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CHUQUICAMATA, CORE OF A PLANETARY SCALE Cu-Mo ANOMALY

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Abstract - The copper and molybdenum mineralisation of the Chuquicamata deposit has been known since the 19th century. The deposit is located within the Codelco Norte District in the Andes Ranges of northern Chile, 200 km northeast of the city of Antofagasta. Small miners initially worked the exposed oxidised outcrops and high grade oxide veins that were the surface expression of the deposit, although industrial scale mining did not commence until 1915 with open pit exploitation of the main disseminated oxides. Mining has continued to the present day, currently removing approximately 170 000 tonnes of ore and 400 000 tonnes of waste per day.

Exploration since the 1950s has delineated a resource of 67 million tonnes (Mt) of *in situ* fine copper at Chuquicamata. It has also outlined additional deposits within the district, including the Mina Sur exotic accumulation with 5 Mt of fine copper derived from Chuquicamata, and Radomiro Tomic (RT) with a potential for 25 Mt of fine copper, representing the northern extension of the main Chuquicamata orebody. Further drilling has located additional mineralisation to the southwest at the MM deposit and the Toki Cluster. Recent deep drilling in the vicinity of these Eocene-Oligocene age porphyry copper deposits of the Codelco Norte District, and new concepts derived from pre-existing information, indicate that Chuquicamata is the core and main deposit of an exceptional regional scale anomalous concentration of copper, molybdenum and other elements of economic interest, that may be called a "planetary scale anomaly". Prior to mining, this "planetary scale anomaly" is estimated to have contained 125 Mt of fine copper and comprises a 39 to 31 Ma mineralised belt, largely covered by recent gravels, but partially exposed over a 30 km long, NNE trending interval. It is the final product of a very complex sequence of processes related to tectonic permeability and structural architecture, with intrusions and multi-episodic pulses of hypogene alteration and mineralisation, and subsequent supergene leaching, oxidation and enrichment.

The Chuquicamata deposit is hosted by a NNE elongated, tabular, 14x1.5 km intrusive complex, which is subvertical to steeply west dipping. This complex, which extends from the Chuquicamata open pit to the RT mine, is known as the Chuqui Porphyry (Chuqui Porphyry) and comprises three phases, the East, West and Banco porphyries. To the east it intrudes a Palaeozoic igneous-metamorphic basement, Triassic granodiorite, sediments and Mesozoic volcanics, while to the west it cuts the 39 to 38 Ma Tertiary Fortuna Intrusive Complex, and both to the east and west the 37.3 Ma Elena Granodiorite. The West Fissure, an important district scale branch of the regional Domeyko Fault System, is a regional, north-south trending, subvertical fault located to the west of the deposit. It exhibits post mineral displacement which splits the Chuquicamata deposit, dividing the highly mineralised Chuqui Porphyry to the east, from the barren Fortuna Complex to the west. The West Fissure is believed to be Cenozoic in age. It has a complex kinematic history including transcurrent and probably reverse movements, and has had a strong structural control over the setting of the ore hosting porphyries, the mineralisation itself and the post mineral evolution of the Chuquicamata deposit. The Messabi Fault-East Deformation Zone, which is recognised on the east and north-east margins of the Chuquicamata and RT pits, affects the wall rocks of the Chuqui Porphyry, and produced ductile and semi-ductile fabrics, including mylonites and cataclastic flows, and was active before, during and after the intrusion of the Chuqui Porphyry, and probably during the early stages of mineralisation.

Recent work has supported a new synthesis of the geological evolution of this giant deposit, commencing with the syntectonic intrusion of the 34.6 Ma East Porphyry as a roughly NNE trending dyke. There is evidence that the Messabi Fault-East Deformation Zone, probably associated with a transpressive dextral tectonic environment, played a key role in localising this intrusive phase. The East Porphyry appears to have been barren or only accompanied by weak, late-magmatic alteration and mineralisation. A more pronounced mineralising event was synchronous with the intrusion of the smaller West and Banco porphyries, dated at 33.4 Ma. This event produced an intense stockwork of barren "A-type" quartz veins, mostly in the northern part of the deposit, with a huge *background potassic* alteration halo of selective biotitisation of

mafics, and secondary potassic feldspar partially replacing plagioclase. This halo affects most of the Chuqui Porphyry, carrying weak and mostly disseminated chalcopyrite, pyrite and bornite, while in its outer fringes chloritic alteration with pyrite predominates, with little or no copper. The background potassic alteration preserved the original texture of the porphyry, adding, depending on the alteration intensity, copper values ranging from 0.1 to 0.5% Cu. Following the background potassic alteration, an *intense potassic* event ensued which was responsible for the main hypogene mineralisation stage at Chuquicamata. This intense potassic alteration occurred as NNE oriented bands, probably related to repeated reactivation of the Messabi Fault-East Deformation Zone. The two resultant alteration assemblages (potassic feldspar-fine quartz and grey-green sericite) shared the same locus as earlier pulses, destroying the porphyry textures and adding abundant veining and disseminated assemblages of bornite-digenite-chalcopyrite-covellite with cumulative grades in the range of 0.6 to 1.2% Cu. Toward the end of the intense potassic event a late pulse of chalcopyrite was zonally deposited on its fringes, generating an average grade of 0.8% Cu, and marking the onset of the more destructive episodes of phyllic alteration. During the transition from the potassic feldspar-fine quartz to the immediately following grey-green sericite phase, a series of massive quartz-molybdenite veins were emplaced. This veining produced a tabular, subvertical, north-south to NNE oriented core zone in the central-south portion of the deposit, with average molybdenum grades ranging from of 0.1 to 0.2% Mo.

Clear evidence of brittle-ductile deformation is registered from the period between the early alteration/ barren to weak mineralisation stages and the later main poly-episodic quartz-sericitic (phyllic) event. During this period, which extended from 33.4 to 31.1 Ma, the deposit was subjected to important tectonic stresses. Intense main and late stage quartz sericitic alteration was imposed on a north-south elongated zone in the western part of the deposit at 31.1 Ma. This phase obliterated the former mineralogy and generated a telescoped, high sulphidation, primary mineral assemblage, with the addition of abundant pyrite and variable amounts of digenite, covellite, enargite, chalcopyrite and bornite, representing a significant increase in S, Fe, As and Cu. There is evidence to suggest that the copper grades following this last phase of intense quartz-sericite alteration largely reflect the distribution inherited from the intense potassic phase with rare remobilisation and the addition of no more than 0.3 to 0.5% Cu. Dextral-normal, north-east oriented, distributive faulting, e.g., the Estanques Blancos and Portezuelo Systems, produced *en echelon,* progressive "south block down" displacement, finally truncating the ore body to the south, while exposing it close to the roots of the mineralised system to the north, in the direction of the RT mine. This was followed by uplift and sinistral displacement along the West Fissure juxtaposing the barren block on its western side with the orebody to the east. Finally a sinistral-normal north-west fault system was reactivated to produce weak segmentation of both the hypogene mineralisation and the West Fissure, while increasing the permeability that influenced the subsequent supergene processes.

Between 19 and 15 Ma the deposit was subjected to at least two leaching, oxidising and enrichment events. The first generated a thick, strongly enriched blanket with grades averaging 2 to 3% Cu, which was focussed by the late and waning stage quartz sericitic alteration that produced non-reactive rocks with abundant pyrite. This blanket extended, although relatively thinly developed, beyond the quartz-sericitic zone, into more reactive sectors to the east and north with lesser pyrite and predominantly early potassic alteration. Subsequent tectonic uplift lowered the meteoric water table, oxidising the enriched blanket to produce hematitic leached remnants in the quartz-sericite rich lithologies, and high grade copper sulphates in the potassic alteration of the near surface in the eastern and northern sectors, which were the target of early mining activity at Chuquicamata. Low grade remnants of this oxide cap may still be observed in the northern part of the present pit. The leaching, which originated in the phenomenon of sudden downward fluctuation of the meteoric water table, also produced exotic mineralisation that was principally transported south from the main deposit through a palaeo-channel to form the Mina Sur orebody.

Introduction

Historic Evolution of the Mining Operation

The presently named Codelco Norte District has been known for its copper mineralisation since the 19th century, although it is most famous for the Chuquicamata deposit. Chuquicamata is located 198 km northeast of the port of Antofagasta and 18 km due north of the city of Calama, in northern Chile, close to the gulch and hills of the same name. The district lies within an extensive metallogenic belt of large Eocene-Oligocene aged copper porphyries, between the El Abra district to the north and the La Escondida-Zaldívar cluster to the south (Fig. 2).

The Chuquicamata deposit was originally exposed at the surface as a band of altered and mineralised rock a couple of kilometres long and some few hundred metres wide. It branched into several strands before passing beneath gravels in the north, while it was structurally truncated to the south. Intense fracturing, grading to brecciation, was characteristic of the outcropping orebody, particularly at "La Llampera" where leached and oxidised surface ore averaged more than 1.5% Cu, although the same fracturing continued into the low grade adjacent zones to the west. The western fringe of the deposit was characterised by intense silicification and rare to no copper mineralisation. To the east, at Cerros de Chuquicamata, early small miners exploited several 'metre wide' veins with average grades of 8% Cu, hosted by barren wall rocks. Initially the main orebody was believed to dip at 60 to 70° west. The first general resource estimation for the Chuquicamata deposit, undertaken in 1916, projected a potential for 700 million tonnes (Mt) of ore with an average grade of 2.0% Cu (approximately 14 Mt of *in situ* fine copper). Today's estimates have multiplied that figure by almost five times to 67 Mt, of which some 34 Mt of fine copper have already been recovered by mining and beneficiation at Chuquicamata.

Large, industrial scale open pit operations began during 1915, centred on the eastern part of the La Llampera area, on bench C, exploiting oxides (atacamite-brochantite) with grades in excess of 1.5% Cu. The ore was processed at the Vat Leaching Plant, which has since been adapted and is still in use for exotic oxide ore from the current Mina Sur mine. Between 1915 and the 1930s the open pit, which coexisted with several small scale underground mines, used massive extraction techniques initially developed for construction of the Panamá canal. These included drilling blast holes for powder, dynamite and more recently 'Anfo' blasting and using steam shovels to load trains with 20 tonne rail cars that hauled the ore and waste out of the pit. Teams of workers advanced the rails as required by the development programming. The train haulage system, later to be equipped with larger lateral dumping cars, survived to the 1970´s, although trucks had been utilised in the mine from 1950 for short distance hauling. The trains were finally completely abandoned during the 1970´s.

The following statistics provide an insight into the characteristics and value of the ore. During 1952 the ore:waste ratio was 1:0.6. By 1960, a total of 407 Mt of ore had been processed, although the leach tailings of the Vat process averaged 0.27% Cu. The treatment of mixed ores in the transition from oxides to the sulphide enrichment blanket commenced in the early 1930s utilising the Vat Plant. Secondary and primary ores were first processed through the concentrator during the 1950s when the sulphur plant was built. By 1960, 39 Mt of mixed tailings had also been processed by the concentrator. Up until the 1960s, both production lines, the oxides and sulphides, had been of equal importance. Subsequently, Chuquicamata´s oxide production progressively decreased until it finally ceased during 1986. During 1987, a Bioleaching Plant with a capacity to produce 18 000 t of fine copper per year was commissioned to treat low grade (<0.5% Cu) sulphides and mixed ores.

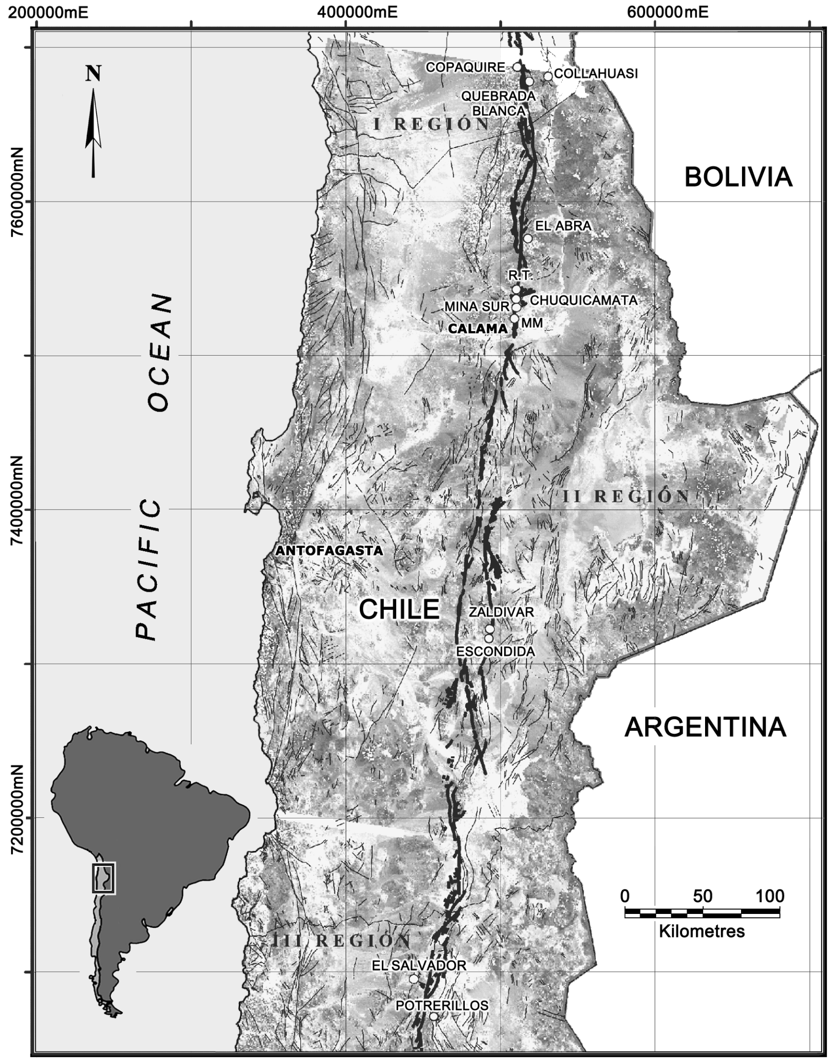

Figure 1: ***Location plan showing the fault pattern in northen Chile,*** the main faults of the Domeyko Fault System (heavier lines) and the major late Eocene to Oligocene porphyry Cu-Mo deposits of the region.

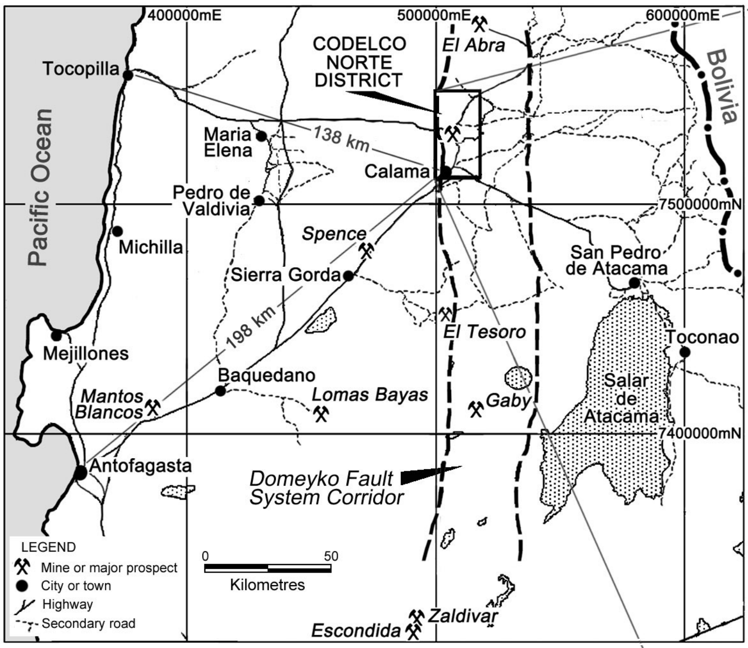

Figure 2: ***Location plan showing the Codelco Norte District*** within northern Chile and an aerial photograph with the key deposits and prospects within the district.

Exploration drilling programs, which commenced in 1957, discovered the exotic deposit, now known as Mina Sur, with potential for 5 Mt of recoverable fine copper. This exotic mineralisation was formed by the leaching of sulphides at Chuquicamata and transport in solution through a palaeo channel to finally be deposited at the basement-gravel contact at Mina Sur. The centre of this deposit is approximately 2.5 km SSE of the fringe of the primary ore, below a totally barren overburden of thick gravels.

Mining began at Mina Sur in 1967, removing the overburden and exploiting exotic ores with average grades ranging from 2.0 to 3.0% Cu. These ores prolonged the life of the Vat Leaching Plant, although in places fine clays made it difficult to recover copper, and although the grades were good, such metallurgically complicated material was stockpiled and is now known as the 'Stocks de Alterados de Mina Sur'. The rate of production has been incrementally increased to the current 30 000 tonnes per day of ore with a grade of 1.5% Cu. To date, close to 2.5 Mt of fine copper has been recovered from Mina Sur.

From the exploration drilling program commenced in 1957 to the present day, the NNE extension of Chuquicamata, mostly concealed below barren gravels and occurring as oxidised and sulphide bearing porphyries, has been a target for advanced drilling reconnaissance. Those extensions, now part of the Radomiro Tomic (RT) deposit, are relatively low grade compared to Chuquicamata, but due to the length of the mineralised interval (up to 10 km), has potential to contain 25 Mt of recoverable fine copper.

Mining operations were started on the northern side of the RT mine during 1995, with production schedules growing to the present 180 000 t of ore per day, at an average grade of 0.5% Cu, and processing in a heap/dump leaching facility located close to the mine. To the present, 2 Mt of fine copper has been produced by that plant.

A review of production from all of Chuquicamata´s facilities to 2001 showed that close to 2000 Mt of ore had been processed at the different plants, comprising: i). 1300 Mt of 1 to 2% Cu sulphides (the tailings from which are in the Talabre Dump with grades of 0.2% Cu and 0.08% Mo); ii). 550 Mt of Chuquicamata oxides treated through the Vat Leaching Process with tailings grades of 0.25% Cu; and iii). 150 Mt of exotic ores from Mina Sur with a head grade of 1.5 to 2.5% Cu, and stock piled tailings of 0.44% Cu. Additional high grade resources are available in other untreated stock piles.

The progressive deepening and consequent lateral expansion of the Chuquicamata open pit has resulted in an increase in the waste:ore ratio which, in the first 65 years of mining had remained very low. Efficient management of the additional material which must now be sent to waste dumps has been made possible by the intensive use of high tonnage trucks, that for newer expansion requirements can also remove older train dumps and haul them to more distant sites, or even to be retreated.

In summary, to the present, approximately 34 Mt of fine copper has been produced from the Chuquicamata Mine, while a fairly well constrained potential resource of 33 Mt remains available within the deposit.

Objectives for the Development of an Updated Geological Model for Chuquicamata

By 1995, the geological model generated for the Chuquicamata orebody had begun to reveal an unsatisfactory degree of certainty in its prediction of grade. In addition, it did not have the capacity to project, within the necessary high levels of confidence, the geological controls on the deeper portion of the deposit below the 1800 m elevation relative level (RL). At the same time, linkage was required between the geology and models of the RT mine and the northern extension of Chuquicamata, as well as between its southern fringe and the Mina Sur extension. Better information was also required to support the generation of additional resources to accommodate the increasing reserve consumption resulting from the open pit expansion program. In particular, the official business plan for the year 2001 programmed 2017 as the scheduled end of Chuquicamata open pit operations. Consequently, as a matter of urgency, efforts had to be concentrated on achieving a better mining base figure to continue the operational life of the mine. Having these requirements, in mind, the Geology Manager and his technical board financed and commenced an intensive program of resources reconnaissance and updating of the geological model for Chuquicamata.

The strategic approach for the new resources goal involved acquisition of a significant quantity of additional information from deep drilling and the generation of new geological concepts to overcome the inconsistencies and weaknesses inherent in the 1995 model. Consequently, during 2001, 2002 and 2003 a total of 40 024 metres of deep drilling was undertaken within the Chuquicamata pit. The data from this drilling confirmed the presence of resources of economic significance, mostly below the programmed final pit limit, which in the central part of the deposit was at the 1800 m elevation RL. With this additional data and the generation of new geological approaches for logging and using new geological concepts, the updating of the geological model of the whole Chuquicamata deposit was finally achieved in June 2003 and presented as the December 2003 Model.

The December 2003 Model, as discussed and summarised in this paper, permitted: i) the definition of a new set of alteration/mineralisation events; ii) allowed the updating and more accurate calculation of the copper resource inventory for the Chuquicamata deposit; iii) the estimation of resources down to the 1660 m elevation RL; iv) the projection of potential tonnages to as deep as the 1200 m elevation RL, (ie. to 1 km below the 2003 open pit floor).

The generation and release of the December 2003 Geological Model provides a better knowledge of the controls on copper grade, especially in the deeper portions of the deposit, while also allowing for a greater level of confidence in the long term resource calculation. In particular, the better understanding of the controls on ore in the primary and secondary domains brings the necessary support to project copper grades to depth, as well as the rock stability conditions and characteristics below the scheduled open pit. The December 2003 Geological Model will also provide the required support for the economic and mining programs to be developed for the future underground mine to profitably exploit Chuquicamata's deep mineral resources.

Logging and Relogging of Drill Holes

At an early stage of the modelling program a new method of logging and relogging drill core was generated, based on a new logging sheet which was the product of progressive improvements arising from linked consultants-modelling geologists work.

The logging method is based on the description and measurement (in absolute volume percentage) of the successive superimposed alteration and mineralisation events observed within the deposit. It is performed by recording the mineral associations (both ore and gangue) representing each event, and the observable contact relationships between the individual minerals. The intensity of each alteration-mineralisation event is then represented in the logging sheet by three specific parameters: i) the *occurrence* of the mineralogical association, ii) the *percentage of textures destroyed* by alteration and iii) the *pre-existing minerals replaced* by the superimposed alteration. In parallel, the effects of leaching, oxidation and supergene enrichment are included in a column indicating the "mineral zone" that is present with emphasis on the primary and secondary sulphide identification and discrimination. Due to their relevance, the presence of gypsum and anhydrite, or their remnant leaching cavities, are registered in the same column.

Using this approach, geological information was recorded from drill core for close to 40 000 m of new drilling conducted during the period, while about 50 000 m of pre-existing core was relogged, and plotted at a scale of 1:200. In addition, more than 85 000 m of other historic core was relogged at a scale of 1:1000, to provide complementary information from specific portions and locations within the deposit. This program provided geological information from a total of 175 000 m of new and relogged core (at both scales) to generate the 2003 Model of the Chuquicamata ore deposit, representing approximately 50% of the total 353 000 m of drill core within the modelled solid.

Pre-existing drill holes were selected for re-logging on the basis of the following criteria: i) the deepest holes, reaching the lower levels of the deposit; ii) the longest and preferably lowest angle holes cutting the subvertical contacts as close as possible to normal, and which could also be used to define the lateral fringes of the mineralisation; iii) holes cutting the ore deposit on each of the 47 established, east-west oriented, 100 m spaced, "main sections". These drill sections were subsequently re-interpreted at a scale of 1:1000. In addition to the information recorded in the new logging sheets, as described above, during the interpretation of the "main sections" other geological aspects such as tops and bottoms, lithological details, copper oxides, etc., were reviewed as "thematic logging" for the 144 000 m of previously logged core. This information was relevant for the local understanding of the deposit and section modelling and was appropriately registered.

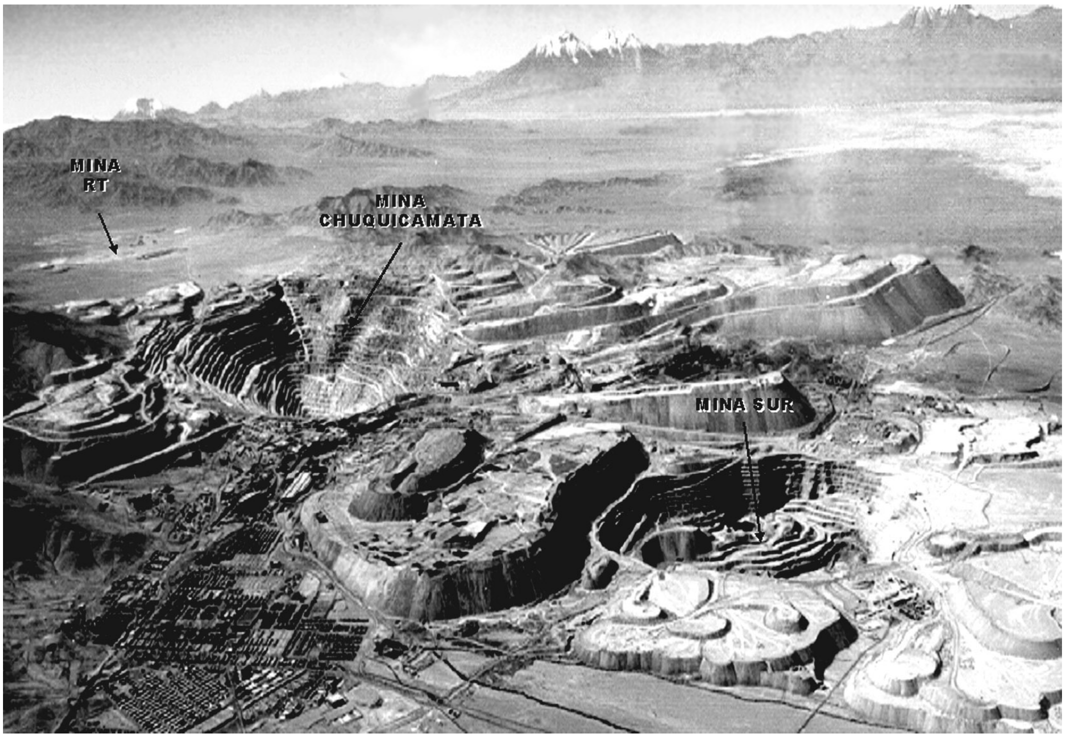

Figure 3: ***Aerial photograph of the Codelco Norte District operations***

Regional Geodynamic Framework

Chuquicamata is the main deposit of the Codelco Norte District, located in the Precordilleran ranges of Region II in northern Chile, and west of the recent volcanic arc of the Los Andes Mountains. It is a porphyry style deposit, associated with Eocene-Oligocene age magmatic intrusives (Maksaev *et al*., 1988; Maksaev, 1990) emplaced within, and related to, the Domeyko Fault System (Maksaev, 1990, *op. cit.*; Lindsay *et al*., 1995; Tomlinson and Blanco, 1997 a,b). This regional system of north-south trending faults has been interpreted to represent a transcurrent intra arc system or a *trench-linked strike slip fault system* (Sylvester, 1988), formed by transpressive tectonics which originated during oblique Eocene-Oligocene subduction (Lindsay *et al*., 1995; Reutter *et al*., 1996).

The Codelco Norte District is part of a major belt of porphyry copper deposits aligned along the Domeyko Fault System (Fig. 1). This belt extends from Potrerillos-El Salvador to the south to Quebrada Blanca-Collahuasi in the north, also including La Escondida. Maksaev and Zentilli (1988) determined that those deposits were formed during a restricted interval (from 41 to 31 Ma) at the culmination of a major compressive event (the Incaic Phase), which resulted in shortening, thickening, uplift and termination of the widely distributed period of Upper Cretaceous to Lower Tertiary magmatism. As such these porphyry deposits and their related plutons represent the final magmatic activity prior to eastward migration of the volcanic arc. This event is interpreted to have provided the geodynamic framework responsible for the optimal tectonic, magmatic and hydrothermal conditions required to generate these huge porphyry copper deposits.

Geochemical studies of the intrusions related to these Eocene-Oligocene porphyries showed them be "I-type", calc-alkaline plutons of the Magnetite Series. Their isotopic and trace element compositions suggest a deep magmatic mantle origin in the Benioff Zone, with a residual garnet phase (> 70 km), and subducted oceanic, but no continental crustal components (Maksaev and Zentilli, 1988; Maksaev, 1990).

Using Ce(IV)/Ce(III) ratios in zircons, Ballard (2001) and Ballard *et al*. (2002), demonstrated that the magmatic evolution of the intrusives related to El Abra, Chuquicamata and Opache (the Toki Cluster), corresponded to a systematic incremental increase in the oxidation state of the magmas, culminating in a maximum in the younger felsic phases. This incrementing of the magmatic oxidation state is a key geochemical factor in the magma's potential to deposit copper mineralisation. Similar conclusions were obtained from studies of the Upper Miocene porphyry deposits of Central Chile (Garrido *et al*., 2002).

Geology of the Codelco Norte District

The Codelco Norte District constitutes a world class porphyry copper cluster (Ossandón and Zentilli, 1997). The district includes the deposits of Chuquicamata, Radomiro Tomic (RT), Mansa Mina (MM), Toki, Opache and Genoveva, and the exotic ores of Mina Sur (Fig. 2). All lie within a NNE trending, 30 km long and 10 km wide mineralised corridor (Fig. 2). On the basis of production records from the mines, drilled reserves and resources, and figures from advanced exploration projects (Ossandón and Zentilli, *op. cit.*), it has been estimated that the district originally contained a total of approximately 125 million tonnes of fine copper, of which close to 38.5 Mt have been extracted to date, leaving around 86.5 Mt in situ. A range of age dating determinations on the remaining copper mineralisation indicate that it was emplaced during a restricted time period between 38 and 31 Ma.

The oldest rocks with the Codelco Norte District belong to a Palaeozoic to Lower Triassic *Igneous-Metamorphic Complex,* which outcrops both within the Mina Sur pit, and 1 km east of the Chuquicamata Mine. Dioritic rocks of this same complex intrude the Carboniferous *Mesa Granite*, a pink, microcline granite with a partially gneissic texture (Marinovic and Lahsen, 1984). The Triassic *East Granodiorite*, a coarse to medium grained equigranular intrusive (Ossandón *et al*., 2001), intrudes the Palaeozoic Complex due northeast of the Chuquicamata pit and to the east of the Radomiro Tomic mine. In the same areas, stratified Mesozoic *metavolcanics* and *metasediments,* which have been contact metamorphosed, are exposed in fault contact with basement rocks and as deformed and dislocated lenses along the Messabi Fault-East Deformation Zone (Reutter *et al*., 1996; Lindsay, 1998).

In the vicinity of the old Carmen Mine, located to the northeast of the Chuquicamata pit, and in drill core from the eastern fringe of the deposit, the metavolcanics are intruded by the *East Porphyry*, the main lithology of the *Chuquicamata Porphyry Complex (the "Chuqui Porphyry")*. The East Porphyry was dated at 34.6 Ma from U-Pb in zircon (Ballard *et al*., 2001). The *Chuqui Porphyry* is the dominant host to the mineralisation at both the Chuquicamata and Radomiro Tomic mines and is exposed as an elongate, subvertical to west dipping, NNE trending, dyke-like intrusive stock with exposed dimensions of some 14x1.5 km.

The West Fissure, an important branch of the Domeyko Fault System, occurs as a regional north-south trending fault that exhibits post ore movement, dissecting the Chuquicamata deposit, and separating the intensively mineralised Chuqui Porphyry to the east from the barren Fortuna Intrusive Complex (39-38 Ma, U-Pb in zircon; Ballard 2001), to the west. The West Fissure has been the subject of several studies and interpretations focussed on its evolution and relationship to copper mineralisation in the district (e.g. Maksaev, 1990; Reutter *et al*., 1993, 1996; Lindsay *et al*., 1995; Lindsay, 1998; Tomlinson and Blanco, 1997; Dilles *et al*., 1997; McInnes *et al*., 1999). It is interpreted to be Cenozoic in age, but has a complex kinematic history, including varying degrees of both transcurrent and probable reverse displacement, but with severe changes in the sense and direction of movement over time. Most of the aforementioned authors agree that the West Fissure had a key structural influence on the localisation of ore forming processes, as well as being responsible for post ore displacement of the Chuquicamata deposit. Nevertheless, the detailed geology of the deposit indicates that deformation on the fault was predominantly post ore and that it took advantage of a pre-existing anisotropy that coincided with the latest alteration and mineralisation stages, but that the early hydrothermal alteration phases were definitely displaced by post ore movement on the West Fissure.

Dilles *et al*. (1997) and Tomlinson and Blanco (1997) concluded that there was a net sinistral displacement of 35 km over the length of the West Fissure. Their conclusions were based on geological, structural, geochronological and petrographic correlations between the Fortuna Intrusive Complex and the El Abra Complex. More recent studies (Ballard, 2001), using detailed crystallisation ages from U-Pb in zircon, zircon heritage and trace elements geochemistry, have confirmed the correlation between those complexes, supporting the hypothesis that they are part of the same batholith sinistrally displaced by the West Fissure. The alternative is that they represent two separate magmatic centres that are contemporary, or of similar age, derived from a common magmatic chamber, without significant displacement along the West Fissure.

The Messabi Fault is the other significant structure in the Codelco Norte District, recognised on the east and NNE margins of the Chuquicamata pit. In these areas it separates the Chuqui Porphyry from wall rocks, mainly Mesozoic metavolcanics and meta andesites, but also the *Elena Granodiorite* (37.7 Ma, U-Pb in zircon; Ballard, 2001), that is generally believed to be a precursor of the Chuqui Porphyry due to its age, the petrographic similarity of the two intrusives and their gradual and diffuse mutual contacts. The Messabi Fault Zone exhibits a ductile to semi ductile deformation fabric, including mylonites and cataclastic flows with dextral kinematic indicators, as described by Lindsay *et al.* (1995) and Reutter *et al.* (1996). These authors offered evidence that the fault was active before and after emplacement of the Chuqui Porphyry, and probably also during the early stages of mineralisation, implying the Messabi fault played a key role in the location and formation of the deposit. This is in part consistent with the previously developed hypothesis presented by Maksaev (1990), which proposed that the West Fissure and Messabi Fault represented an active extensional duplex (step over or pull apart types), resulting from the dextral translational movement on both structures, providing a favourable focus controlling the emplacement of both the Chuqui Porphyry and the processes influencing formation of the Eocene-Oligocene mineralisation.

Geology of the Chuquicamata Deposit

Chuquicamata is a 4000 m long, NNE elongated deposit, widest in the north (900 m), tapering to the south (300 m). The known vertical extent of economic grade mineralisation is 1800 m, extending to about 1000 m below the floor of the current pit. Mineralisation of the same grade remains open at depth below this level.

Chuquicamata Porphyry Complex

The Chuquicamata ore deposit is hosted entirely within the Chuquicamata Porphyry Complex (the "*Chuqui Porphyry*"). This complex is divided in three main textural varieties, the *East, Banco* and *West Porphyries*. The East Porphyry is, volumetrically, by far the most important.

The Chuquicamata Porphyry Complex has the form of a large dyke like intrusive stock, widest in the north (900 m), while it is structurally tapered to the south. It is bounded by important faults, namely: the West Fissure, to the west; the East Deformation Zone to the east and the Portezuelo Fault to the south of the deposit (Fig. 4), where it persists as a 30 to 40 m thick, structurally wedged, tabular sliver along the West Fissure before finally being truncated. At depth, in the same area, where it is represented by the East Porphyry, it is structurally wedged to a width of only a few metres. To the north, the complex is continuously exposed over a length of several kilometres, through the Chuqui Norte Project area, into the Radomiro Tomic mine.

The *East Porphyry* varies in composition from granodiorite to biotite quartz monzonite, with phaneritic to incipient porphyritic textures within a medium grained fabric. It contains sparse to increasingly abundant centimetric megacrysts of K feldspar, accompanied by subhedral to euhedral plagioclase, producing a poikilitic texture with interstitial quartz, K feldspar, subhedral biotite and rare hornblende. Magnetite, titanite and zircon are accessories. The crystallisation age of the East Porphyry was dated at 34.6 Ma by U-Pb in zircon (Ballard *et al*., 2001).

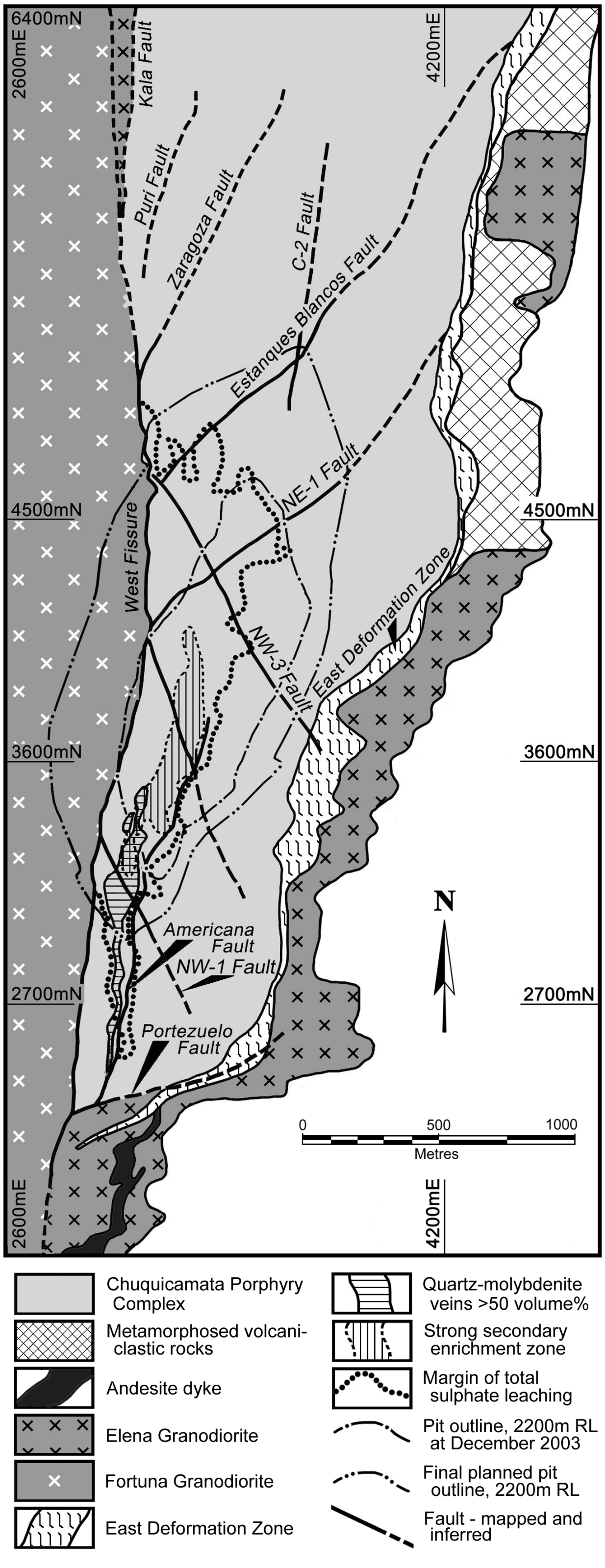

Figure 4: ***Geology and structure on the 2200m RL, bench Q3, of the Chuquicamata Mine.***

The East Porphyry is locally intruded by smaller bodies of *Banco Porphyry* and *West Porphyry*, both of which are preferentially located in the northern part of the deposit. These two porphyries have a similar composition to that of the East Porphyry, but are distinguished by their bimodal textures, which are clearly porphyritic, within fine aplitic ground masses. Although the Banco and West porphyries are similar, the Banco is characterised by the presence of plagioclase in its ground mass. In addition, the Banco Porphyry occurs in the form of dykes and its contacts with the East Porphyry are both sharp and regular. In contrast the West Porphyry bodies have more irregular shapes with diffuse gradational contacts with the East Porphyry.

The crystallisation ages of the West and Banco porphyries are similar (33.5 Ma and 33.3 Ma respectively from U-Pb in zircon determinations; Ballard *et al.*, 2001). The final copper grade distribution is not influenced by the presence of Banco and West porphyries, although locally these lithologies may correspond to small zones of lower grades. Both the Banco and West porphyries are crosscut and overprinted, to the same intensity, by the same main alteration and mineralisation events as the East Porphyry. Consequently, the Chuqui Porphyry as a whole is considered to be essentially "pre-mineral" with respect to the main mineralising events that were responsible for the formation of the deposit. Nevertheless, as the West and Banco porphyries are similar in age to the early pulses of alteration, the porphyries could represent the locus of late magmatic alteration, chloritic and potassic halos and mineralisation.

Wall Rocks to the Chuqui Porphyry

The Chuqui Porphyry is truncated on its western margin by the West Fissure, separating it from the locally weakly mineralised to totally barren *Fortuna Granodiorite Complex,* which has been dated at 39-38 Ma (U-Pb in zircon; Ballard, 2001). The Fortuna Complex occurs as a stock of hornblende-biotite granodiorite which has a medium to coarse grained phaneritic texture with local variations, specifically the Grey and Clear Granodiorites, and the San Lorenzo Porphyry. Close to the West Fissure this intrusive is brecciated and sheared with abundant calcite and hematite veining. The mafics are generally chloritised by low intensity alteration which is not clearly related to the mineralising events occurring within the neighbouring Chuqui Porphyry. In places, some deep zones, located 1 to 2 km west of the West Fissure, and related to the San Lorenzo facies of the Fortune Granodiorite Complex, contain weak potassic alteration (secondary biotite and K feldspar), accompanied by low grade, late magmatic, mineralisation (pyrite, chalcopyrite and molybdenite).

On the southeastern margin of the deposit, the Chuqui Porphyry has a diffuse, gradational contact to the east with the *Elena Granodiorite*. The two intrusives are macroscopically similar and their relationship is controversial. The only petrographic difference is the absence of K-feldspar macrocrysts in the equigranular Elena Granodiorite. Nevertheless, during the generation of the 2003 Geological Model the contact was traced and modelled with some confidence following the recognition that it constitutes a poly-episodic brittle-ductile deformation zone of variable thickness which is continuously developed along the entire eastern flank of the deposit. This zone, now termed the *East Deformation Zone* (see 'Structure' below) encompasses a complex of mylonites, cataclasites and cohesive fault breccias, which have probably undergone recrystallisation, and encroaches into both the Elena Granodiorite and the East Porphyry. The East Deformation Zone was logged in past drill holes and in newer deep drilling and carefully interpreted from section to section, in plans and in the solid model, making a detailed delineation of the contact between the Elena Granodiorite and the East Porphyry possible on the central and southern margins of the Chuquicamata deposit.

The Elena Granodiorite is also recognised on the northwest flank of the deposit as a structural wedge sandwiched between the Chuqui Porphyry and the Fortuna Granodiorite, bounded by the West Fissure and the northeast striking Kala Fault (Fig. 4). The remaining geological aspect of the Elena Granodiorite's occurrence yet be clarified is its age. Older studies assigned it a doubtful Mesozoic age, based on radiometric Pb-α in zircon and K-Ar in biotite (Ambrus, 1979; Lindsay *et al.,* 1995; Ossandón *et al.,* 2001). A more recent and comprehensive study using U-Pb in zircon, returned a crystallisation age of 37.7 Ma (Ballard, 2001). This more recent age, in conjunction with the petrographic and geological relationships mentioned above, suggest the Elena Granodiorite may be a precursor intrusive to the main Chuqui Porphyry.

Overall, the Elena Granodiorite is barren, although its mafic minerals are usually chloritised and it locally contains minor disseminated pyrite. On the southern margin of the deposit, rare specularite ±chalcopyrite has been observed locally as breccia mineralisation, with pyrite in "D-type" veinlets, similar to, and probably representing late pulses of the Chuquicamata mineralisation system.

In the northern half of the deposit, the East Porphyry is exposed in intrusive contact with metavolcanics and metasediments on its eastern margin. These stratified volcanics and sediments are part of the Mesozoic sequence, and occur as lenses or structurally dislocated zones which have been intensely deformed and folded, with locally developed mylonites and chloritised tectonic breccias. The style of deformation suggests a correlation of this northern tectonised zone with both the East Deformation Zone recognised on the central and southern margins of the deposit and also with the Messabi Fault to the north. In general, these metamorphic rocks are barren, although in some recent deep drill holes the metavolcanics and metasediments have ore grade copper intersections of chalcopyrite and magnetite bearing skarn.

Structure

The most detailed structural studies of the Chuquicamata deposit are incorporated in Lindsay *et al*., (1995); Reutter *et al.,* (1996) and Lindsay (1998). Nevertheless, due to its complexity, the structural control of the mineralisation and alteration in all of the different stages is an important geological feature not yet clearly understood. This incomplete understanding is also due in part to the variability in quality of the historic data, the lack of systemic bench mapping in the past, and the failure in general to record age relationships between the huge number of structures seen in the pit and their relation to alteration and mineralisation. At present therefore, only the general framework of the structural geology of Chuquicamata is appreciated, based mainly on the principal structures.

The following paragraphs describe the most relevant structural features in the deposit, in chronological order. Strike directions are quoted relative to the Chuquicamata mine grid.

Brittle-Ductile NNE Shear Zones (Messabi System)

This group includes the East Deformation Zone, the cataclastic zones that control the distribution of Intense Potassic Alteration (detailed below), and probably the Americana, C-2 and Zaragoza faults. This NNE trending system is the earliest set observed at the deposit and probably controlled the intrusion of the Chuqui Porphyry and the earliest stages of mineralisation relevant to the copper content of the deposit.

The *East Deformation Zone* have been recognised and interpreted with spatial continuity along the central and southeastern margins of the deposit. It forms the contact between the mineralised Chuqui Porphyry and the Elena Granodiorite. The understanding of this important structural feature is one of the most significant conclusions that has arisen from the new model of Chuquicamata. It is a complex zone encompassing cohesive bands of mylonites, cataclasites and recrystallised fault breccias, all of which have variable thickness, but dip steeply (~80º) to the west. The breccias include fragments of the different intrusive lithologies the structure cuts, as well as quartz, (probably from the early stages of mineralisation), incorporated within a recrystallised matrix of chlorite, feldspar and magnetite which has been derived from an igneous protolith. The ductile, penetrative fabric of the mylonites has been superimposed on the breccia texture. Both lithologies bounding the structure are cut by later veinlets and small breccias of specularite, with traces of pyrite and chalcopyrite. In places the mylonites are cut by late, undeformed epidote veinlets. The cataclasites represent intervals of less intense tectonic activity. These different structural fabrics reflect a strong variation in the degree and locus of deformation along the strike length of the East Deformation Zone, which in turn displays a variability in its geometry. In the southern sections of the deposit (south of local coordinate 2400mN), the East Deformation Zone has undergone a strong offset to the west in the vicinity of the Portezuelo Fault, making it possible to correlate the East Deformation Zone with the structural feature that narrows the East Porphyry on its eastern side in the south to a wedge only a few tens of metres in width. As noted previously, both structural features control the eastern margin of the Chuqui Porphyry, although their characteristics and thicknesses are different, probably reflecting different levels of exposure from north to south across the Portezuelo Fault and hence the degree of ductile versus brittle deformation.

An equivalent offset across a NNE trending deformation zone separating the Chuqui Porphyry and the Mesozoic metasediments and metavolcanics on the northeastern side of the deposit has allowed the East Deformation Zone to be extrapolated further to the north of the orebody. On the basis of this extrapolation, the East Deformation Zone can now be considered to be the southern projection of the Messabi Fault. In fact, Reutter *et al* (1996) refers to the East Deformation Zone as the East Messabi Fault, while Lindsay (1998) shows it to be part of the Messabi Fault. The progressive curvature to the west of the East Deformation Zone in the south is explained as a wedging and dextral displacement of the fault produced by the Estanques Blancos-Portezuelo Systems. Both authors identify a dextral displacement along the Messabi Fault-East Deformation Zone based on ductile kinematic indicators. The geological contact relations observed between the individual mylonites, zones of brecciation, quartz fragments and the Chuqui Porphyry imply that the East Deformation Zone had a complex and multi-episodic history. It certainly existed prior to the emplacement of the Chuqui Porphyry, but was reactivated after the intrusion, to produce deep, intra-mineral structures within the porphyry, while also confining the hydrothermal system along the its eastern margin.

The *Americana Fault* (Fig. 4) is another important deformation zone that can probably be included within this same group of structures. It is a subvertical feature, mostly developed in the southern part of the deposit, where it is expressed as a breccia zone that fractures and deforms quartz-molybdenite veins. The Americana fault, not only controls the location of late stage pulses of quartz-sericite alteration but also appears to exert control over the emplacement of the earliest quartz-molybdenite veining. To the south of the deposit the Americana Fault is offset by the Portezuelo Fault.

In the northern part of the deposit, other north-south trending and sub-vertically dipping structure are recorded, including the: *Zaragoza Fault* and *C-2 Fault* (part of the Zaragoza Domain of Lindsay *et al.*, 1995). These are similar to the Americana Fault in the southern portion of the deposit. In the north, the margins of the Chuqui Porphyry intrusive correspond to the Zaragoza Fault System to the east and the West Fissure to the west, defining the northern end and original symmetry of the deposit. The C-2 Fault System is an important structural feature influencing both primary and secondary mineralisation, as well as the development of copper oxides at the northern end of the Chuquicamata Mine, where these north-south to NNE striking faults are relatively abundant. The latter observation supports the inference that the C-2 System faults were developed early in the evolution of the deposit and participated in the localisation of the primary mineralisation, before being reactivated.

Ductile Foliation within the Chuqui Porphyry

This structural characteristic corresponds in different zones to either foliated mylonitic shearing, stress foliation or ductile lineation resulting from the translation and stretching of mafic and silicate minerals in the different lithological phases of the Chuqui Porphyry. Contact relationships indicate that this deformation followed the early potassic alteration but preceded the late quartz-sericitic (phyllic) pulses.

Estanques Blancos and Portezuelo Fault System

This system comprises a set of northeast trending, subvertical faults that are exposed across the deposit, but are more penetrative in its northern sections where the *Estanques Blancos Fault* is mapped (the Estanques Blancos Domain of Lindsay *et al*., 1995). This fault has a dextral sense of movement in the north-eastern parts of the Chuquicamata pit. In the northern sections of the deposit, the Estanques Blancos System plays an important role in the localisation of both early and late episodes of alteration and mineralisation, as well as supergene processes. This is reflected in the strike of the alteration zones (Fig. 5) and the anisotropy of mineralised veins and veinlets, indicating that this fault system is 'old' and influenced hydrothermal processes throughout the evolution of the deposit. In parallel with this, well documented evidence from previous structural reports and studies show that this same system was reactivated with a post mineral dextral sense of movement e.g., Renzetti's (1955) geological surface map which considers the Estanques Blancos Fault to have produced a 200 m to 300 m dextral displacement of various mapped units. The *Balmaceda Fault*, located in the central portion of the deposit, also belongs to the Estanques Blancos System.

The *Portezuelo Fault*, which strikes at 80° and dips 80°N, is located at the southern end of the mine, and has been mapped in the eastern sections of the main Chuquicamata pit. It can be correlated with fault traces which have a similar dip/strike that have recently been mapped in the old K1 drainage tunnel, and recognised in about 6500 m of drill core from the same area. The trace of this fault is well defined, particularly where it limits the chlorite-specularite-chalcopyrite mineralisation of the Chuqui Porphyry to produce the sharp southern margin of the ore deposit. It also results in the abrupt folding and westward displacement of the East Deformation Zone, which defines the eastern margin of the Chuqui Porphyry, to bring it closer to the West Fissure thereby tapering the Chuqui Porphyry on its southern side to become a narrow tabular slab wedged between the West Fissure and East Deformation Zone. These observations suggest that the Portezuelo Fault either: i) cut and dextrally displaced the Chuqui Porphyry and the East Deformation Zone by more than 300 m, or ii) that it was a pre-existing, pre-mineral structure that controlled the intrusion of the Chuqui Porphyry. Further detailed work and acquisition of data from drilling is required to resolve this question.

Structural investigations conducted in the northern part of the deposit and the geological work carried out for the present model, indicate that the faults of the Estanques Blancos-Portezuelo System all have an important "south block down" component of normal movement. This has produced a series of en echelon fault blocks with progressive structural lowering from north of Chuquicamata to the Loa River basin in the south, explaining the differences in the exposed levels of mineralisation and alteration. In the south, at MM, preserved late stage and near surface (high level) advanced argillic alteration is preserved, while at Radomiro Tomic in the north, deeper level alteration and mineralisation of the potassic core of the deposit is exposed, with subordinate phyllic and the total absence of the advanced argillic phase.

The West Fissure

The West Fissure fault, in general, strikes north-south to NNE with dips angles of 75° to 80°W which progressively shallow with depth. It is the most recognisable fault at Chuquicamata, and was systematically and consistently defined for the 2003 Geological Model to determine its kinematic evolution and the role it played in controlling the location of the Chuquicamata porphyry copper deposit. Observations within the pit however, indicate that it is a post mineral structure, with sinistral transverse and reverse senses of movement. It defines the abrupt western limit of the ore deposit, juxtaposing the Chuqui Porphyry and early mineralisation with the barren Fortuna Granodiorite across the fault to the west. The distribution and symmetry of hypogene alteration and mineralisation revealed by the new deep drilling, clearly indicate that the West Fissure does not represent the axis of the deposit, but that it is located to the west of the centre of hypogene hydrothermal activity. This work further suggests that the section of the body dissected and displaced by the West Fissure represents less than 30% of the original mineralised system. These conclusion are also supported by the differences in strike direction between the predominantly north-south trending fault and the approximately NNE axis of the main alteration and mineralisation. The West Fissure, does however, appear to control very late stage sericite/pyrite mineralising events which are centred on the structure.

NNW Trending Faults

This suite of faults includes important NNW to NW trending, subvertical structures (the Northwest Domain of Lindsay *et al.,* 1995) which are most abundant in the central and southern sections of the ore deposit. Earlier structural studies have concluded that this set of faults are late stage and post mineral. These observations are based on their metre scale sinistral displacement of mineralised veins, sinistral north-south faults and geological contacts, as well as evidence that they also cut and displace both the West Fissure and the supergene enrichment blanket, producing a modified drag fold in the latter with a "few" metres of sinistral displacement. However, there is also evidence within the deposit that some veins and veinlets belonging to the different evolutionary stages of the deposit are controlled by these NNW faults. It is therefore likely that the NNW set of faults existed and were probably active during the genesis of the deposit, and are a conjugate suite to the Estanques Blancos-Portezuelo Fault System, reactivated during late post mineral and recent periods.

In addition, in the central sections of the deposit, the NNW trending fault set appears to in part control the morphology of the basin that contains the secondary enrichment blanket, although the distribution of supergene enrichment also follows the locus and physico-chemical reactivity of the pervasive quartz-sericitic alteration.

Hypogene Mineralisation & Alteration

One of the main advances arising from the development of the 2003 Geological Model has been the recognition, mapping and detailed interpretation of the multiple events of hypogene mineralisation and alteration that took place within the deposit. This conceptual focus provided the opportunity to secure important geological information relevant to the introduction of copper and the poly-episodic history of the hydrothermal system. This work has revealed that, while some high copper grades were generated during development of the late quartz-sericite (phyllic) phase, most of the copper was introduced as part of the early alteration associations which have been largely obliterated by late stage alteration.

The hypogene mineralisation-alteration events may be temporally divided into: i) early low sulphidation, with low pyrite within the sulphide assemblage, and ii) late phyllic event, with much higher sulphidation mineralisation, and abundant pyrite.

Early Low Sulphidation (Low-Pyrite) Associations

Background Potassic (PF)

This early stage alteration style is characterised by the selective replacement of mafics in the Chuqui Porphyry by secondary biotite, while plagioclase is usually in part or selectively altered to K feldspar, sericite and/or clays. Original intrusive magnetite is destroyed or converted to hematite. Biotite and K feldspar can also occur as rare micro-veinlets accompanied by quartz, calcite and sulphides. A very distinctive characteristic of the background potassic alteration is that the original texture of the Chuqui Porphyry is clearly preserved. Mineralisation occurs mainly as disseminations and, to a lesser extent as micro-veinlets. The total sulphide content is low (<1%), occurring as hypogene chalcopyrite ±bornite or chalcopyrite ±pyrite associations. In general terms, chalcopyrite is the dominant sulphide, bornite or pyrite only being important locally. Other sulphides present include digenite, covellite, chalcocite, sphalerite and molybdenite, but only in very subordinate quantities. Copper grades in the background potassic alteration is low, in general varying from 0.1 to 0.5% Cu, even in local zones of minor enrichment.

This is the earliest alteration/mineralisation event observed, and is widely distributed in the eastern and northern sections of the deposit. Relicts are also scattered through the remainder of the deposit, suggesting it was more widespread, but was obliterated by subsequent overprinting stages.

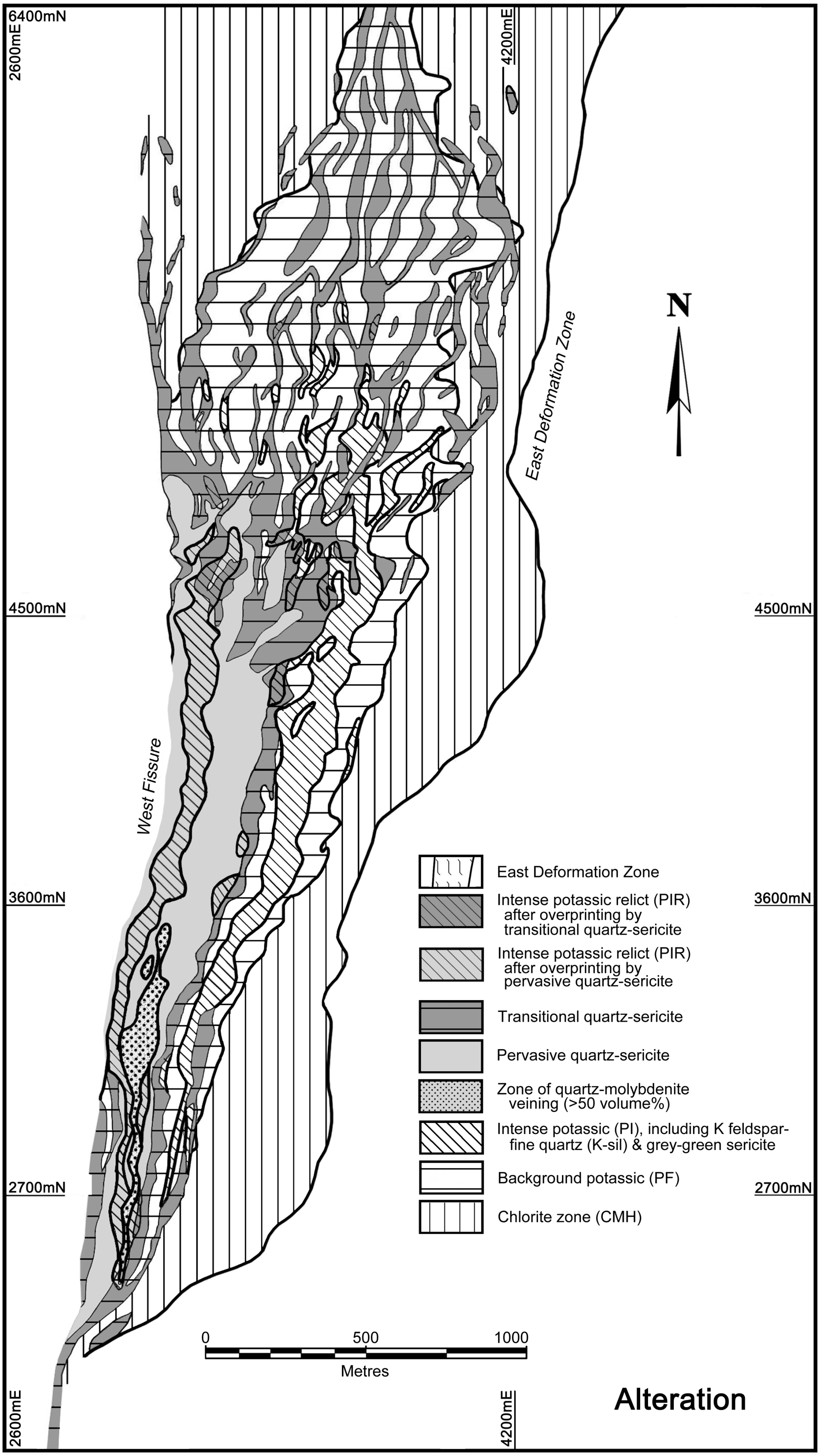

Figure 5: ***The styles and distribution of alteration on the 2200m RL, bench Q3, of the Chuquicamata Mine.*** Fig. 7 shows the same alteration styles on three representative sections through the deposit (2700mN, 3600mN and 4500mN - indicated on the plans above).

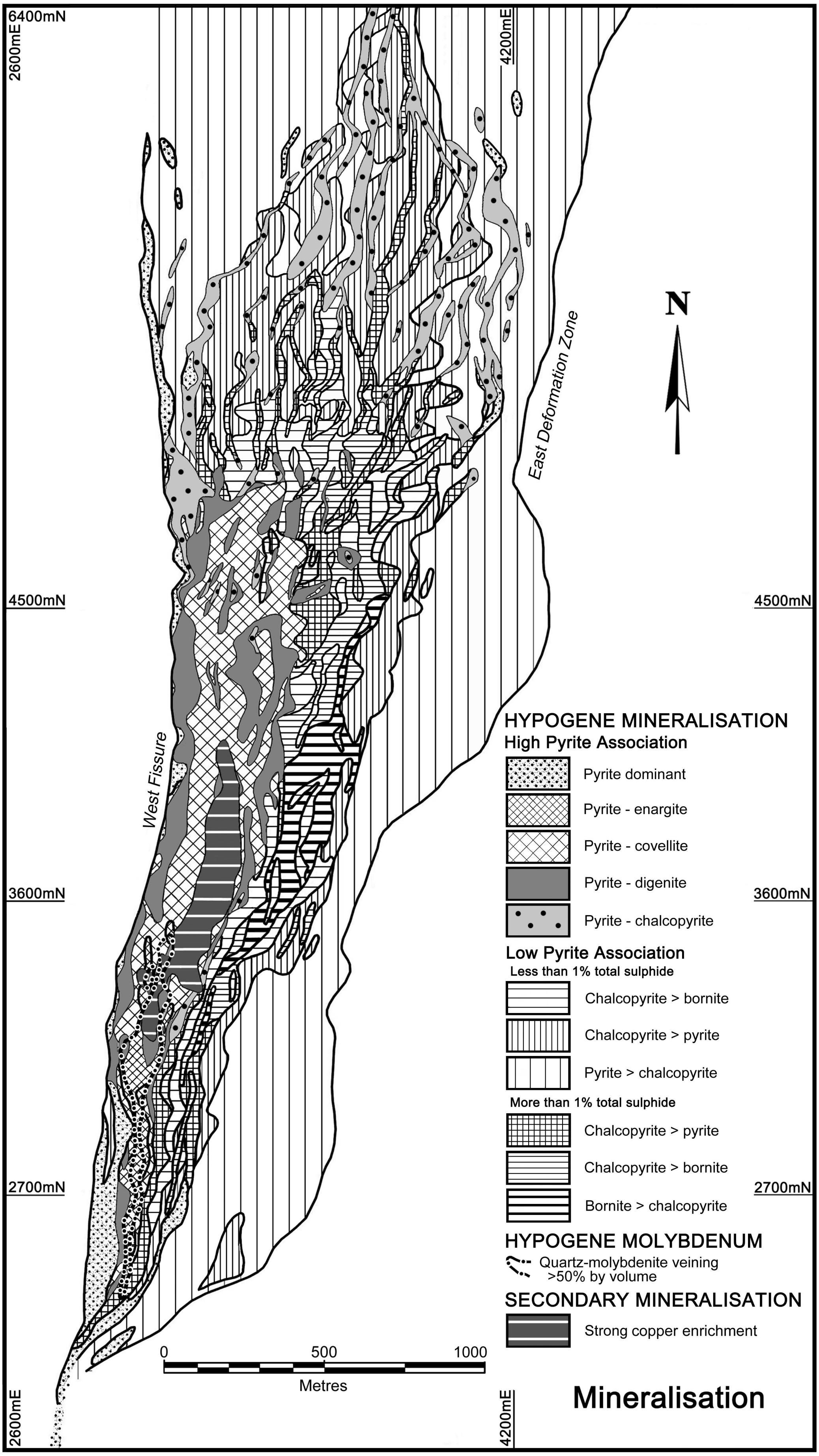

Figure 6: ***The styles and distribution of mineralisation on the 2200m RL, bench Q3, of the Chuquicamata Mine.*** Fig. 8 shows the the same mineralisation assemblages on three sections through the deposit (2700mN, 3600mN and 4500mN - indicated on the plans above).

Background potassic alteration has been dated at 33.4 Ma, based on a set of Ar-Ar in biotite and K feldspar measurements (Reynolds *et al*., 1998). This date is very similar to the age of crystallisation obtained for the West and Banco porphyries, implying a genetic link. The implied link is supported by a spatial association in the north of the deposit between the background potassic alteration and the main bodies of the West and Banco porphyries, and by a dense stockwork of barren "A-type" veinlets that are usually accompanied by irregular K feldspar halos, most of which are in equilibrium with the alteration.

Chloritic Alteration (CMH)

Selective chloritic alteration of primary and secondary mafic minerals, and the development of chlorite veinlets, are found on the fringes of the deposit, accompanied by low grade copper (<0.3% Cu) mineralisation. In the higher benches of the mine, where drilling information is more

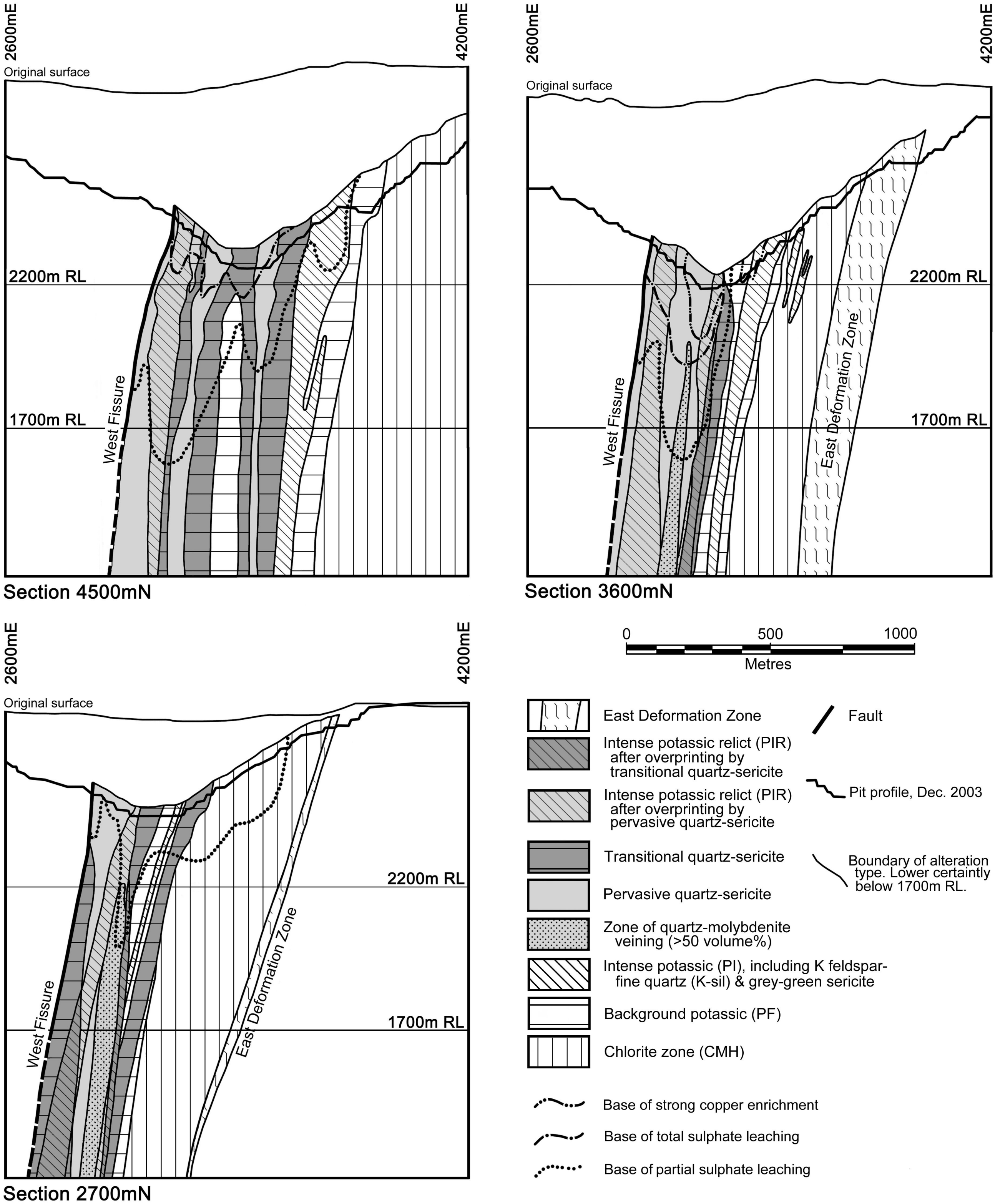

Figure 7: ***Sections through the Chuquicamata deposit illustrating the distribution of alteration styles.*** For locations see Figs. 4 and 5 which illustrate the geology and mineralisation styles on level 2200m. Compare also with the mineralisation styles as shown on Fig. 6.

abundant, this chloritic margin is coincident with the occurrence of preserved primary magnetite and marks the outer limit to the background potassic alteration. However, in new deep drill holes, some intersections of low grade mineralisation were accompanied by low chlorite, but with preserved primary magnetite and hornblende, suggesting these zones are not part of the background potassic alteration system. The CMH alteration classification has been applied to the low grade fringe of the background potassic phase defined by selective chloritisation of mafics and/or preserved primary magnetite and/or primary fresh hornblende, with, in all cases, predominantly preserved primary textures. Selective albitisation of plagioclase and calcite-ankerite veinlets are also included as characteristics of this style of alteration. Epidote is only recognised locally.

X-ray diffraction analyses of samples of CMH alteration indicate that the mineral macroscopically and microscopically identified as "chlorite" corresponds to clinochlore, a member of the chlorite group. The distribution of CMH alteration as a restricted fringe to the background potassic alteration, differs from the typical more extended halo normally encountered on the margins of orthomagmatic porphyry copper deposits.

The low grade mineralisation associated with the CMH alteration occurs as low total sulphide (<1% by volume) disseminations, characteristically comprising a pyrite ±chalcopyrite association with local, rare chalcopyrite. Late specular hematite, both as disseminations and in veinlets, is relatively frequent, locally brecciating the rock, and is found mainly on the southeastern margins of the deposit. Specularite may in isolated instances be intergrown with chalcopyrite.

K Feldspar-Fine Grained Quartz Association (K-Sil)

The alteration style known locally at Chuquicamata as "K-Sil" comprises moderate to intense replacement of feldspar and biotite by secondary K feldspar, in some instances also accompanied by secondary albite and quartz. The original texture of the protolith is partially to totally destroyed and takes on a characteristic grey colour. Under the microscope, the fabric of this alteration is strongly cataclastic, frequently forming a micro-breccia with a fine matrix of micro- to crypto-crystalline quartz and feldspar. Quartz and K feldspar are also present as micro-veinlets. In the deeper hypogene sections of the deposit, occurrences of disseminated, veinlet and massive anhydrite are frequent.

Mineralisation associated with K-Sil alteration preferentially occurs as veinlets and micro-veinlets and generally contains significant copper grades, with >1% total sulphides, which are usually unevenly distributed. The typical mineral assemblages accompanying K-Sil alteration are bornite ±digenite ±covellite, or chalcopyrite ±covellite ±bornite ±digenite. Although these two associations, one with bornite predominating, the other with dominant chalcopyrite, may be found together, on the basis of detailed studies, they seem to represent two separate, clearly differentiated ore pulses. Two alternative, but not mutually exclusive, hypotheses have been proposed. The first is that the sulphide mineralisation is contemporaneous with and genetically linked to the K-Sil alteration, while the second suggests the mineralisation is produced by a late pulse, related to the early stages of the succeeding grey-green sericite alteration (described below), with the mineralisation being introduced into the K-Sil through mechanical/structural processes associated with cataclastic deformation (Ossandón *et al.,* 2001).

Two types of K-Sil alteration are recognised, leading to some controversy regarding their origin. The first is fractures controlled, occurring as halos to sulphide veinlets with a high total sulphide and copper grade, and is characterised by strong destruction of the original host porphyry texture. The second is more pervasive, is not texture destructive, and forms diffuse, irregular zones with a total sulphide content and copper grade just slightly above that of the background potassic alteration phase. Although it is possible to find low grade intervals within K-Sil alteration zones, multiple observations, supported by statistical studies, show that where K-Sil alteration is abundant (>30%), the hypogene copper grade is also high, ranging from 0.8 to 1.5% Cu. The K-Sil alteration zones and related mineralisation are distributed as "vein-like" domains or relatively well defined belts within the deposit, suggesting for this alteration was essentially structurally controlled.

Quartz-Molybdenite Veins and Veinlets

Quartz-molybdenite mineralisation is present in important quantities, occurring as "blue veins" and banded "B-type" veinlets, both of which have a spatial association with the grey-green sericite and the late quartz-sericite alteration (described below). Nevertheless, contact relationships between the quartz-molybdenite veining and high-pyrite "D-type" veins directly associated to the late quartz-sericite (phyllic) event, clearly demonstrates that the quartz-molybdenite event is earlier. This suggests that the spatial association is coincidental, possibly reflecting the sharing of a common structural locus, rather than a temporal or genetic link.

The zone of abundant (i.e., >50% by volume) quartz-molybdenite veins and veinlets, defines a structurally controlled core, generally striking north-south to NNE and dipping at 80°W, within the south-central part of the deposit. This core, with an average grade of 0.13% Mo, has dimensions of 1000 m in length, 50 m average width and has been recognised over a vertical interval of 600 m, but is still open at depth. However while this zone has high molybdenite grades, copper is reduced (<0.6% Cu), due to the mass dilution of the early copper mineralisation by the abundant quartz-molybdenite veining, and the lack of permeability and sulphide content of the veins which restricted the emplacement of subsequent fracture controlled and disseminated copper mineralisation.

While molybdenite is also recognised in other alteration/mineralisation events, particularly the early background potassic phase, and in very late stage remobilised veins and fractures (Ambrus and Soto, 1974), the quartz-molybdenite vein and veinlet event is by far the most important and introduced the bulk of the molybdenite into

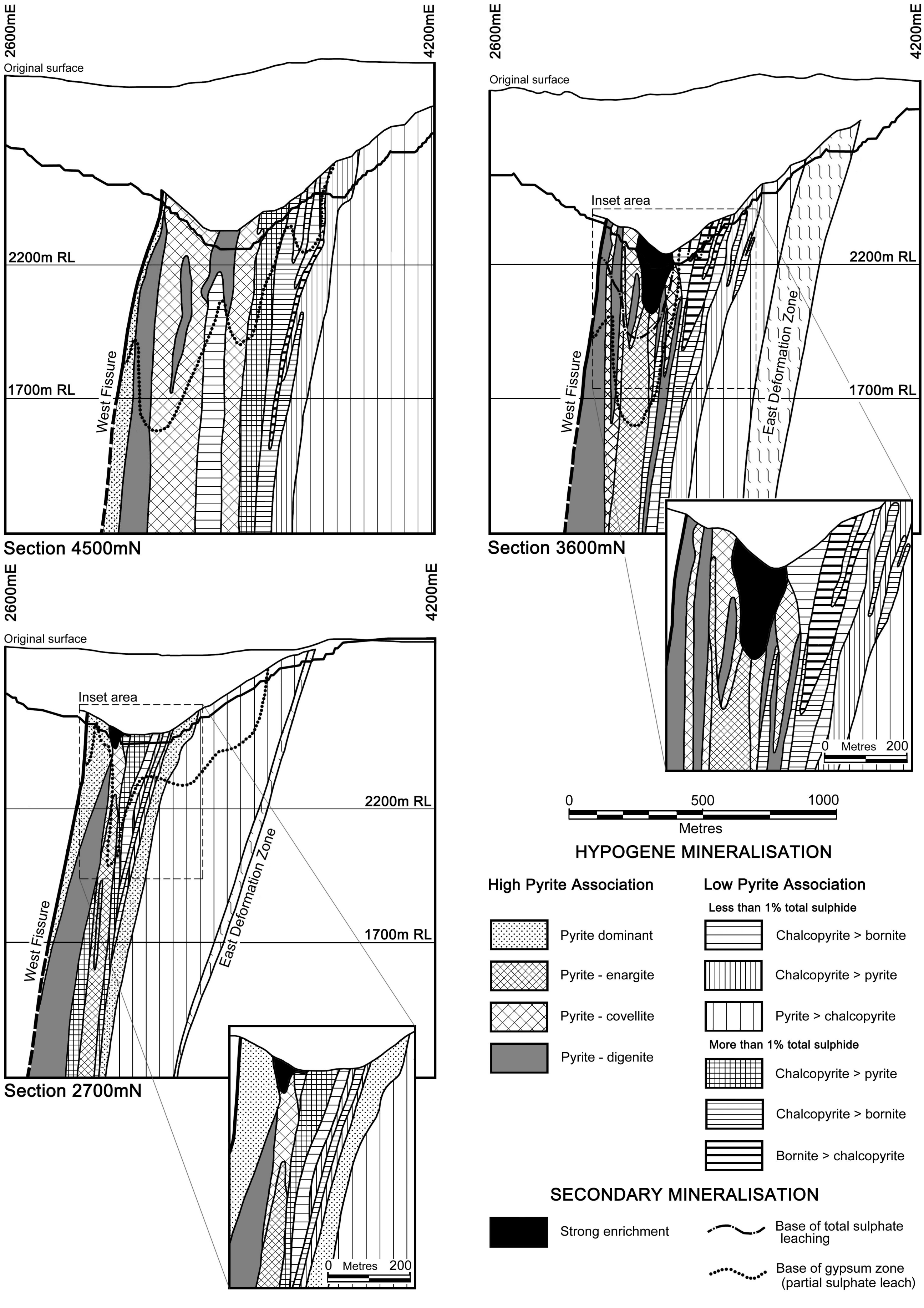

Figure 8: ***Sections through the Chuquicamata deposit illustrating the distribution of mineralisation styles.*** For locations see Figs. 4 and 5 which illustrate the geology and mineralisation styles on level 2200m. Compare with the distribution of alteration styles as shown on Fig. 6.

the system. The principal geological control on the Mo grade is the volumetric frequency of the quartz-molybdenite veining (Ossandón *et al.,* 2001), reflecting the intensity of the event.

Early Grey-green Sericite

This alteration style results in the intense destruction of the rock texture of the Chuqui Porphyry accompanying the replacement of its mineralogy by aggregates of sericite, quartz, abundant disseminated copper sulphides and some K feldspar. The early sericite is characterised by its greenish-grey colour and by its notorious coarse texture compared to sericite accompanying later alteration phases. Grey-green sericite occurs as irregularly shaped pervasive zones, or as halos to early, frequently sub-parallel veinlets of quartz, quartz-bornite or quartz-molybdenite. The affects of ductile foliation are sometimes superimposed on this alteration assemblage, to produce a texture characterised by re-oriented, sub-parallel sericite plates.

Ore mineralisation associated with grey-green sericite alteration occurs as abundant fine disseminations. It comprises the same mineral assemblages, without pyrite, that accompany the *K-Sil* alteration, namely: bornite ±digenite ±chalcocite ±covellite, or chalcopyrite ±bornite ±covellite ±digenite. In the latter episode, when "D-type" veins are superimposed on the grey-green sericite, early sulphides are replaced by pyrite-digenite ±bornite or pyrite-covellite.

The zones of abundant grey-green sericite alteration (i.e., >10% by volume), represent significant sections of the deposit and contain >1% copper sulphides by volume, with grades of consistently >1% Cu, making this phase the main hypogene ore event within the Chuquicamata deposit. There is commonly a very close spatial link between the distribution of grey-green sericite and K-Sil alteration, but also between the grey-green sericite and the quartz-molybdenite veining, although locally the latter may also have an inverse relation. These associations suggest these events could be very close in age.

On the basis of the close spatial correlation/distribution of the K-Sil and early grey-green sericite events, and their shared characteristics (i.e., intense destruction of precursor textures and very similar high copper sulphide assemblages), both alteration styles have been functionally grouped into a bigger alteration unit, the *Intense Potassic (PI)*. This intense potassic (PI) grouping is predominantly localised in the eastern part of the deposit, where it occurs as a series of irregular tabular zones, trending NNE and dipping at 70 to 85°W. In these zones cataclastic textures, and locally, ductile deformation features are exposed. Within the intense potassic (PI) zones there is an observable gradation from grey-green sericite to the north and at depth, to K-Sil which is more abundant at higher levels and in the central and southern sections of the deposit.

Veinlets of Chalcopyrite with Sericitic Halos

Sections of the deposit located on the fringes of the intense potassic (PI) altered zones have a greyish colouration and contain massive chalcopyrite veinlets with quartz-sericite halos containing disseminated chalcopyrite. These veinlets carry subordinate to rare to no pyrite and although they cut all of the previously described alteration/mineralisation phases, belong to the early low pyrite association. Copper grades within these chalcopyritic zones are of the order of 0.7 to 0.8% Cu, corresponding to >1% sulphides by volume. Chalcopyrite is locally accompanied by molybdenite. Apart from the colour difference, the chalcopyrite veinlets with sericitic halos differ from the early grey-green sericite alteration in the following respect:

i) The chalcopyrite is mostly in the veinlets and only partially in the halos. In the grey-green sericite, the situation is the reverse.
ii) The typical sulphide association within the veinlets is chalcopyrite ±pyrite, with no bornite. In the grey-green sericite alteration zone, the sulphide assemblage comprises chalcopyrite ±bornite with no pyrite.
iii) When individual chalcopyrite veins are isolated, the sericite halo is weak and the precursor porphyry texture may at least be partially preserved. The grey-green sericite alteration totally destroys the precursor texture.

Late, High Sulphidation (High-Pyrite) Associations

Most of the western half of the Chuquicamata deposit has undergone late quartz-sericite (phyllic) alteration, typically with associated copper sulphides and high pyrite mineralisation (i.e., with pyrite>50% of total sulphides; and pyrite>1% of the rock, by volume). This alteration is either pervasive, or in the form of halos to "D-type" veins.

At least two consecutive phases of the *quartz-sericite (phyllic) alteration* event are identified, namely the *Main* and *Late* sub-events. These sub-events are spatially related and are very difficult to separate in routine mapping. The quartz-sericite alteration comprises sericite aggregates, with quartz and pyrite which obliterate the original texture of the porphyry through the intensive replacement of feldspar and biotite. Minor amounts of kaolinitic clay replace plagioclase, while rare veinlets and breccia-veins of quartz-alunite are found, especially in the Late sub-event. X-ray diffraction analyses of sericite from the quartz-sericite alteration reveal it comprises aggregates of illite and muscovite.

This quartz-sericite alteration occurs as a huge, north-south trending and vertically dipping mass, located on the western side of the deposit, adjacent to the West Fissure. The intensity of alteration is weaker on the peripheries of the altered mass in what is termed the 'transitional quartz-sericite zone', occurring as quartz-sericite superimposed on (but not entirely obliterating) earlier textures and alteration assemblages which are still discernible. This transitional quartz-sericite alteration is evident in the northern portion of the deposit, towards the Radomiro Tomic (RT) mine.

The mineralisation associated with the late quartz-sericite (phyllic) alteration event comprised a series of progressive pulses of sulphide mineralisation, overlapping in time and space, and reflecting the evolution of the high pyrite association and the degree of sulphidation, as follows: pyrite-chalcopyrite, pyrite-digenite (±bornite), pyrite-covellite (±enargite), pyrite-enargite (±sphalerite). The ore and gangue minerals have open space filling textures within the "D-type" veins, and occur as disseminations in their halos, and in local breccia-veins. Pyrite (usually >2% by volume) is the dominant sulphide.

The late pyrite-enargite sulphide pulse was the dominant source of arsenic within the system. This arsenic event was structurally controlled, being emplaced in a brittle environment in the form of massive veins or as breccia matrix in zones of abundant tectonised quartz-molybdenite veins, fringed by pyrite-enargite stockwork veins superimposed on earlier associations.

The late quartz-sericite (phyllic) alteration stage apparently terminated with a final post-ore pulse located adjacent to the West Fissure, comprising barren to very low total copper bearing pyrite veinlets (pyrite >90%, and copper sulphides <10% of total sulphides).

The contact relations between the late quartz-sericite (phyllic) alteration, with its high pyrite associations, and the earlier mainly potassic low pyrite associations, clearly demonstrate that the quartz-sericite event is later and that it cuts and obliterates the earlier mineral association. Radiometric ages of sericite (determined by Ar-Ar techniques) from this late quartz-sericite (phyllic) event yield an alteration age of 31.1 Ma (Reynolds *et al.,* 1998), 2 Ma younger than the background potassic alteration event, and 3 Ma younger than the crystallisation age of the East Porphyry.

Superimposed Relations (PIR)

The copper grade distribution within the late quartz-sericite altered body is very uneven and independent of the locally dominant sulphide assemblage (with the exception of the very late pulse of pyrite-low copper sulphide which averages around 0.5% Cu). For all of the other sulphide associations, the grade is variable, particularly the primary zones that have not undergone supergene enrichment.

There is evidence to suggest that the grade distribution was largely inherited from earlier associations that were overprinted and modified by the late quartz-sericite (phyllic) alteration. Locally, within the late quartz-sericite alteration zone, relicts of previous alteration assemblages may be recognised, as halos to early veinlets, or on a larger scale, as irregular bands with ghost textures from earlier alteration events such as K-Sil or grey-green sericite of the intense potassic (PI) stage. These relicts contain abundant sulphides as veinlets and very fine disseminations, suggesting that prior to the imposition of late quartz-sericite alteration, the pre-existing intense potassic (PI) alteration/mineralisation stage had been responsible for emplacing high grade mineralisation. The earlier associations were replaced, transformed and upgraded by the higher sulphidation late quartz-sericite (phyllic) event, although the early grade distribution was preserved, at least partially, as were the textures and mineralisation style characteristic of the previous intense potassic event (PI), in the form of micro-veinlets or sulphides disseminations. These preserved zones have, in general, higher contents of copper sulphides (>1%) as digenite, bornite or covellite, all associated with pyrite, and copper grades of about 1.4-1.5% Cu. Those zones which have more or less spatial continuity and exhibit these characteristics are referred to as *Intense Potassic Relict (PIR)*. However, while the grade distribution has been inherited, the PIR has clearly experienced important grade improvement and occurs as a continuous band, sub-parallel to the West Fissure but located in the central-eastern part of the deposit.

Following with the same analysis, but *contrario sensu*, the lower grade (0.7-0.8% Cu), low copper sulphide content (<1% by volume) zones within the late quartz-sericite (phyllic) alteration zone, that do not contain relict textures from the intense potassic (PI) stage, are now interpreted to represent pre-existing background potassic associations with original lower grades.

These observations and conclusions suggest that the pervasive late quartz-sericite (phyllic) event contributed S, Fe, As and Cu to the system, but only sufficient to incrementally upgrade the pre-existing mineralisation by 0.3 to 0.4% Cu.

In summary, it may be concluded that the grade and distribution of primary copper within the late quartz-sericite (phyllic) zone is largely inherited from the pre-existing potassic events over which the late quartz-sericitic association has been superimposed, but with an accompanying upgrading through the addition of further copper.

Late Veins, Veinlets and Micro-breccias

The final known hypogene mineralisation event at Chuquicamata corresponds to very locally distributed veinlets, micro-veinlets and micro-breccias carrying chalcopyrite ±covellite ±digenite ±red hematite ±anhydrite ±gypsum. This very last pulse does not however, include pyrite. It cuts all the events previously described, including the high pyrite associations of the late quartz-sericite (phyllic) events and, in general, does not produce alteration halos. In the zones where this event is observed, it does not appear to have had any affect on the copper grade, implying that the pre-existing mineral assemblage was locally altered and remobilised without the introduction of additional copper.

Supergene Mineralisation

Supergene processes have resulted in important modifications of hypogene mineralisation throughout the Chuquicamata deposit, mainly in its uppermost portions, with the generation of extensive zones of leaching, oxidation and enrichment of sulphides, and total/partial leaching of sulphates.

Copper dissolved through the leaching of hypogene sulphides also migrated, mainly to the south, via palaeo-channels and was deposited at the gravel-basement interface at the base of the channel to produce substantial accumulations of exotic copper mineralisation. Radiometric K-Ar age dating of supergene alunite from these palaeo-channels indicate that the main supergene processes at Chuquicamata occurred between 19 and 15 Ma (Sillitoe and McKee, 1996). The following describes the different supergene processes and related zones of secondary mineralisation at Chuquicamata.

Sulphate Zones

Anhydrite and gypsum are important components of most of the hypogene alteration zones within the Chuquicamata deposit. Anhydrite occurs both as disseminations and as veinlets, while gypsum is chiefly present in veinlets and is probably the product of late hydration of anhydrite. Both minerals are particularly abundant within both the intense potassic (PI) and late quartz-sericite (phyllic) alteration zones, but are rare in both the background potassic (PF) alteration and are rare to virtually absent in the chloritic (CMH) zones.

One of the most prominent effects of supergene processes within the upper portions of the Chuquicamata deposit has been the total to partial leaching of sulphates. In the primary zone, below the level of influence of supergene processes, anhydrite and gypsum seal the rocks, preserving the original rock mass, with low fracturing and good geomechanical characteristics. Conversely, where these sulphates have been totally or partially leached, the rock is more porous and the previously sealed fractures are opened, to produce a rock mass with lesser competence and reduced geomechanical properties.

Based on sulphate content and the degree of sulphate leaching, three main zones are distinguished (Figs. 7 & 8):

i) *Primary Zone* - containing anhydrite and gypsum, without cavities, rock mass sealed, competent.
ii) *Transitional or Partially Leached Zone* - with gypsum, very sporadic and rare anhydrite, cavities and open fractures, less competent rock mass.
iii) *Secondary Zone* - gypsum and anhydrite are absent as they are completely leached, abundant cavities and open fractures, rock mass incompetent to less competent. In this zone, a very late selenitic supergene gypsum may occur at local scales, although it is not considered in the modelling of sulphate zones

The *Transitional* and *Secondary* zones are more deeply developed in the late quartz-sericite (phyllic) alteration zone on the western fringe of the deposit, locally extending to elevations as low as 1600 m.a.s.l. This is a direct result of the less chemically reactive nature of the phyllic alteration assemblage and its higher pyrite content, which combined to produce more acid (lower pH) supergene solutions.

Secondary Enrichment

The secondary enrichment factor (or degree of supergene enrichment) at Chuquicamata is most intense within the zones of phyllic alteration with strong permeability, low reactivity and high pyrite (i.e., conditions favouring strong acid generation). In the core of the late quartz-sericite (phyllic) alteration zone, the primary copper grade was roughly doubled by secondary enrichment, while on the fringes and at depth the enrichment factor progressively declined.

Three zones are recognised and defined on the basis of the enrichment factor, namely:

i) *Primary Zone* - No supergene activity or secondary sulphides are recognised and consequently no enrichment is found. The ores are completely hypogene in character. This zone is coincident at the deposit scale with that of the 'primary zone' of gypsum and anhydrite sealed fractures as described previously.
ii) *Weak Enrichment Zone* - Secondary sulphides are recognised but are subordinate to the hypogene minerals. They occur in fractures, fault zones and partially or wholly replace hypogene copper minerals, with pyrite remaining clean, bright and unaltered. This interval coincides with the 'transitional sulphate zone' described previously and coexists with gypsum, but corresponds to the zone of cavities and open fractures produced by the leaching of sulphates, particularly anhydrite.
iii) *Strong Enrichment Zone* - Secondary sulphides predominate, replacing more than 75% of the primary copper sulphides. Bornite is totally replaced and pyrite is "dirty" with coatings of secondary copper sulphides. This zone corresponds to the 'secondary zone' of the leached sulphates described previously, with abundant cavities and a high degree of fracturing. However, the lower limit of the strong enrichment zone does not coincide exactly with the "gypsum roof", with the strong enrichment usually ending around ±20 m above the last occurrence of gypsum.
iii) *Oxidised and Leached Zone* - The upper oxidised copper minerals and the leached/overburden zones are only exposed at the northern and southern extremities of the current pit. Both have been modelled but are not currently of major significance, nor are they included in the definitions above.

Chalcocite is the most important secondary copper mineral at Chuquicamata, although supergene covellite is also found in significative quantities. In general, chalcocite predominates in the 'strong enrichment zone' while covellite tends to be more abundant at greater depth within the 'weak enrichment zone'. Despite this, there are reduced zones where covellite is important in the strong enrichment and, *vice versa*, there are weak enrichment zones with only chalcocite. Consequently, the exclusive use of the mineralogy of the secondary copper sulphides is not useful in defining the intensity of supergene enrichment and the use of textural criteria as described above is essential.

Zones of 'In Situ' Oxidation and Leaching

As described previously, much of the upper leached and oxidised sections of the Chuquicamata deposit have been removed and/or exploited and only lower grade remnants are exposed on the northern and southern extremities of the current open pit, developed over the peripheries of the primary and secondary ore zone. These comprise both limonite rich leached capping rocks and/or oxide copper mineralisation (both *in situ* and exotic types).

The principal remnant zones of oxide copper are localised at the northern end of the deposit, where the oxide bodies occur as subvertical, elongate bands, interspersed with leached zones in which limonites coexist in variable proportions with copper oxides. The general trend of the copper oxides in this area is consistent with structural control related to the northeast striking Estanques Blancos Fault System, and the north-south to NNE trending C-2 Fault System. The higher grade and volume oxide bodies are developed vertically above, and are the upward continuation of higher hypogene grades located below the 'top of dominant sulphides' modelled surface. Hypogene alteration is predominantly a late quartz-sericite (phyllic) assemblage, with copper occurring in veinlets locally superimposed on the widespread background potassic (PF) alteration.

The dominant mineralogy in these northern oxide ores comprise the sulphate bearing minerals antlerite-brochantite (±atacamite), with accompanying hematite, lesser sericite and rare clays. Sulphide relicts are very common within the oxide ores, mainly as leached chalcocite partially replaced by hematite, indicating that the current oxide ore zones were developed from an earlier supergene enrichment blanket which was oxidised, leached and its copper redistributed to a newer and deeper zone of supergene enrichment.

On the southern margins of the Chuquicamata pit, *in situ* copper oxides are found over the southern sections of the Chuqui Porphyry at a deeper level than the exotic oxides described below. These oxides, which include brochantite, atacamite and antlerite, are considered to be *in situ*, based on their occurrence in oxidised "D veinlets" with quartz-sericitic halos.

Zones with Exotic Oxides

The more important zones with remaining exotic copper oxide resource are at the southern end of the deposit, where the Chuquicamata pit overlaps the Extensión Norte de Mina Sur Project. This area incorporates an exotic palaeo-channel (and its ores) that run due south from Chuquicamata to the Mina Sur mine open pit. The mineralisation associated with this palaeo-channel straddles the contact between the basement and the overburden gravels of the palaeo-channel. The copper oxides developed along this entire zone are chrysocolla, atacamite and copper wad which represent deposition from, or remnant products of, poly-episodic flows of pregnant acid solutions derived from supergene leaching of the main Chuquicamata sulphide mineralisation - both hypogene and supergene. They are present as cement within the gravels or as fillings and coatings of the fractures within the immediately underlying basement lithologies.

Sulphide Zoning & Related Grades

The giant Chuquicamata porphyry copper deposit is the cumulative product of a complex set of evolutionary processes which include: i) its tectonic conditioning and ground preparation resulting from the enhanced structural permeability of the rock mass, ii) the multi intrusive suite of mineralisation related porphyries and iii) the related and subsequent multi-episodic alteration/mineralisation events, of both hypogene and supergene origin. Together, all of these linked processes generated the spectacular polymineralic core of the huge and unique copper-molybdenum deposit at Chuquicamata. The large variety of ore and gangue mineral species, their modes of occurrences, intensities and textural features are specific and characteristic of each of the alteration/mineralisation events. In addition, the focus of each of these events successively migrated, both in space and time to produce a complex overlapping pattern. Patient investigation of this pattern has allowed the differentiation of the individual contributions of each mineralising episode. To do this, it was necessary to consider a range of aspects, such as mineral species, textures, modes of occurrence, intensity, location and contact relations, to correctly identify the individual geological events and model them in a predictive way. Any of these aspects considered in isolation, may not reflect the result of a single event. For example, the contribution of pyrite from the different events is distinguished by studying the variation in its intensity, textures and contact relationships.

The 2003 Model allows the distribution of a range of parameters to be plotted throughout the orebody, including the different mineral species and metal grades, geological units, structures, specific gravity, etc. and the production of plans and sections.

Geological Evolution of Chuquicamata

Using the accumulated geological knowledge of the deposit, as described previously, it is possible to prepare a synthesis of the geological evolution and genesis of the giant Chuquicamata deposit. This synthesis is expressed in a series of steps in geological time order, as follows.

Structural Accommodation for the Intrusion of the Chuqui Porphyry, Elena & Fortuna Granodiorites

The evolution of the deposit geology commenced at the beginning of the Oligocene, with the syntectonic introduction of the Fortuna Intrusive Complex, followed by emplacement of the Elena Granodiorite. This occurred in a dextral transpressive regime (the *Incaic Phase*) which produced shortening along an ENE directed tectonic vector. The deformed country rocks included Carboniferous to Lower Triassic basement rocks, mainly plutonic bodies (locally represented by the Mesa Granite and Este Granodiorite) comprising granites and granodiorites with biotite and orthopyroxene and a mild magmatic foliation, overlain by Jurassic marine carbonate rocks affected by contact metamorphism, discrete mylonites and penetrative subvertical axial plane cleavage striking north-south and dipping at 85°W. The ENE tectonic vergence of the Incaic Phase produced a reverse-dextral NNE foliation and the structurally linked permeability conditions for the next intrusion.

The Fortuna Complex probably post-dates the Paleocene eastward magmatic migration, and was initiated with the emplacement of the Los Picos diorite pluton, a few kilometres to the west of Chuquicamata. The Fortuna Complex comprises a biotite- and hornblende-bearing granodioritic stock dated at 39-38 Ma (U-Pb in zircon), which is cut by several bands of ductile deformation and is characterised by multiple and sequential intrusive pulses, including the Grey Granodiorite, Clear Granodiorite and San Lorenzo Porphyry. The latter pulse has been overprinted by an initial, incipient, late-magmatic background potassic alteration event. This event is represented by secondary biotite altered mafics, local brecciation, and K feldspar which is developed in both the ground mass and as micro-veinlets within the San Lorenzo Porphyry and in its Clear Granodiorite wall rocks. These locally altered zones within the San Lorenzo Porphyry carry weak mineralisation of pyrite, chalcopyrite, minor bornite and subordinate molybdenite, with copper grades of 0.1 to 0.2% Cu, and very locally, up to 0.5% Cu, in deep zones some 3 km southwest of the Chuquicamata open pit. Subsequently, as a precursor to intrusion of the Chuqui Porphyry, the syntectonic Elena Granodiorite was emplaced in the basement contact zone which had been subjected to constant transpressive stress. It is an equigranular, medium grained granodioritic stock with biotite dated at 37.7 Ma (U-Pb in zircon). Both intrusives generated halos of contact metamorphism, have assimilated wall rocks and enclose roof pendants, particularly of Jurassic metasediments, and as a product of the semi-ductile structural regime, have a magmatic foliation and a NNE oriented dextral-reverse tectonic fabric.

Emplacement of the Chuqui Porphyry Complex: East, West & Banco Intrusions, Background Potassic Event and Chloritic Halo

Emplacement of the Chuquicamata Porphyry Complex (the "Chuqui Porphyry") commenced with the intrusion of the East Porphyry at 34.6 Ma. Its NNE oriented dyke-like shape and the deformation of its wall rocks suggest that the anisotropy of the Messabi Fault-East Deformation Zone, associated with a probable dextral transpressive tectonic environment, played a key role in controlling the location of intrusion. Geological evidence implies that the East Porphyry, when intruded, was barren or only weakly mineralised.

The main mineralising process began with the intrusion of the smaller West and Banco Porphyries at 33.4 Ma. This event produced an intense stockwork of barren "A-type" quartz veins, mainly in the northern part of the deposit, as well as the pervasive *background potassic* alteration of most of the Chuqui Porphyry, accompanied by weak, mainly disseminated, chalcopyrite (±pyrite, ±bornite) mineralisation. Following this late-magmatic event, the copper grade of the deposit was approximately 0.3% to 0.4% Cu.

Intense Potassic Alteration Events

Following the background potassic event, a set of tectonic and hydrothermal processes took place that generated the *intense potassic* alteration event, which constituted the main stage of hypogene mineralisation at Chuquicamata. This alteration style was predominantly developed within NNE trending zones of cataclastic deformation, which are believed to represent reactivation of the Messabi Fault-East Deformation Zone System. The alteration associations that define this style were K feldspar with fine quartz (*K-Sil*), and *grey-green sericite,* which together were accompanied by important quantities of ore composed of bornite-digenite-chalcopyrite-covellite. The grade of the zones where the intense potassic alteration is abundant is around 1.0% Cu. At the end of the intense potassic cycle, a late pulse of chalcopyrite veins with sericitic halos was developed on the margins of the main centres of this alteration event, with copper grades of 0.8% Cu

Quartz-Molybdenite Veins and Veinlets

An important set of quartz-molybdenite veins and veinlets were introduced temporally overlapping the intense potassic event. This vein set, which spatially crosscuts the effects of the K-Sil alteration, but is clearly cut by early grey-green sericite mineralisation, was most intense in the southern half of the deposit, but extends over a length of 1000 m in a north-south to NNE direction. It forms an important steeply dipping tabular core to the deposit in its southern and central parts, where it has an average grade of 0.13% Mo, including values of up to 0.2% Mo.

Post-early Mineralisation Deformation

There is strong evidence that between 33.4 and 31.1 Ma, following the early alteration/mineralisation events described above, but prior to the late quartz-sericite alteration event, the ore deposit was subjected to intense tectonic stress. This intra mineralisation/alteration deformation is reflected by: i) mylonitic foliation, locally affecting the Chuqui Porphyry and cutting zones of intense potassic alteration, but overprinted by the late quartz-sericite alteration; ii) the foliation and brecciation of the East Deformation Zone which incorporates quartz fragments from the early alteration/mineralisation events; and iii) the intense brecciation and tectonism that affected the quartz-molybdenite veining, related to the Americana Fault which controls the location of the succeeding late quartz-sericite associations.

Late Quartz-sericite Alteration Events

An important, overprinting, late quartz-sericite (phyllic) alteration event, which commenced at around 31.1 Ma, occupies a north-south to NNE trending zone in the western sections of the current deposit. This event obliterated pre-existing low sulphidation primary alteration/mineralisation assemblages to generate a telescoped pyrite ±digenite, ±covellite, ±enargite (±chalcopyrite, ±bornite) association, reflecting significant introduction of S, Fe, As and Cu into the system. Bands of high grade copper mineralisation (with 1.4-1.5% Cu) are recognised within this zone, mimicking textures and mineralogies from the intense potassic event. These bands, which coincide with modified and upgraded pre-existing higher copper grades, are termed 'intense potassic relict' (PIR) in the 2003 Geological Model. Other sectors, whose original textures have been obliterated by the late quartz-sericite alteration, but have relatively lower copper grades (i.e., 0.7%-0.8% Cu), are now interpreted to represent areas of original background potassic alteration/mineralisation. If these interpretations are accepted, it would mean that the late quartz-sericitic event, even in the most pervasive areas, was only responsible for the upgrading of the pre-existing mineralisation by 0.3 to 0.5% Cu and the grade distribution observed is basically inherited from the earlier events.

Faulting-Dislocation-Displacement & Post-hypogene Mineralisation

Throughout the mineralising events the host rock mass remained under tectonic stress, producing repeated episodes of brittle deformation. Towards the end of, and following the late quartz-sericite (phyllic) event, this continued deformation had resulted in the development of new structures and the reactivation of earlier structural systems that had influenced the position of the pre-existing hypogene mineral zones. Distributive, dextral-normal, NE trending faults, such as the Estanques Blancos, Balmaceda and Portezuelo Systems, produced moderate, *en echelon,* progressive, "south block down" displacement and finally, truncation of the ore bodies to the south, while the "roots" of the mineralised system are exposed to the north in the Radomiro Tomic mine. On a regional scale, the West Fissure system produced a major sinistral displacement of the ore body. This north-south trending, subvertical to steeply west dipping fault zone, locally exhibits clear post-mineral displacement, but also has a deep seated rotational component. The sense of movement of the blocks on either side the fault zone differs. In the mine area, the west block is uplifted relative to the eastern side, but is rotated downwards further to the south. It bisects the deposit and juxtaposes the intensely mineralised and altered Chuqui Porphyry to the east with the barren, unaltered Fortuna Intrusive Complex, to the west, clearly truncating the alteration events up to and including the late quartz-sericite (phyllic). A broad zone of tectonic brecciation and dislocation is evident on the western or hangingwall margin of the fault, producing the complex geomechanical conditions encountered on the western wall of the Chuquicamata pit.

A late, NW trending, sinistral-normal structural system, reactivated, displaced and weakly segmented the hypogene mineralisation and the West Fissure, increasing the permeability, and enhanced subsequent supergene activity.

Supergene Processes

At least two leaching, oxidising and enrichment events have been recognised as having taken place at Chuquicamata between 19 and 15 Ma. The first, a thick blanket of strong enrichment was developed in the zone that was physically and chemically the most favourable, namely, the core of the late quartz-sericite (phyllic) alteration, which was intensively fractured and hence more permeable, but also non-reactive and rich in pyrite to generate acid waters. These acid solutions were able to permeate through the fractured, high grade primary mineralisation to leach and then transport copper via the same permeable, non-reactive host to ultimately be deposited in the supergene blanket when neutralised at the water table. The copper grades resulting from this enrichment averaged 2.0-3.0% Cu. This highly enriched blanket probably extended to the east and north of the main late quartz-sericite (phyllic) zone, but with reduced thicknesses and grades, in sectors with predominantly background potassic alteration, and hence more reactive and less permeable rocks. Subsequent tectonic uplift lowered the meteoric water table and the chalcocite rich supergene blanket in the late quartz-sericite (phyllic) zone was oxidised to produce hematitic leached remnants, while high grade copper sulphates were deposited in the adjacent potassic altered mineralised zones to the north and east. The early historic exploitation was centred on these sulphate zones, which were located close to surface. Weaker sulphate zone remnants are still available at the northern end of the Chuquicamata pit.

Copper solutions, derived from the intense leaching of the sulphide deposit, also circulated laterally, and were transported to the south along a favourable palaeo-channel following a depression topographically controlled by the West Fissure. These solutions were precipitating as exotic copper oxides at the bedrock-channel gravel interface to produce the major Mina Sur oxide copper deposit. Part of the palaeo channel is exposed today on the upper benches at the southern end of the Chuquicamata open pit. Reconnaissance drilling of this palaeo-channel has demonstrated the existence of two more periods of solution flow and copper oxide precipitation, which must been related to similar water table changes over the mother deposit.

Conclusions

- The main mineralising events at the Chuquicamata deposit have affected, been imposed upon, or are structurally emplaced within the different textural phases of the *Chuqui Porphyry*, evidencing that this intrusive complex is essentially a pre-mineral host rock. The source of the fluids responsible for the hypogene alteration-mineralisation and the porphyries that must be genetically related with those same events, have not yet been recognised and are probably deeper in the system, below the reach of the drilling undertaken to date.
- The principal hypogene mineralising event is the *intense potassic* alteration (PI) phase, not recognised as such in previous geological models. This early event contributed abundant bornite, digenite, chalcopyrite and covellite mineralisation, structurally controlled by cataclastic deformation zones, in response to the combination of a complex set of deformational and hydrothermal pulses. More detail needs to be gathered on these grade and ore localisation processes.
- An important set of *quartz-molybdenite* veins and veinlets were emplaced in the core of the deposit to form a body defined by a steeply dipping, tabular, vein-like envelope oriented in a general north-south to NNE direction in the central and southern sections of the mine (mine sections 2500mN to 3500mN). This body averages 0.13% Mo and because of its large tonnage represents an economic deposit in its own right.
- The intense *late quartz-sericite (phyllic)* alteration event, which is located in the western parts of the deposit, adjacent to the West Fissure, obliterated pre-existing mineralogical assemblages by introducing

significative quantities of S, Fe, As and Cu to the system. This event did not significantly remobilise and redistribute pre-existing copper mineralisation, but rather enhanced grades while maintaining the same pattern of copper distribution inherited from earlier alteration/mineralisation events.

- The *East Deformation Zone*, consistently recognised and modelled along the eastern margin of the Chuqui Porphyry in the 2003 Geological Model, is interpreted to be the southern extension of the *Messabi Fault*. This structural zone seems to have played a key role in controlling the emplacement of the *Chuqui Porphyry* and successive mineralising events.
- North of mine section 5100mN, where the *Zaragoza* and *C-2 fault systems* are the main structural features, the highest grade mineralisation events are clearly weaker, especially at depth where the *background potassic* alteration with its lower copper grades predominates. This indicates that the economic potential of that area is diminished at depth.
- The variability and contrast of the copper grade within the deposit is larger than had been appreciated from previous models. The new 2003 Geological Model takes into account the geological controls that affect the grade variability, identifying the different hypogene alteration and mineralisation events, and allowing the new model to better represent the copper distribution throughout the deposit.
- On the basis of the 2003 Geological Model, the estimated geological resource remaining at the giant Chuquicamata deposit is of the order of 3000 Mt at an average grade of 0.85% Cu. This is based on data from ±350 000 m of drilling over a vertical interval of some 1800 m to the 1200 m RL elevation, and a cutoff grade of 0.5% Cu.
- At depth, below the currently planned final open pit base, there are over 1000 Mt of 1% Cu primary ore, currently under detailed evaluation with drilling, ramps and cross cuts. The commencement of the underground phase of operations at the Chuquicamata mine, which will exploit this resource, is schedules for the year 2013.

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