many other porphyry copper deposits, vein relationships lead to the definition of an early stage defined by K feldspar stable alteration and early quartz veinlets, a transitional stage defined by quartz-molybdenite veining, and a main-stage defined by pyrite-bearing veins with sericitic halos. A more unusual and controversial late stage is defined by coarse-grained covellite-digenite veinlets without pyrite and possibly hypogene sphalerite rims on other sulfides (Fréraut, et al., 1997).

Early-stage alteration and mineralization

The earliest events after consolidation of the porphyries are the formation of potassic alteration and more local quartz and K feldspar-quartz veinlets. Characteristic for the potassic zone is the replacing of hornblende phenocrysts by biotite, whereas quartz veinlets and secondary K feldspar are more restricted. A component of potassic alteration assamblages and of all other subsequent stages of hypogene alteration and mineralization is anhydrite, variably hydrated to gypsum and leached from much of the orebody by supergene solutions. Early-stage quartz and quartz-K feldspar veins carry practically no sulfide.

All of the rocks within the Chuqui Porphyry Complex are affected by potassic alteration and are cut by at least some early-stage veins. Furthermore all porphyries have been subjected to pervasive cataclastic deformation.

Quartz-K feldspar alteration, which is interpreted as a distinct alteration type, occurs in a band of hard white to grey rock with obliterated texture. Quartz-K feldspar differs from normal potassic alteration in that biotite is completely replaced by K feldspar and quartz. Furthermore, the texture is further obliterated by pervasive cataclastic deformation and streaking with fine-granular quartz-K feldspar and added silica occurs as a fine granular replacement with K feldspar rather than as quartz veinlets. Any residual plagioclase in the rock is albite. Cataclastic deformation indicates that albitization preceded quartz-K feldspar alteration.

A second zone of silicification and lacking original biotite trends north-northest at the north end of the pit (Hunt, 1962). In contrast to the main quartz-K feldspar zone, this zone has much less intense cataclastic deformation and texture obliteration. Further on, some quartz-molybdenite veins are segmented and intensely recrystallized. Whether this deformation of the veins is related to quartz-K feldspar alteration is not clear. Assumed is that quartz-K feldspar alteration is a separate and later stage of alteration from normal potassic alteration. Alternatively, quartz-K feldspar could be simply an extreme and continuous development of potassic alteration.

The dominant background sulfide association in the potassic zone is chalcopyrite-bornite without pyrite, whereas bornite is subordinated. In the quartz-K feldspar zone bornite-digenite-chalcopyrite association is dominant. Digenite is commonly accompanied by coarse-grained covellite and most sulfides are in fractures and brecciated zones.

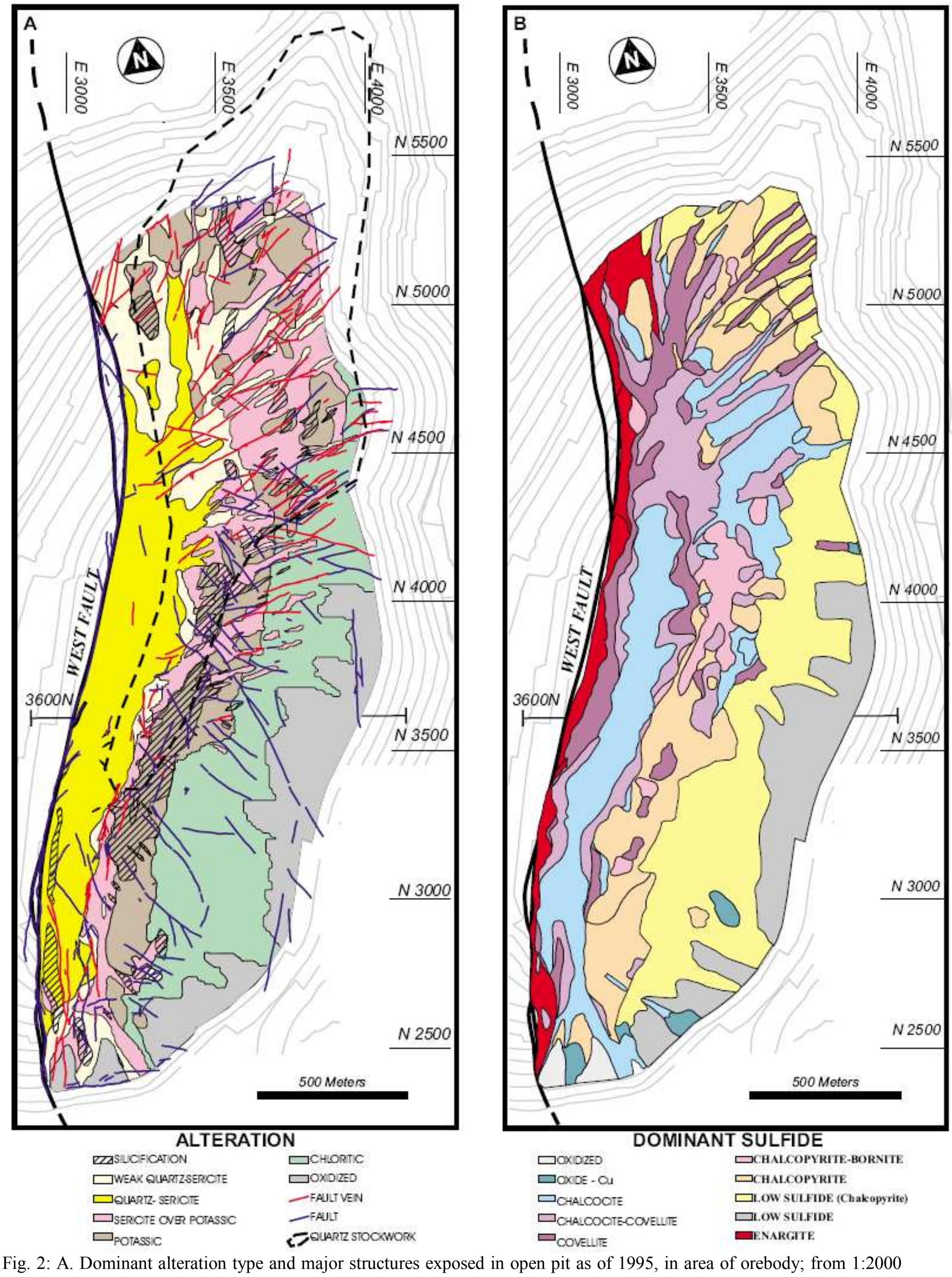

Fig. 2: A. Dominant alteration type and major structures exposed in open pit as of 1995, in area of orebody; from 1:2000 mapping by Rojas and Lindsay (1997). Oxidized rock lies above the top of sulfide but is not necessarily leached. Megascopic silicification is partly equivalent to quartz-K feldspar alteration. B. Dominant copper sulfide exposed in open pit as of 1995; pyrite is ubiquitous, mostly associated with main-stage veins, which are most abundant in quartz-sericite and sericite over potassic alteration zones. Bottom bench is 2,437 m, top mapped bench is 2,697 m. Reference: Ossandon et al. 2001, Geology of the Chuquicamata Mine: A progress report: Economic Geology, v. 96, p. 249–270.

Quartz-molybdenite stage

At Chuquicamata molybdenite is conspicuous, almost all of it carried by quartz veins as disseminated crystals and as "smears" in cracks. These quartz-molybdenite veins are clearly cut by main-

stage veins, which are characterized by pyritic assemblages and sericitic alteration. Ubiquitous is the reopening of earlier formed veins and overprinting of younger sulfide and alteration halo assemblages. There is also a strong correlation between the abundance of quartz veins and molybdenite. The distribution of molybdenite exposed in the pit is illustrated in Figure 3B.
In the quartz-sericite alteration zone very high Mo values of 0.07 to 0.25 wt. % are concentrated. The pattern is asymmetrical, with an abrupt western edge of moderate Mo values (> 0.01 wt. %) and quartz veins, and a more gradational decrease of quartz veins and Mo values to the east.

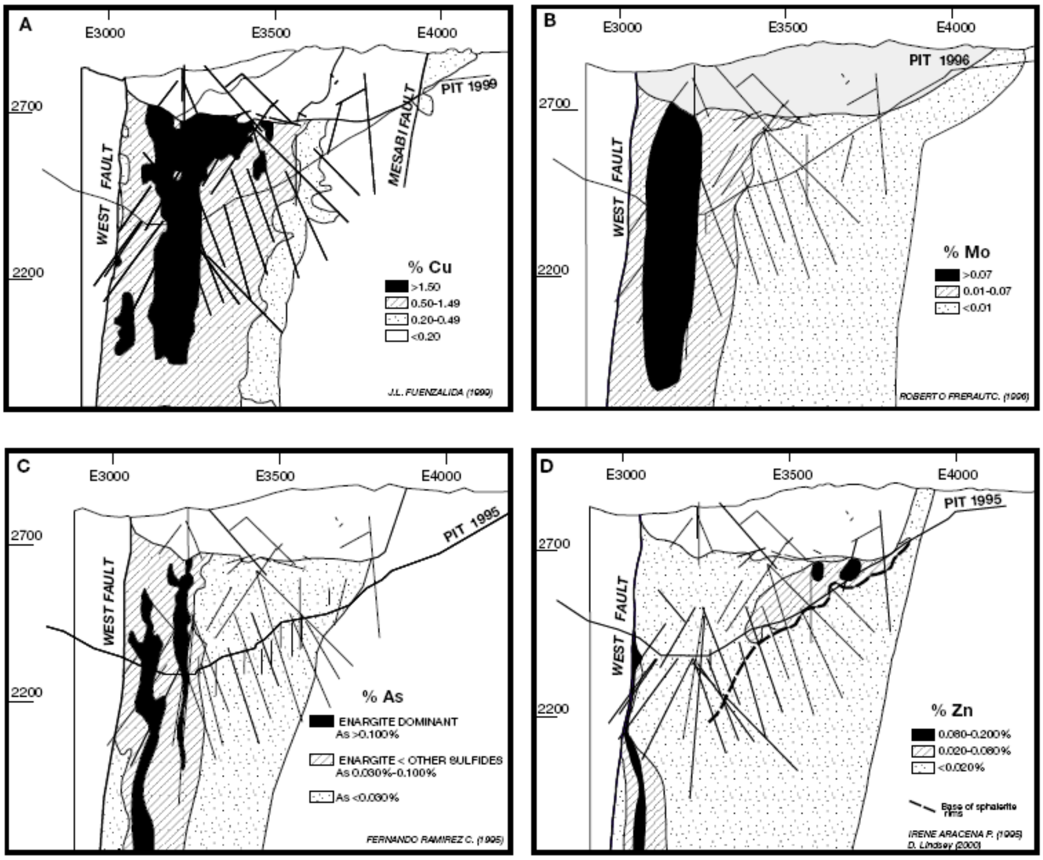

Fig 3: A-D. Distribution of copper, molybdenum, arsenic, and zinc in 3600N section, from diamond drill hole and blast holes. Reference: Ossandon et al. 2001, Geology of the Chuquicamata Mine: A progress report: Economic Geology, v. 96, p. 249–270.

Main-stage

In the western side of the orebody adjacent to the West Fault all traces of earlier assemblages were obliterated by pyritic veins and quartz-sericite alteration of the main-stage of mineralization (Fig. 3). Copper emplaced during the main-stage, plus supergene enrichment of largely main-stage assemblages, accounts for most of the metal production to date and a large part of future reserves, although this part is impossible to quantify. Sulfide veins of this stage are defined by sericitic alteration halos and assemblages of pyrite with varying content of quartz, Cu-Fe sulfides, enargite, tennantite, and sphalerite. Quartz-molybdenite veins were cut by these veins. The quartz-sericite zone represents merging of sericitic halos of this stage of mineralization. Upward and eastward, the zone of quartz-sericite and sericite over potassic alteration encroach on the potassic zone, accompanying pyrite with chalcocite and covellite.
Principal vein assemblages in the main-stage are pyrite-chalcopyrite-bornite, pyrite-bornite-digenite ± enargite, and pyrite-digenite-covellite ± enargite. In the earlier formed main-stage veins quartz is abundant, but it could also be inherited from an earlier quartz-molybdenite vein with only minor molybdenite. Pyrite, the only sulfide in some veinlets, is very abundant (> 3.5 wt. %) in the high enargite part of the quartz-sericite zone. Within much of the quartz-sericite zone enargite-pyrite in veins are dominant.
The dominant sulfides in the western part of the orebody are chalcocite, digenite, and covellite, along with pyrite and enargite (Fig. 2B). Digenite is largely hopogene. Chalcocite is clearly super-

gene at higher elevations, commonly sooty, occurring as thick rims on pyrite and other sulfides. It extends to great depth where the alteration is least reactive. Fine-grained covellite increases relatively to chalcocite downward within the flat west-dipping enrichment blanket. It is of supergene origin and rims chalcopyrite and other primary sulfides. At depth, relatively coarse-grained covellite (0.5 to 2 mm) is clearly hypogene (e.g., Lewis, 1996). Further, chalcocite may be intergrown with coarse-grained covellite or bornite and may lack rimming textures suggestive of supergene origin. In fact it is very difficult to distinguish hypogene from supergene chalcocite and covellite. Although sericite-quartz is the alteration typically associated with main-stage veins, alunite also occurs locally with pyrite-enargite mineralization. Normally one would expect to find pyrophyllite and/or dickite occurring with alunite in high-sulfidation assemblages of pyrite, enargite, covellite and digenite. But after Ossandón et al. (2001) only traces of pyrophyllite and dickite have been detected locally.

Sphalerite, with 0-5 wt % Fe (Zentilli and Graves, 1993), is usual in many veins with enargite, including veinlets which contain little or no pyrite but may contain covellite-digenite. These younger veinlets occupy late-formed northwest structures. Minor tennantite occurs with pyrite-chalcopyrite in veins and veinlets within the potassic zone and contains up to 8 wt. % Zn (Zentilli and Graves, 1993).

Late-stage

In contrast to the covellite-digenite-pyrite veinlets at the main-stage, the veinlets of the late-stage are without quartz, pyrite or other sulfides. But most of them contain red hematite and locally anhydrite.

An impressively feature is a zone of moderate to high Zn values (0.02 to > 0.08 wt. %; Fig. 3D), largely due to rims of sphalerite on chalcopyrite and other copper sulfides. Moderate to high Zn values furthermore extends to depth along with high As and correlates with the presence of coarse-grained sphalerite in the enargite veins. Below the Zn zone in the east are low Zn values which are contained in traces of sphalerite and Zn-bearing tennantite within pyrite-bearing veinlets. Beneath the top of Zn sphalerite rims are continuous in a band about 100 to 200 m wide. They extend from the anomalous Zn zone in potassic and chloritic alteration in the east across the quartz-sericite zone in the west. Because of this distribution and their textures it is supposed that they are formed as a lower zone to the supergene chalcocite blanket (Aracena et al., 1997). Anymore the sphalerite rims occurrence of inner rims of covellite and/or digenite and it seams that they are coeval with the late-stage covellite-digenite veining. They appear also within anhydrite-saturated rock, which would confirm their hydrothermal origin. The iron content of rim sphalerite is up to 1.2 wt %, highest where rims are on chalcopyrite.

Supergene Mineralization and Alteration

After Taylor (1935) and Jarrell (1944) the rich oxide copper orebody has been largely mined out, but considerable resources of lower grade material remain in the north end of the pit and beyond (North zone, Fig. 1; Cuadra et al., 1997; Ossandón and Zentilli, 1997). Oxide ores contain a large variety of minerals but in chief antlerite, brochantite, atacamite, chrysocolla, and copper pitch. Also residuals of chalcocite are implied. The ore was overlain by leached capping and was an eastward and upward extension of the chalcocite zone, indicating it was a supergene chalcocite enrichment blanket oxidized in situ. It is the upper of two chalcocite blankets with a leached horizon in between. A lower enrichment zone has more reactive alteration assemblages and contains decreasing chalcocite and/or covellite proportions downward. In the central zone of intense brecciation, the two enrichment blankets (copper leaching and chalcocite enrichment) merge and reach their maximum depth.

So this is the largest enriched orebody in the world. Clearly a large thickness of leached capping above the premine surface was necessary to produce the copper. The leached rock in the north is largely goethite with jarosite, what one would expect from oxidation of moderately pyritic protore (Anderson, 1982). Copper has also been leached out of Fe-rich, steep structural zones within the copper oxide horizon. Here the limonite is hematitic, as one would expect from oxidation of chalcocite-enriched pyritic vein zones, and consistent with the interpretation of two stages of oxidation and sulfide enrichment related to a changing water table. A component of each of the hypogene alteration assemblages is anhydrite, variably hydrated to gypsum. It saturates all porosity in rocks in which it occurs. Before any supergene leaching or enrichment of sulfide could appear, it had to be leached by supergene solutions. This sulfate zone rock in continuous intervals was only found in

drill holes in more than 800 m below the premine surface (Hunt, 1969; Gustafson and Hunt, 1975). At 1200 m anhydrite has been hydrated and leached from most fault zones, and what was once a continuous sulfate zone has been reduced to isolated residuals of gypsum and rarer anhydrite diminishing upward between structural zones.
In fact very important quantities of copper were leached from the oxidized capping and probably from the chalcocite blanket and moved laterally. Originally over 300 Mt of exotic copper ore was deposited in gravels south of the pit to form the Exótic orebody.

Geochronology
Because the dating of significant events at Chuquicamata has proven to be an extraordinary difficult problem, there are many different published efforts at dating events.
Ballard (2000) has applied eximer laser ablation inductively coupled plasma mass spectrometry (ELA-ICP-MS) dating of zircon from the intrusive units and got ages of 34.8 ± 0.3 Ma for East Porphyry, 33.3 ± 0.3 Ma for West Porphyry, and 33.4 ± 0.4 Ma for Banco Porphyry. East Porphyry was also dated by Larry Heaman and Marcos Zentilli by the use of U-Pb single grain and multigrain ages in zircon. They obtained ages for zircon crystallization of 35 to 36 Ma and for the inherited grains 37 to 38 Ma. The $^{40}Ar/^{39}Ar$ dating of sericite formed during the main-stage of mineralization gives an age of 31.1 ± 0.2 Ma. Feldspar and biotite in the potassic alteration zones relatively distant from major sericitic veins and at higher elevation show $^{40}Ar/^{39}Ar$ ages of 35 to 34 Ma. Closer to zones of sericite alteration and from deep below the pit they yield in contrast ages of 31 to 32 Ma (Reynolds et al., 1998).
By using the Re-Os technique Joaquin Ruiz (1998) has obtained an age of molybdenite, collected from typical blue quartz vein, of 34.9 ± 0.17 Ma. Ages of 30 Ma were dated at fission track in apatite within the deposit by Maksaey (1990). This indicates fast cooling of the system to ca. 100° C soon after the main stage of mineralization. Sillitoe and McKee (1996) has used K-Ar dating of alunite from supergene enrichment and alteration and estimated an age of 15 to19 Ma.
Based on all analyses it can conclude that East Porphyry is probably significantly older than West and Banco porphyries, and that all were emplaced before 33 Ma. After Ossandón et al. (2001) potassic alteration and subsequent quartz-molybdenite veining was probably closely associated with the emplacement and cooling of West, Fine Texture, and/or Banco porphyries. At least 2 m.y. later main-stage hydrothermal activity followed as a separate event. An intrusion related to this event has certainly not been identified.

Discussion
Premain stages: Between East Porphyry to Banco Porphyry is a clear succession of intrusion followed by potassic alteration (biotite formed and texture largely preserved), and early-stage quartz-K feldspar veining, and quartz-K feldspar alteration (biotite and texture destroyed) with extreme cataclastic deformation afterward. It is not clear where West Porphyry and Fine Texture Porphyry fit in, but both are cut by early-stage quartz vein and potassic alteration. Before or at the beginning of quartz-K feldspar alteration, and linked to the cataclastic deformation, there was local albitization, which may or may not be relate to potassic alteration. Furthermore not clear is the timing of quartz-K feldspar development relative to formation of quartz-molybdenite veins.
Early stage quartz veins contain outside of clearly younger fractures little more than trace sulfide. The quartz is completely recrystallized by younger events, which released any fluids trapped in early fluid inclusions and could have remobilized any original sulfide. Even though the quartz-K feldspar zone is the locus of the bornite-digenite center of the premain hydrothermal stage sulfide zoning pattern, most of the sulfide fills brittle fractures. These are clearly younger than the quartz-K feldspar alteration itself. Such fractures lacking in quartz-K feldspar rock and disseminated sulfide is sparse. Furthermore, this central sulfide assemblage often includes coarse-grained covellite with digenite. Thos association characterizes the late-stage assemblage here but is not reported in deep central zones of other porphyry copper deposits. Nevertheless typical of standard porphyry copper zoning are the gradational decrease of Cu-Fe in the background sulfides eastward (and westward prior to the main stage), with pyrite appearing outside of sericitic veins and halos only after bornite disappears, and the disseminated to veinlet textures.
Main stage: The complexity of superimposed events, complicated by supergene effects, makes it difficult to differ between the individual evolutionary events and estimate how much of the copper was actually contained in each.

The pervasive deformation and recrystallization of early quartz veins, along with the low sulfide content of these veins and most potassic altered rock, suggests that much of the early-formed mineralization may have been remobilized. This copper could have been reprecipitated in main-stage veins. Therefore a magmatic source of heat and sulphur vapour has been required.
Late stage: The upward and eastward flaring of coarse-grained covellite was formed probably during main and late stage. The pattern correlates with increased sericitic overprinting of potassic alteration and represents an upward zonation, which is here less structurally focused than in the quartz-sericite zone. Anhydrite in the late coarse-grained covellite veinlets confirms their formation above the temperature stability limit of gypsum, at least 55°C (Holland and Malinin, 1979). However, the association with apparently amorphous hematite argues against a much higher temperature. Furthermore, supergene sphalerite has never been reported in porphyry copper deposits. This indicates that very unusual conditions would have prevailed at Chuquicamata. Normally Zn is soluble in supergene solutions that it is completely lost from oxidized orebodies unless precipitated as carbonates or sulfates. Here an extraordinary sulphur activity was present to produce covellite.

Further not clear is the question how much of the orebody was displaced by the West Fault and where it has gone. The north-northeast elongate pattern of early potassic alteration does appear at depth to be truncated over more than 2 km, suggesting that much of the early-stage mineralization was lost by faulting, possibly displaced initially to the north. The much younger patterns of As and Zn (Fig. 3C and D) appear to be closing as they get near the West Fault. They, too, have formed at least partly under the influence of this structure. After Ossandón et al. (2001) this suggests there has been much less displacement of later main-stage mineralization and supergene enrichment than of early stages.

Conclusions

Chuquicamata is both the world's greatest copper orebody and the most unusual of all porphyry copper deposits. We can not understand all its phenomena and much more work has to be done. The greatest challenges for geology at Chuquicamata is to document the discovery of all oxide and sulfide ore, which is still lying hidden in the district, and to define accurately the distribution, grade, rock mechanical and metallurgical characteristics of ore. As a result planning, mining, and metallurgical operations can be optimized.

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