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THE ESCONDIDA PORPHYRY COPPER DEPOSIT, NORTHERN CHILE: DISCOVERY, SETTING, GEOLOGY, HYPOGENE MINERALISATION AND SUPERGENE ORE - A REVIEW

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Abstract - The Escondida porphyry copper deposit and its satellites are the source of ore for the world's current largest copper mine, with an installed capacity of 1.2 Mt of fine copper per annum. The published ore reserve + mineral resource at Escondida and the satellite Escondida Norte deposits at the end of 2004 totalled 2.88 Gt @ 1.13% Cu, or 10.11 Gt @ 0.70% Cu when lower grade leach and oxide ores are included. Escondida was discovered in 1981 as the culmination of an exploration program initiated in 1978. This program, the Atacama Project, was specifically targeted at locating supergene enriched porphyry copper ore within the 500 km interval between Chuquicamata and El Salvador, in the established porphyry copper belt of northern Chile.

The supergene sulphide enrichment blanket at Escondida is entirely concealed below the remnant of a 'superleached' capping which is from a few to 350 m in thickness and contained <100 to 600 ppm Cu and 10 to 480 ppm Mo. The enriched blanket covers an area of some 4.5 x 1 km and varies from a few metres to 500 m in thickness. A zone of oxide ore occurs on one margin of the overlying leached capping. Supergene enrichment largely took place between 18.0 and 14.7 Ma.

Hypogene mineralisation is associated with the emplacement of the elliptical, 4.5 x 2.5 km, 38 Ma Escondida stock, a composite granodiorite-porphyry intrusive within a country rock largely composed of Paleocene to early Eocene andesites. Subsequent intrusions of 36 to 34 Ma rhyolite intrusive rocks, cutting the Escondida stock, post dated the first two of three hydrothermal stages related to the emplacement of ore, while the latest intrusives are 31 Ma barren rhyodacite dykes.

Three stages of hydrothermal alteration and mineralisation are recognised. The first, stage A, was potassic, comprising mainly K feldspar in the Escondida stock, and biotite in the surrounding andesites, passing out into a broad propylitic zone. Stage B is characterised by phyllic alteration, comprising an earlier chlorite-sericite ±quartz and a later quartz-sericite, with the latter predominating in the core of the deposit and the former in the surrounding andesites. Stage C hydrothermal activity is the first to post date the intrusion of the rhyolites and is predominantly a multipulse, acid-sulphate, advanced argillic event that persisted from 36 to 34 Ma. Hypogene copper grades associated with stage A potassic alteration alone, are typically <0.3% Cu, while in areas of intense chlorite-sericite and quartz-sericite overprint, grades are, on average, between 0.4 and 0.6% Cu. Locally, where stage C veins cut earlier mineralisation, the hypogene grades may reach >1% Cu. Mineralisation is predominantly contained within stage B quartz-sulphide stockworks, with associated stage A disseminations and stage C polymetallic sulphide veining.

In addition to the main Escondida orebody, there are three other significant deposits within the Escondida District, namely: Escondida Norte, Zaldivar and Pinta Verde, all of which fall within a broad zone of propylitisation covering an area of some 25 x 15 km. The Escondida district lies within the Domeyko Fault Zone, a roughly 30 to 50 km wide, orogen parallel belt that stretches over a length of at least 1000 km in northern Chile, and embraces the giant porphyry copper deposits at Chuquicamata, Collahuasi and El Salvador and other smaller examples. During the late Eocene to early Oligocene, the Domeyko Fault Zone was the focus of, i). a major pulse of the eastward migrating magmatic arc related to the subduction zone to the west of the current coast, and ii). strike slip faulting arising from the NE directed convergence of the oceanic Nazca plate with the South American continent. The intrusions hosting the major deposits, including Escondida, appear to have been emplaced during a change in the sense of deformation in the Domeyko Fault Zone, from transpression to transtension, and focussed at points of intersection between this orogen parallel fault zone, and a series of long lived cross orogen lineaments.

Introduction

Escondida is currently the world's largest single copper producing mine, having expanded its annual installed capacity to 1.2 million tonnes (Mt) of fine copper during 2003. Production in 2004, following the completion of the expansion, totalled 1.2071 Mt of fine copper, 5.75 tonnes of gold and 178.75 tonnes of silver. The total material mined was 377.356 Mt of ore + waste, while 82.378 Mt of ore was milled at an average grade of 1.51% recovered copper (Rio Tinto 2004).

The deposit is located at an altitude of 3000 to 3500 metres in the Andes Mountains of Region II, northern Chile, some 160 km ESE of the Pacific coast port of Antofagasta. It lies within the world's premier porphyry copper district and is one of a string of deposits, including some of the largest on the globe which are distributed at regular intervals within the generally north-south trending Domeyko Fault Zone. The Domeyko Fault Zone comprises a roughly 30 to 50 km wide, orogen parallel belt that stretches over a length of at least 1000 km in northern Chile, and possibly beyond into southern Peru. In addition to Escondida, super-giant deposits in this string include Collahuasi and Chuquicamata, as well as the giant El Salvador and El Abra deposits and others.

In addition to the main Escondida orebody, there are three other significant deposits within the Escondida District, namely: Escondida Norte, Zaldivar and Pinta Verde, as well

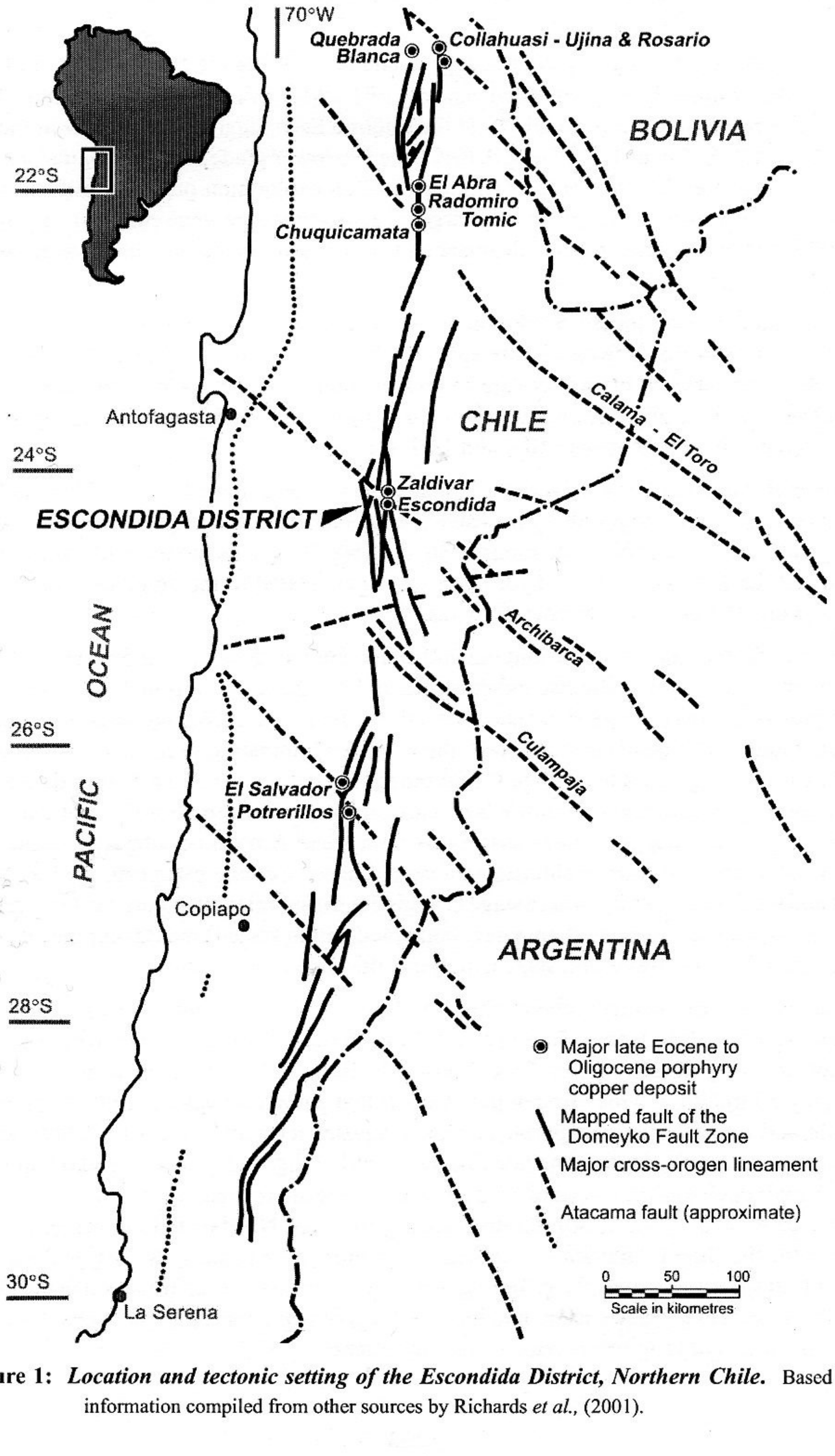

Figure 1: ***Location and tectonic setting of the Escondida District, Northern Chile.*** Based on information compiled from other sources by Richards *et al.*, (2001).

as a number of zones of mineralisation, such as Carmen and Ricardo not currently declared in reserves. All of the major resources lie within an approximately 8x10 km transtensional cymoidal area delimited by the intersection of north-south trending, sinistral, strike slip faults of the Domeyko fault system and a regional NW trending structural corridor, the Archibarca lineament (Richards *et al.*, 2001; Padilla *et al.*, 2001), as described later in this paper. This cymoidal area is believed to have structurally focussed emplacement of the mineralisation related intrusives and hydrothermal systems.

Hypogene mineralisation is associated with a number of 38 to 36 Ma (late Eocene) granodioritic to rhyolitic quartz-feldspar porphyry intrusions within this cymoidal area. The bulk of the high grade ore occurs as extensive, thick, supergene enrichment chalcocite blankets, superimposed upon the hypogene mineralisation by the favourable structural and climatic regime that has persisted in the district over a protracted period.

The main Escondida deposit was discovered in 1981 as the result of a specific exploration program, the Atacama Exploration Project, commenced in 1979 by a joint venture of Minera Utah de Chile Inc and the Getty Oil Company. At the start of production in 1990 the known "reserves" totalled 1.76 billion tonnes (Gt) @ 1.59% Cu (Ortiz, 1995).

At December 2004 the total ore reserve + mineral resource at Escondida, as defined by the Australian JORC code, and reported by Rio Tinto (2004), was as follows: i). sulphide ore = 2.109 Gt @ 1.08% Cu; ii). sulphide leach ore = 5.033 Gt @ 0.51% Cu; iii). oxide ore = 0.206 Gt @ 0.62% soluble Cu. Total combined ore reserves = 2.735 Gt @ 0.87% Cu and mineral resources = 4.613 Gt @ 0.56% Cu. In total this represents **7.348 Gt @ 0.68% Cu.**

At the same date, the satellite Escondida Norte deposit, 7 km to the north, had ore reserves + mineral resources, as defined by the Australian JORC code, and reported by Rio Tinto (2004), as follows: i). sulphide ore = 0.772 Gt @ 1.25% Cu; ii). sulphide leach ore = 1.824 Gt @ 0.52% Cu; iii). oxide ore = 0.164 Gt @ 0.74% soluble Cu. Total combined ore reserves = 1.208 Gt @ 0.97% Cu and mineral resources = 1.552 Gt @ 0.55% Cu. In total this represents **2.760 Gt @ 0.74% Cu.**

Editors Note: Pressure of work prevented the authors who agreed to prepare a paper on Escondida from completing their contribution. Consequently this comprehensive *Editors Review* has been prepared instead, based on published sources, including the most recently released. It allows the reader to compare the characteristics of this very significant deposit with the other giants described within this volume as part of the global coverage promised by the title. **There is no original input from the author,** either in fact or concept. All information recorded has been drawn from published sources which are appropriately acknowledged throughout the text. The sources cited are not necessarily those that made the original observation or conclusion, but rather are the source consulted, and from which information was derived. The key sources include Padilla *et al.*, 2004; Padilla *et al.*, 2001; Richards *et al.*, 2001; Ortiz, 1995; Lowell, 1991; Ojeda, 1990; Richards *et al.*, 1999; Sillitoe and McKee, 1996; Alpers and Brimhall, 1989; and others. Consult these papers for additional information and data.

Resource figures at Carmen and Ricardo (Fig. 2) are not declared in annual reports. Carmen is covered by gravels and there is insufficient information to determine its main characteristics, while Ricardo occurs along the Zaldivar Fault and is composed of secondary chalcocite rimming pyrite within the Cerro Sureste rhyolite (Fig. 3), with no apparent associated hypogene copper sulphides (Padilla *et al.*, 2001),

The reserves and resources that comprise Escondida and Escondida Norte amount to approximately 70.4 Mt of contained copper.

The principal owners of the operator, Mineral Escondida Ltda, are BHP Billiton Pty Ltd 57.5%, Rio Tinto Plc 30%, JECO (Mitsubishi and Nippon Mining) 10% and International Finance Corporation 2.5%.

The Zaldivar deposit, which is the western continuation of Escondida Norte, lies within a mining title that is 100% controlled by Placer Dome Inc., and comprises a reserve + resource of 675 Mt @ 0.63% Cu as leach ore (Placer Dome, 2003) representing 4.2 Mt of contained copper. In 2003 the mine produced 150 500 tonnes of fine copper. The Pinta Verde deposit, also within the Placer Dome title, is the westward continuation of the Zaldivar resource, separated by an arbitrary boundary. The Zaldivar mine exploits a supergene chalcocite blanket and lesser oxide ore, while Pinta Verde comprises 70% oxide ore (Placer Dome, 2003).

The Chimborazo prospect, some 15 km NNW of Escondida and 10 km NW of Zaldiva, still within the gross propylitic alteration zone encompassing the Escondida district deposits, is quoted as containing a geological resource of 264 Mt @ 0.64% Cu (Richards *et al.*, 2001). While the mineralisation at Chimborazo was known prior to the discovery of Escondida or Zaldivar, mineable resources have not as yet been defined (Richards *et al.*, 2001).

Geological Setting

Regional Setting

The Escondida district, in the Cordillera Domeyko, is located within the Andean Mountains of northern Chile, near the present day western margin of South America. This margin has been an active, destructive plate boundary since the Mesozoic when it formed the western seaboard of Gondwana. The geology is dominated by Mesozoic and Cenozoic sedimentation, magmatism and tectonic deformation of the Andean cycle, superimposed on and over a Proterozoic to Palaeozoic basement (Camus, 2005).

The basement, which is not well exposed in the central Andes, represents two earlier tectonic cycles, i). the lower Palaeozoic to late Devonian, multi-pulse, Famatinian cycle (Mpodozis and Ramos, 1989; Camus 2005), and ii). the late Palaeozoic (Carboniferous to middle Triassic Variscan/ Hercynian) Gondwana cycle. In place of the Famatinian cycle, Richards *et al.*, (2001) lists three cycles, namely, the Mesoproterozoic (1460 to 1210 Ma) Pampean, the late Neoproterozoic to Cambrian Pan American, and the Ordovician to Silurian Caledonian (or Oclóyic orogeny) cycles.

The pre-Carboniferous cycle(s) are believed to have involved progressive episodes of subduction, collision and accretion of north-south elongated allochthonous terranes, including the Arequipa Massif in southern Peru and northern Chile, the Precordillera terrane in northern to central Chile and western Argentina, and the Chilenia terrane in central Chile. These cycles are characterised by S-type granitoids and coeval volcanics, by periodic metamorphism in a mainly cratonic setting of ensialic extensional rifts and basins, and by periods of compression interpreted to have been associated with terrane accretion (Richards *et al.,* 2001).

Turbiditic sediments were deposited to the west, lapping onto the margin of the thick continental crust of the accreted terranes and the older continental margins in the east, where they passed into equivalent shelf carbonate facies. Deformed belts of these sediments are found along the sutures separating the mosaic of accreted terranes (Mpodozis and Ramos, 1989; Fig. 4 in Camus, 2005, in this volume).

The Gondwana cycle is much better represented in uplifted blocks of basement in the central Andes than the earlier events. There does not appear to have been any accretion of allochthonous terranes in north and central Chile during this period. A substantial accretionary prism of turbiditic sediments was deposited to the west, possibly in part on oceanic crust. This prism laps onto the margin of the thick continental crust to the east where it passes into shelf carbonates (Mpodozis and Ramos, 1989; Padilla *et al.,* 2001). The Gondwana cycle is characterised by extensive magmatism and metamorphism to the east of the accretionary prism, particularly S- and I-type granitoid complexes and coeval felsic to intermediate volcanic and subvolcanic rocks, emplaced throughout the Carboniferous,

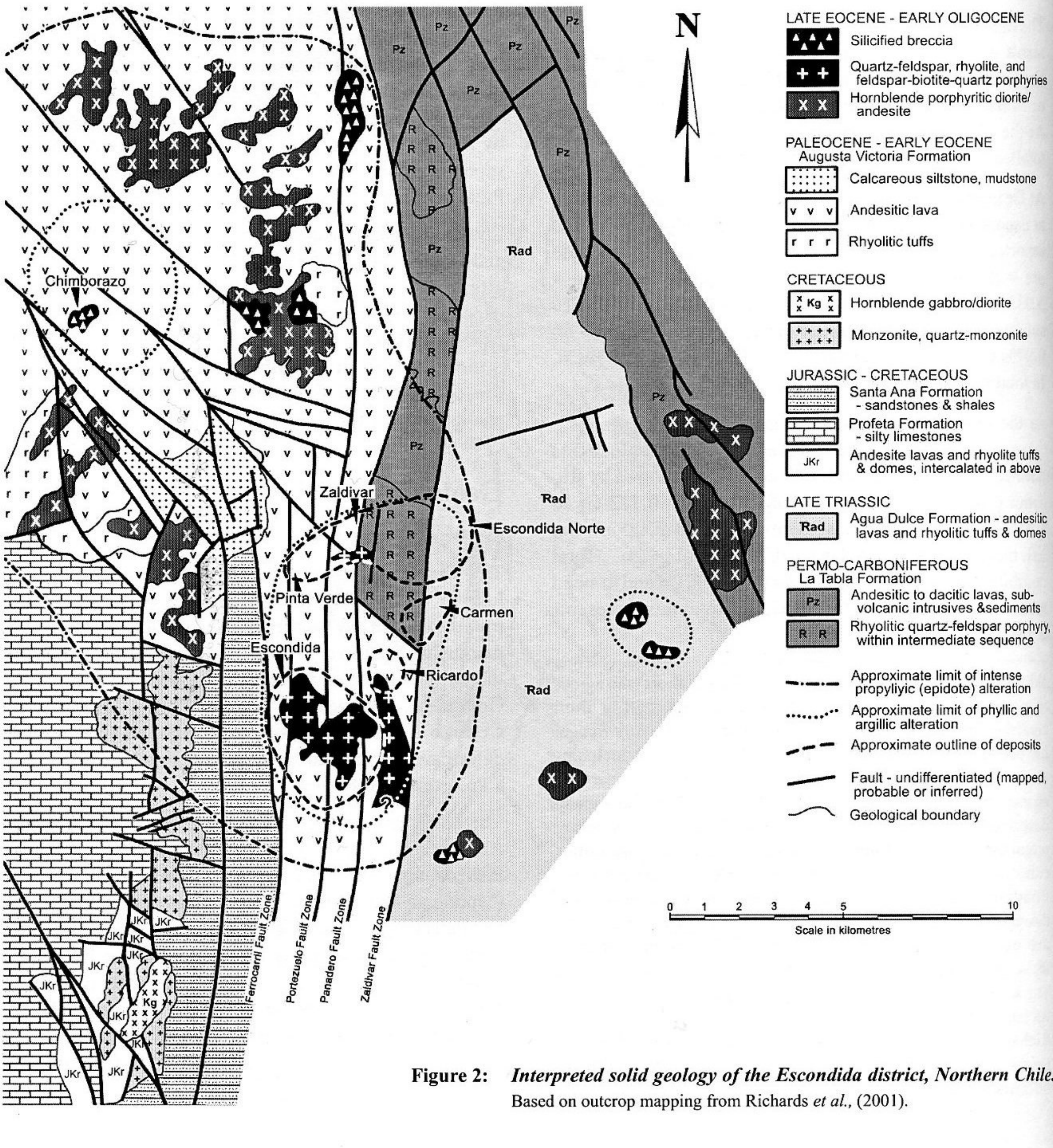

Figure 2: ***Interpreted solid geology of the Escondida district, Northern Chile.*** Based on outcrop mapping from Richards *et al.,* (2001).

from ~350 Ma to ~240 Ma in the Permian (Richards *et al.*, 2001; Camus, 2005). This magmatic activity is interpreted to relate to subduction below a trench to the west of the accretionary prism (Mpodozis and Ramos, 1989; Camus, 2005). The Cordillera Domeyko and the Escondida district are located at the transition from the thick continental basement in the east, to the turbiditic wedge/accretionary prism to the west (Padilla *et al.*, 2001).

There is no evidence of collision of major terranes during the Mesozoic and Cenozoic Andean cycle, which is a diachronous event, related to the breakup of the Gondwana super-continent. A magmatic arc and ensialic back-arc basin were established in the region from the Triassic to early Cretaceous. In the Escondida district, these are represented by the Triassic andesitic lavas and felsic tuffs of the Agua Dulce Formation, and the thick sequence of carbonates and siliciclastics of the Jurassic to Cretaceous Profeta and Santa Ana Formations respectively (Fig. 2). The opening of the Atlantic Ocean at ~127 Ma, corresponded to the cessation of back arc activity in northern Chile. The area occupied by that back arc was uplifted to expose the basement and erode sections of the Mesozoic sequence. However, shifts in the global tectonic pattern resulted in the resumption of subduction in the late Cretaceous, which has continued to the present. The resultant magmatic arc has migrated steadily eastward relative to the plate margin, punctuated by more intense pulses of activity to produce a series of orogen-parallel belts of coeval volcanics and intrusives (Richards *et al.*, 2001).

During the Eocene, the magmatic arc reached what is now the Cordillera Domeyko (and the Escondida district) to develop the extensive andesitic to rhyolitic volcanics of the Augusta Victoria Formation (Fig. 2). This prominent magmatic event has been correlated with a period of rapid, NE directed, oblique convergence, between the Nazca and South American plates, and subduction at a consistently steep angle (Richards *et al.*, 2001, after Pilger, 1983, and Pardo-Casas and Molnar 1987). A reduction in the rate of convergence towards the end of the Eocene corresponded to the strong Incaic phase of tectonism. This tectonic activity produced NW oriented folding and dextral strike-slip concentrated on a major orogen parallel structural array, the Domeyko Fault (or West Fissure) Zone in the current Cordillera Domeyko (see *Tectonic Setting* below). The onset of the Incaic phase also coincided with of the cessation of volcanism (Richards *et al.*, 2001).

At the end of the Incaic tectonic phase, the stress field is interpreted to have been reversed, and transtensional movement in the Domeyko Fault Zone facilitated the emplacement of late Eocene to early Oligocene intrusives ranging from diorite to felsic porphyries. This was the last mid Tertiary event before the arc moved eastward with a renewed increase in the rate of convergence and a flattening of the subduction angle (Richards *et al.*, 2001).

The ensuing Quechua phase tectonism of the late Oligocene was characterised by rapid, high angle plate convergence of more than 10 cm per annum, accompanied by the uplift of the Andean mountain belt (Richards *et al.*, 2001, after Coira *et al.*, 1982, and Pardo-Casas and Molnar 1987). During this period, as a result of the uplift, there was pediplanation in the Cordillera Domeyko and deposition of the Atacama gravels. At the same time, changes in the dynamics of the Pacific Ocean produced the cool, northward flowing Humboldt Current on the western margin of Chile. This current, and the uplift of the Andes mountains to produce a rain shadow, resulted in desertification of the western slopes of the Andes and the northern Chile coastal belt in the middle Miocene (around 15 Ma). The climate change halted erosion before the hypogene mineralisation could be removed and facilitated the development of supergene enrichment over a prolonged period (Richards *et al.*, 2001).

Tectonic Setting

Throughout much of the Cenozoic, the Andean cycle has been characterised by eastward (normal), or NE (oblique) directed subduction convergence of the Nazca plate (to the west, below the Pacific Ocean) and South America (to the east). This resulted in transpressional and transtensional movement along arc parallel fault zones, accompanied by minor, but important strike slip movement on NE and NW trending cross-orogen structures (Fig 1). While this convergence has produced compression, shortening and arc-parallel dextral strike slip in the upper continental plate, there has also been intervals of extension, transtension and sinistral fault movement throughout the Mesozoic and Tertiary (Richards *et al.*, 2001, quoting other sources).

Following the increase in spreading rates at the end of the Mesozoic, and the coincident change in convergence direction of the Nazca oceanic plate from SE to NE by the late Eocene, the focus of strike-slip movement in the upper plate had transferred from the Atacama Fault of the older Mesozoic La Negra arc (in the current coastal belt), to the Domeyko Fault (or West Fissure) Zone (Fig. 1).

The Domeyko Fault Zone is a generally 30 to 50 km wide, orogen parallel belt of faulting that stretches over a length of at least 1000 km in northern Chile, and possibly beyond into southern Peru (Fig. 1). It includes the West Fissure Zone mapped in the Chuquicamata district (see Faunes *et al.*, 2005 in this volume). Mpodozis *et al.*, (1993) separated the Domeyko Fault Zone into five segments along strike, each with its own peculiar characteristics. In the Escondida district the fault zone is characterised by cymoid-shape elongate basins in a zone 200 km long by 20 to 50 km wide.

Padilla *et al.*, (2001) suggest that the Domeyko Fault Zone may have originated during the formation of the Mesozoic extensional back-arc basin, as a series of growth faults that marked the eastern limit of that basin. They add, that it was probably not originally a continuous structure, but more likely was a series of north-south faults that broke off and down-faulted section of the western margin of the Palaeozoic crust to floor the back-arc basin to the west. According to Padilla *et al.*, (2001) the facies distribution indicates the eastern margin of the Mesozoic back-arc basin broadly corresponded to the transition from Palaeozoic crystalline crust in the east, to Palaeozoic oceanic turbidites to the west, possibly reflecting reactivation of Palaeozoic faults. They also suggest that, at the end of the Cretaceous, and into the early Cenozoic, these same faults were reactivated as thrust and transpressive structures, that later still became strike slip faults representing the current Domeyko Fault Zone within the Cordillera Domeyko.

Dextral displacement is recorded in the Domeyko Fault Zone until the late Eocene and, in places, probably into the early Oligocene. However, by the late Oligocene the movement on this structural zone was markedly sinistral, persisting into the Miocene. This change, which may have taken affect at different times along the length of the Domeyko Fault Zone, coincides in general with the cessation of volcanism and the subsequent emplacement of the giant Eocene to Oligocene porphyry copper deposits of northern Chile, including Escondida. It is also most likely to have taken place during an interval of stress relaxation or reversal, promoting the introduction and emplacement of voluminous shallow level magmas (Richards *et al.*, 2001, quoting other sources). See Richards (2005) in this volume, for more background on these processes.

Richards *et al.*, (2001), also consider it likely that transtension developed where oblique structures intersected the main strike-slip fault, causing deflections, points of weakness, and the development of pull part basins. They also utilised the structural interpretations of Salfity (1985) and Salfity and Gorustovich (1998) who identified a number of systems of NW and NE trending lineaments, and lineament corridors (plotted on Fig. 1) that cut across the entire Andean Orogen in northern Argentina and Chile and intersect the Domeyko Fault Zone. The intervals of intersection of these cross trending lineaments with the Domeyko Fault Zone exhibit a good correlation with the location of many of the known major late Eocene to Oligocene porphyry Cu-Mo deposits within the Domeyko Fault Zone (Fig. 1).

One such cluster of deposits is that of the Escondida district, at the intersection of the Domeyko Fault Zone and the NW trending Archibarca Lineament of Salfity (1985) and Salfity and Gorustovich (1998). Figs. 1 and 2 illustrate the intersection in a regional and on a district scale respectively. On Fig. 2, the Domeyko Fault (West Fissure) Zone is represented by the north-south set of faults that include the Ferrocarril, Portezuelo, Panadero and Zaldivar Faults, while the prominent set of NW oriented structures encompassing Zaldivar and Chimborazo belong to the Archibarca Lineament. These latter NW oriented faults have a sinistral displacement, as is indicated for the regional Archibarca Lineament by Salfity (1985).

Richards *et al.*, (2001), speculate on the nature of the basement configuration reflected by the observable cross lineaments. These same cross lineaments also appear to control the location of major ore deposits in the other narrow, parallel north-south trending Cenozoic mineral belts in the central Andes, each of which reflects a separate pulse of the eastward progressing magmatic arc (see Camus, 2005, this volume).

The Escondida District

Fig. 2 is an interpreted summary of the solid geology of the Escondida district, based on published mapping in Richards *et al.*, (2001), and Padilla *et al.*, (2001). The main rock units may be summarised as follows:

Permo-Carboniferous La Tabla Formation - These are the oldest rocks mapped in the immediate Escondida district and represent the local basement. They outcrop as fault bounded massifs to the east of the main faults of the West Fissure Zone (Domeyko Fault Zone). The most widespread exposed lithology of the La Tabla Formation in the district is a quartz-feldspar porphyritic vitrophyre showing very little macroscopic structure, and occurring as units which rarely have non-faulted contacts with other units. It is composed of abundant phenocrysts (typically <5 mm across) of quartz and feldspar (saussuritised plagioclase) with lesser mafic minerals (chlorite altered biotite and hornblende) in a matrix of devitrified glass. This lithology is believed to represent an original glassy or pumiceous rock of volcanic origin, but also includes sub-volcanic intrusives. It ranges from a high K rhyolitic affinity to dacitic and andesitic compositions. The chemistry is characteristic of arc magmas, with an I-type calc-alkaline magmatic affinity. Local units of Palaeozoic calcareous siltstones and mudstones are found overlying the volcanics with no skarn or hornfels development, suggesting the porphyries are mainly extrusive (Richards *et al.*, 2001).

Late Triassic Agua Dulce Formation - This is the first formation of the Andean cycle in the district, and is part of the back arc basin to the La Negra arc in the Chilean Coastal belt (straddling the Atacama Fault shown on Fig. 1). The back arc basin also contained widespread volcanic rocks, which in the Escondida district are largely characterised by a subdued topography, covered by a gravel pediment to the east of the West Fissure Zone. Due to the extensive cover and some lithological similarities with neighbouring units, both the eastern and western contacts of the formation are unclear and conjectural. It is composed of andesitic lavas, and rhyolitic tuffs and domes, and is cut by quartz monzonite to quartz-diorite intrusives. The andesitic volcanic rocks are porphyritic with altered hornblende, clinopyroxene and saussuritised plagioclase phenocrysts set in a fine grained matrix which is sometimes trachytic in composition. The rhyolitic rocks contain phenocrysts of quartz, feldspar (plagioclase with lesser K feldspar) and locally, minor biotite in a glassy, usually devitrified, matrix. Some have textures suggesting a pyroclastic origin, while others appear to represent flow domes. The geochemistry of the andesites and rhyolites are quite different and are suggestive of separate sources, specifically, arc magmatic andesites and rhyolites with a crustal melting component (Richards *et al.*, 2001). Padilla *et al.*, (2001) did not differentiate the Triassic Agua Dolce Formation. They included all rocks mapped by Richards *et al.*, (2001) as Agua Dolce Formation within the La Tabla Formation.

Jurassic to Cretaceous Profeta Formation and *Santa Ana Formation* - These units were developed in a subsiding back-arc basin, and represent an apparently continuous sequence, subdivided into the older, dominantly calcareous Profeta, and younger, mainly arenaceous Santa Ana Formations. The *Profeta Formation* unconformably overlies andesites of the Agua Dulce Formation to the north of Fig. 2, above a basal rubbly conglomerate and overlying silty carbonate. The sequence is up to 1 km thick in the north, and is composed of fossiliferous, micritic limestones, limestone breccias, and sandy and/or silty lenses. The *Santa Ana Formation* is characterised by orange- and yellow-weathering sandstone and siltstones with subordinate carbonate bands. The contact between the two units outside of the mapped area is gradational. Within the area of Fig. 2, voluminous rhyolitic and minor andesitic rocks of the same age are mapped. Some are intercalated with the sediments, though most of the felsic rocks appear to represent flow domes from which the conformable volcanics extend (Richards *et al.*, 2001). Padilla *et al.*, (2001) consider the Profeta Formation to represent Triassic to Jurassic marine sediments and the Santa Ana Formation to be Cretaceous continental-subaqueous rocks.

Cretaceous Monzonite and Gabbro Intrusives - Approximately 5 km west of the Escondida pit, a north-south elongated composite body of quartz monzonite and lesser hornblende gabbro intrudes the volcano-sedimentary rocks of the Profeta and Santa Ana Formation. It is surrounded by a halo of hornfels and calc-silicate alteration, and separates the two intruded units in the map area. The gabbros cross-cut and postdate the quartz-monzonite. The quartz-monzonites are equigranular and medium grained, with rare quartz and plagioclase. The hornblende gabbros are dated at 76.9 to 74.0 Ma, giving a minimum age for both the Santa Ana Formation and the quartz-monzonites. They comprise porphyritic to ophitic rocks with brown hornblende crystals to more than 1 cm across, intergrown with clinopyroxene and plagioclase laths with interstitial biotite and minor quartz, and have an alkalic geochemistry (Richards *et al.*, 2001).

Paleocene to Early Eocene Augusta Victoria Formation - The progressive eastward movement of the Cenozoic volcanic arc resulted in widespread Paleocene to Early Eocene andesitic and felsic volcanism of the Augusta Victoria Formation in the Cordillera Domeyko, accompanied by intercalated arenaceous and calcareous sediments. The volcanics and sediments of this unit, like the Agua Dulce Formation, form a subdued topography, masked by gravels, although the more felsic units form low, poorly exposed ridges. The unit appears to largely comprise a gently folded, sub-horizontal, alternating sequence of locally vesicular, crystal rich andesitic lavas, and felsic tuffs which have devitrification and eutaxitic textures. These volcanics overlie the Profeta and Santa Ana Formations with an angular unconformity (Richards *et al.*, 2001). Marinovic *et al.*, (1992) quote a biotite K-Ar age of 55 ±1.4 Ma from volcanics at the base of the unit.

Late Eocene to Early Oligocene Dioritic Intrusions - Aeromagnetic data indicates clusters of magnetic diorite intrusions regionally distributed along the West Fissure (Domeyko Fault) Zone. One such cluster surrounds the Escondida-Zaldivar-Chimborazo deposits, with the greatest density being to the NE of Chimborazo (Fig. 2). Dykes and stocks of diorite, which characteristically carry abundant hornblende phenocrysts and magnetite, intrude both the Augusta Victoria and the Profeta Formations. $^{40}Ar/^{39}Ar$ dating of samples has returned ages of between 38.28 ±0.32 and 39.94 ±0.46 Ma, similar to the ages of syn-mineral porphyries at Escondida, Zaldivar and Chimborazo (see below). The diorites have a very similar geochemical signature to the Augusta Victoria Formation andesites, with both lithologies being characterised by arc-like trace and major elements (Richards *et al.*, 2001).

Late Eocene to Early Oligocene Porphyry Intrusions - A multiphase episode of late Eocene to early Oligocene porphyries accompanied mineralisation at the deposits of the Escondida district, as described below. At *Escondida*, mineralisation is associated with the Escondida stock, which is composed of at least four phases of intrusion, dated at 37.9 ±1.1 Ma (U-Pb in zircon), and which have an overall granodioritic composition. The phases of this stock were subsequently intruded by two main bodies of rhyolite porphyry which have returned ages of 35.7 ±0.3, 35.2 ±0.3 and 34.7 ±1.7 Ma. Later still, dacitic and quartz-latite porphyry dykes were intruded along NW trending, post-mineralisation faults, cutting the earlier intrusives. These dykes are weakly altered, with sericite K-Ar dates of ~31 Ma. At *Zaldivar* and *Escondida Norte*, mineralisation is mostly hosted by Palaeozoic rhyolitic porphyries of the La Tabla Formation, although it is controlled by dykes of dacitic feldspar-biotite-quartz porphyry which outcrop at Zaldivar, and occur below the pit floor at *Pinta Verde*. These dykes have been dated at 38.7 ±1.3 Ma (U-Pb in zircon) and 37.4 ±0.18 Ma ($^{40}Ar/^{39}Ar$). At Chimborazo, small, poorly altered dykes of andesitic feldspar-biotite-quartz porphyry, similar to the mineralisation associated intrusive at Zaldivar, have been dated at 38.09 ±0.30 Ma ($^{40}Ar/^{39}Ar$) (Richards *et al.*, 2001; Padilla *et al.*, 2001 and 2004).

Late Eocene to Early Oligocene Silicified Breccias and Veining - Veining is widespread in faults of both the north-south and NW structural corridors, producing trails of quartz, jasper, carbonate or barite float, which indicating concealed faults in areas of little of no outcrop. Barite veins more than a metre thick, some with copper colours, were pitted by early prospectors in the NW fault corridor between Zaldivar and Chimborazo. Closer to the porphyry centres, these vein are characterised by epithermal-style chalcedonic and vuggy quartz, passing into extensive zones of brecciation and silicification, as at Chimborazo and to the north and east of Zaldivar (Fig. 2). Alteration associated with these breccias is exemplified by the breccias some 10 km ENE of Escondida. At this location, pervasive silicification of fragmented (Agua Dulce?) volcanic country rock is accompanied by coarse grained hypogene alunite, granular diaspore and kaolinite, within a broader zone of argillic alteration. These breccias have some associated Cu mineralisation although drilling has not defined an economic resource. Similarly, at Chimborazo, the deposit is marked by a prominent hill of silicified and brecciated andesitic lavas and felsic tuffs of the Augusta Victoria

Formation, with potassic, propylitic and late advanced argillic alteration, and associated dykes of altered porphyry, as described above. Mineralisation at Chimborazo is mainly of supergene origin, hosted by the brecciated country rock volcanics (Richards *et al.,* 2001).

The Escondida Deposit

Hypogene porphyry copper mineralisation at the Escondida deposit is associated with an elliptical, 4.5 x 2.5 km, late Eocene to early Oligocene, composite granodiorite-porphyritic stock. This stock is elongated in a 140 to 150° direction and intrudes andesites correlated with the Palaeocene to early Eocene Augusta Victoria Formation (Padilla *et al.,* 2001; Padilla *et al.,* 2004).

The composite granodiorite-porphyritic intrusive, known as the Escondida stock, comprises at least four phases. The two earliest are porphyritic and have a similar mineralogy. They may be distinguished however, on the basis of their phenocryst content, vein continuity and alteration intensity. The older of this pair is the Colorado Grande intrusion, which has been dated (by U-Pb in zircon) at 37.9 ±1.3 Ma and 37.2 ±0.8 Ma, and is cut by the Escondida intrusion. The Escondida intrusion has been dated at 37.7 ±0.8 Ma. The Colorado Grande intrusion is a crowded porphyry with an average of 60% phenocrysts, while the Escondida intrusive has less than 40% (Padilla *et al.,* 2001).

Phenocrysts from both the Colorado Grande and Escondida intrusions comprise quartz, orthoclase, plagioclase and biotite and, in general, range for 1 to 5 mm across, although they may occasionally be up to 8 mm. The quartz is subrounded, from 0.5 to 3 mm in diameter, and totals 2 to 8% of the phenocrysts. Plagioclase however, comprises 60 to 70 volume % of the total phenocrysts, is of oligoclase to andesine composition, are euhedral to subhedral with concentric zoning and may be 0.5 to 5 mm across. Subhedral, Carlsbad twinned orthoclase comprises 20 to 30% of the phenocrysts, and ranges from 0.5 to 3 mm in length. Euhedral biotite phenocrysts occur as brown books with a diameter of 0.5 to 1.5 mm and comprises around 1 to 3% of the phenocrysts. The groundmass is composed mainly of plagioclase, orthoclase, quartz and biotite as smaller crystals of less than 0.5 mm diameter (Padilla *et al.,* 2001).

The third phase of the Escondida stock is a 350° elongated, 1000 x 250 m zone of porphyry breccia, which has a similar composition and phenocryst content to the Escondida intrusion, but incorporates mineralised fragments of the previous two phases, while being crosscut by later mineralised veins. The overall fragment content averages 8%, although this may locally be as high as 60% where it has the texture of an intrusive breccia.. The fourth phase comprises narrow granodioritic dykes containing copper and iron sulphides and associated quartz-sericite alteration, cutting all of the three previous intrusive phases (Padilla *et al.,* 2001).

Approximately 3 m.y. after the emplacement of the Escondida stock and the development of the mineralised porphyry system, both were intruded by the Colorado Chico rhyolitic dome within the Escondida mine area, and the large Cerro Sureste rhyolite dyke to the east, with ages interpreted to be between 34.9 ±0.4 and 32.6 ±2 Ma. These rhyolites post date the main mineralisation associated

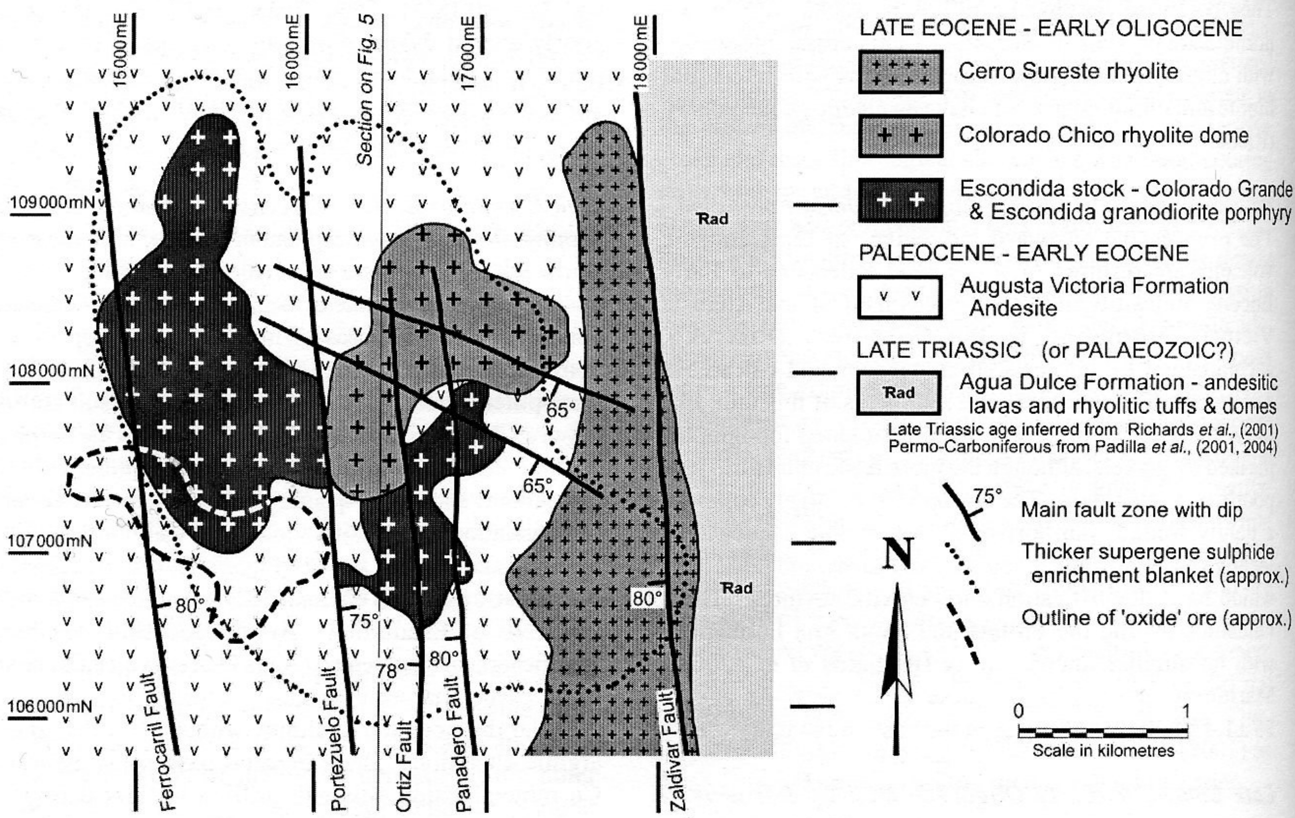

Figure 3: ***Geological plan of the Escondida deposit on the 2800 mRL level*** showing lithologies, structure and the approximate outlines of the supergene sulphide enrichment blanket and oxide orebodies. Modified after Padilla *et al.,* (2004), with additional information from Richards *et al.,* (2001) and Ojeda (1990).

potassic and sericitic alteration, but were accompanied by a moderate to intense advanced argillic phase (Padilla *et al.*, 2001 and 2004).

The final intrusive episode is represented by narrow, copper-barren, but weakly sericite altered, rhyodacitic dykes that cut the rhyolite dome. Dating of the sericite alteration (K-Ar) yielded dates of 31.5 ±2.8 Ma, while whole rock samples gave 31.0 ±2.8 Ma (Padilla *et al.*, 2001).

At least four types of breccia have been recognised within the Escondida stock, namely: i). the intrusive breccias of the third phase of the stock, as described above; ii). cooling breccias at the contacts between the rhyolite dome and andesite country rocks; iii). mineralised and barren pebble dykes that post date the rhyolites; and iv). tectonic breccias of various ages (Padilla *et al.*, 2001).

The mineralised Escondida stock is cut by two main fault systems, namely: i). *mineralised faults,* comprising both a north to NNW set and an associated secondary WNW trend; and ii). NE trending, dextral displacement *post-mineralisation* faults (Padilla *et al.*, 2001).

The *mineralised faults* of the north to NNW trending set have an average strike of 350° (varying from 340° to 20°), parallel to the main Domeyko Fault Zone. There are five main faults in this system in the mine area, the Ferrocarril, Portezuelo, Ortiz, Panadero and Zaldivar faults (Figs. 2 and 3). The two faults to the west, the Ferrocarril and Portezuelo, dip east, while the remainder, which are to the east, dip west (Fig. 3). At around the level of Fig. 3, these faults are represented by corridors of brittle, cataclastic deformation, ranging from 50 to 250 m in width. Each has associated parallel zones of strong alteration carrying veins with early quartz-sericite and late advanced argillic alteration. In addition, the majority of the pebble dykes and late barren rhyodacitic dykes have the same NNW preferred orientation. Each of the main fault zones is composed of a series of discrete, parallel, undulose planes of fractured rock and gouge which have maximum strike lengths of <1 km and are up to 0.5 m thick. The continuity of each of the main fault zones results from the persistent development of the parallel, overlapping planes throughout its length. These faults are more continuous within the andesitic country rocks than within the intrusives. The secondary WNW trending set of mineralised faults strike at between 290° and 340°, dip to the south and are parallel the cross-orogen Archibarca lineament (Figs. 1, 2 and 3) (Padilla *et al.*, 2001; Richards *et al.*, 2001).

The NE trending, dextral displacement *post-mineralisation faults* dip at 60° to 70°S and are characterised by a series of thin, 0.3 m thick, continuous and highly fractured zones of red clay gouge with sharp contacts. Some are continuous over strike lengths of more than 2 km and are current pathways of meteoric water. Lateral displacement on these fault zones is generally less than 50 m (Padilla *et al.*, 2001).

Stress analysis suggests that both the *mineralised* and *post-mineralisation* faults are related to the dominantly transcurrent Domeyko Fault system, with NW-SE and WSW-ENE directed maximum compressive stress axes respectively (Padilla *et al.*, 2001).

Hypogene Mineralisation

Hypogene mineralisation and alteration at Escondida went through three stages of progressive development. Each overprinted the preceding stage and corresponded to a separate phase of hydrothermal activity. Understanding of the early stages in particular, is complicated by the high level, deeply penetrating effects of the third stage, a late advanced argillic event, and by the subsequent supergene oxidation, leaching and concentration. Both of these late events was accompanied by pervasive alteration which modified both shallow and deep hydrothermal characteristics. In addition, the fact that specific alteration minerals may occur in different stages, and different zones within those stages, further confuses the issue. The characteristics of the stages may be summarised (Fig. 4) as follows, from Padilla *et al.*, (2001) and Padilla *et al.*, (2004).

Stage A Alteration and Mineralisation

Stage A hydrothermal activity is reflected as both pervasive and fracture controlled alteration and mineralisation. Two zones of pervasive alteration are evident, specifically, an inner *potassic* and an outer *propylitic* zone.

The *potassic phase,* is lithologically controlled, as follows: i). Within the Escondida stock, weak, disseminated *K feldspar* replaces plagioclase phenocrysts and groundmass to produce a pink tinge in the rock. Locally, significant masses (of the order of cubic metres) have been altered to orthoclase, although much of the K feldspar alteration is found in the vicinity of discontinuous quartz and quartz-orthoclase stockwork veins. ii). Within the andesitic country rock, mafic minerals in both the phenocrysts and groundmass are extensively, and locally completely altered, to *biotite,* accompanied by minor and vein controlled K feldspar and anhydrite. Most of the biotite is fine grained (<0.1 mm) and developed in the groundmass, while the larger phenocrysts are commonly only altered in their outer fringes. This zone of biotite development partially fringes the intrusive with a semi-elliptical/crescent shape, grading outwards into propylitic alteration. iii). At the contact between the Escondida stock intrusives and the andesitic country rock, there is a 20 to 40 m wide shell of pervasive texture destructive *silicification* which has altered both lithologies, and is interpreted to represent a contact metasomatic phenomena. It takes the form of an aphanitic, hard and strongly fractured rock, comprising fine grained aggregates of <50μm quartz grains. This silicification is one of the earliest alteration events, cut by veins associated with all of the following alteration assemblages described below (Padilla e*t al.*, 2001).

Propylitic alteration at Escondida is characterised by the i). sporadic conversion of plagioclase to grossular and more frequently to epidote and montmorillonite; ii). modification of hornblende and biotite to chlorite; iii). partial albitisation of plagioclase; and iv). by widespread carbonate and zeolite veins. The resultant assemblage comprises epidote, with lesser chlorite, montmorillonite, minor biotite and grossular, and widespread carbonate and zeolite veins (Padilla *et al.*, 2001). The propylitic zone forms a wide halo around the deposit (Fig. 4) and the larger mineralised system in the district, encompassing all of the significant deposits (including Zaldivar-Escondida Norte-Pinta Verde and Chimborazo as well as Escondida) over an area of some 25 x 15 km (Fig. 2) (Richards *et al.*, 2001).

Veining associated with *stage A,* which compares closely with the A-type veins of Gustafson and Hunt (1975), represent the transition from the pervasive phase of alteration that dominates *stage A*, to the more vein controlled alteration of *stage B*. The earliest veins are composed of quartz or quartz-orthoclase ±biotite ±anhydrite and are currently best preserved at depth to the northwest, although relicts can be seen throughout the deposit, re-opened by later vein stages. These *stage A* veins can be sub-divided into: i). *Substage A-a* - which are strongly sinuous, discontinuous (generally <100 mm long, but 1 to 20 mm thick), have no alteration halo and are filled with quartz, occurring mainly within the Escondida stock, but also just beyond the contact within andesite country rock. ii). *Substage A-b* - which are still irregular, but more continuous and less sinuous than *substage A-a* veins, and are filled with quartz-K feldspar ±biotite-anhydrite. They are 1 to 30 mm thick and are characterised by halos of pink feldspar making the vein margins diffuse and very irregular. iii). *Substage A-c* - although still irregular, these veins are more continuous than either of the preceding veins, with lengths of up to 0.7 m and thicknesses of from 10 to 50 mm. Their walls are well defined with no alteration selvages. They are filled by quartz, accompanied by chalcopyrite and bornite. The three vein stages exhibit multiple pulses of emplacement, although in most cases *substage A-b* and *A-c* postdate *substage A-a* veins (Padilla *et al.*, 2001).

Mineralisation associated with the *stage A* hydrothermal activity was characterised by a magnetite-bornite-chalcopyrite assemblage with generally <0.5 volume % sulphides in the potassic zone. However, at a microscopic scale, it is common to see *stage A* veins opened and cross-cut by younger stage veins. Copper grades in zones of potassic alteration and only weak overprinting by *stage B* and *C* alteration and mineralisation, normally have grades of <0.3% Cu, although values are dependent upon the alteration assemblage. For example, andesites which have been pervasively biotite altered, contain up to 2 volume % magnetite as generally <60μm grains, <0.5 volume % sulphides and <0.2% Cu. As the proportion of K-feldspar increases, the magnetite decreases and the sulphides content becomes higher. Where K feldspar predominates, the rock

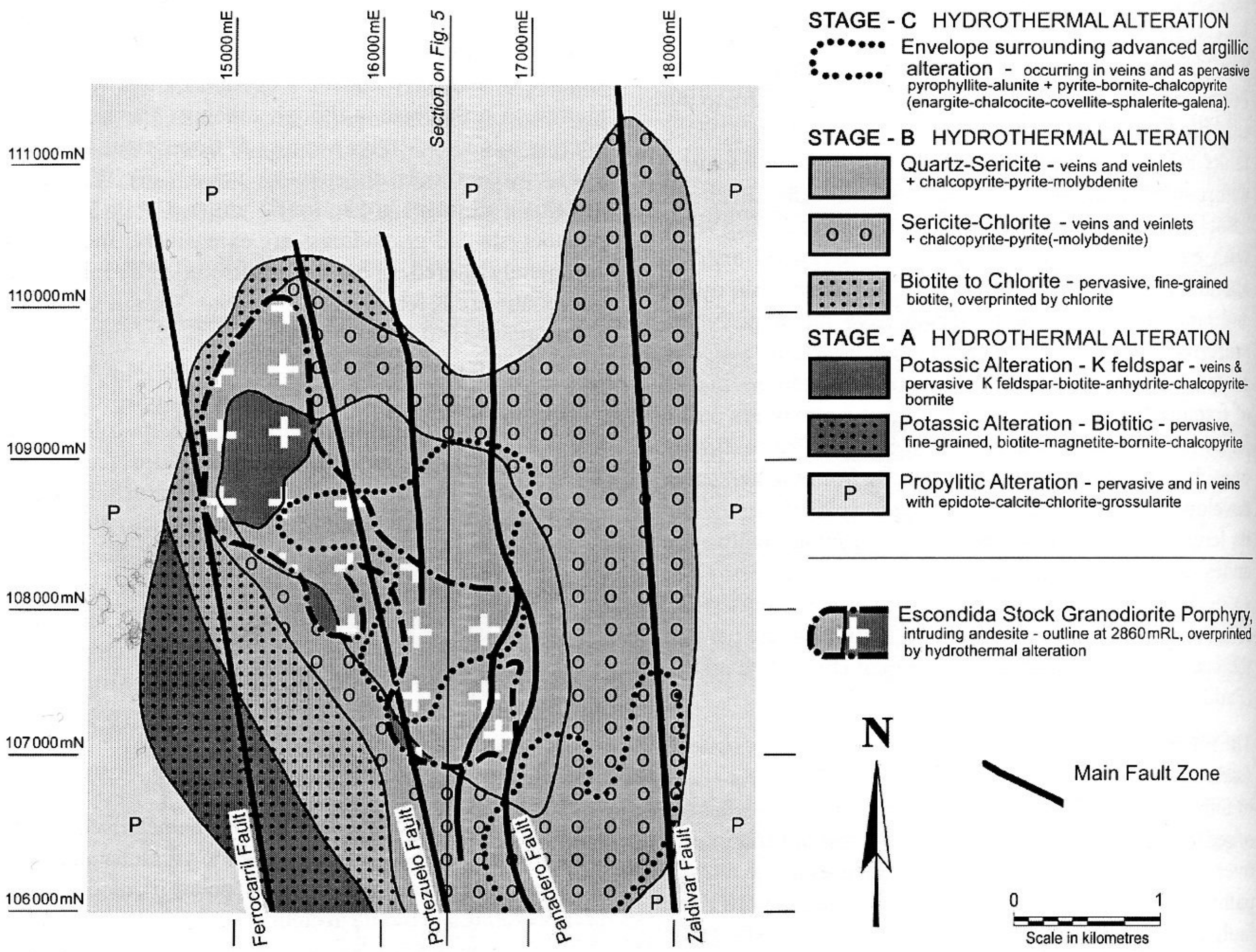

Figure 4: ***Schematic map of the hypogene hydrothermal alteration stages and their distribution in the upper sections of the Escondida deposit,*** prior to the intrusion of the Colorado Chico and Cerro Sureste rhyolites. The outline of the Escondida stock, which precedes, and is altered by stages A and B, is also shown. See Fig. 3 for the location of the Colorado Chico and Cerro Sureste rhyolites, which fall within, but postdate and displace stage B alteration. The envelope surrounding stage C advanced argillic alteration, which was formed after the emplacement of, and overprints the rhyolites, is also indicated. Modified after Padilla *et al.*, (2001).

contains closer to 0.5 volume % sulphides, comprising 90% chalcopyrite and <10% bornite of 20 to 600 μm grain size, and grades of <0.1 to 0.3% Cu (Padilla *et al.*, 2001).

Within the propylitic zone, pyrite is the dominant sulphide, although locally there are small volumes of veins carrying both pyrite and chalcopyrite. Grades are generally <0.1% Cu (Padilla *et al.*, 2001).

To date no high grade potassic core has been encountered, with all holes below the zones of overprinting *stage B* and *C* veining being low grade (~0.2% Cu) and low fracture density (0.2/cm), in contrast to the high fracture densities (1/cm) where the system is cut by the veins of *stages B* and *C* (Padilla *et al.*, 2001).

Stage B Alteration and Mineralisation

Stage B hydrothermal activity produced predominantly fracture controlled alteration and mineralisation, with the alteration concentrated in selvages adjacent to veinlets. Two successive alteration assemblages were developed, specifically an earlier *chlorite-sericite ±quartz,* and a later *quartz-sericite* stage.

The assemblages produced by *chlorite-sericite* alteration are dependent upon the pre-alteration mineralogy of the intrusive and country rocks. Within biotite altered andesite, disseminated and vein controlled chlorite-sericite replaces biotite. Within the Escondida stock, there is a selective alteration of biotite and other mafic minerals and of *stage A* K feldspar to chlorite-sericite, accompanied by the introduction of smaller volumes of chlorite in fractures and re-opened earlier veins. In general, this process is texture preserving, except in the cores of veins and their immediate inner alteration halos. Towards the outer margin of the chlorite-sericite zone, mainly in andesites, chlorite predominates, while sericite is more prevalent closer to the stock. The chlorite-sericite zone is 1 to 2 km wide and open to the NE and SE of the deposit. The fracture density in this zone is moderate and the alteration is a dark to pastel green colour.

Substage B-a veining is associated with the *chlorite-sericite* alteration phase. These veins cut or re-opened *stage A* veins and have lengths of from a few tens to 500 mm, with thicknesses of <10 to 30 mm. As such they are more continuous than the *stage A* veining, although their margins are still irregular and diffuse, and they are sinuous with branching geometries. Within andesite, *substage B-a* veins have a <10 mm core filled by sulphides and only minor quartz, sandwiched by a halo of sericite with subordinate chlorite, grading out into predominantly dark green chlorite (Padilla *et al.*, 2001).

The *quartz-sericite* assemblage represents the dominant alteration within the core of the deposit and is located mainly in the southeastern portion of the Escondida stock, and in the adjacent andesites, occurring mainly in veins and in their selvages. Where most strongly developed, it is a texture destructive alteration, with intense *substage B-b* and *B-c veining* cutting a white sericite-quartz mass in which only the quartz phenocrysts of the original porphyry are recognisable. These veins, which are composed of quartz and sulphides, are usually more than 200 mm up to 1 m in length, and vary from 10 to 150 mm in thickness. They have irregular selvages, with a mottled pastel green, dark grey and white colouration, and grade from intense (texture destructive) to moderate to weak (where original rock textures are recognisable) quartz-sericite alteration (Padilla et *al.*, 2001).

Within the *stage B* alteration zone, the average sulphide content increases to as much as 2 volume %, with chalcopyrite being dominant, accompanied by lesser pyrite and minor molybdenite, for a chalcopyrite:pyrite ratio of 3:1. Where best developed, hypogene grades vary from 0.4 to 0.6% Cu. *Substage B-a* chlorite-sericite ±quartz veins in andesite carry up to 20% of 50 to 500μm sized sulphides in thin veins, while their halos have <2% sulphide which are <30μm. Within the Escondida stock, quartz of the quartz-sericite *substage B-b and B-c* veins carries very fine sulphides in <20μm cracks between grains, and as up to 900μm diameter sulphides within quartz crystals. Within the intense quartz-sericite halos there are up to 10% sulphides that vary from 50 to 600μm across, grading outwards to 2% as 30 to 300μm grains in the weakly altered fringes. The *substage B-c* veining represents the final phase of the *stage B* hydrothermal activity. It is characterised by dominant white sericite and pyrite within the core of the deposit and along the main fault zones, and has up to 5% sulphides, with the chalcopyrite:pyrite ratio being reduced to 1:3. The vein filling is commonly subhedral to euhedral pyrite with diameters up to 3 mm (±chalcopyrite), embraced by a quartz-sericite halo (Padilla *et al.*, 2001; Padilla *et al.*, 2004).

Stage C Alteration and Mineralisation

Stage C is the final, two pulse hypogene hydrothermal event at Escondida, dated at 36 and 34 Ma respectively. It is characterised by polymetallic sulphide veins that vary in width from a few millimetres to 3 m, and are oriented at 320°. Both pulses post date the emplacement of the Colorado Chico and the Sureste rhyolites, while *stages A* and *B* were entirely prior to these rhyolite intrusions (Padilla *et al.*, 2001; Padilla *et al.*, 2004).

Stage C represents acid-sulphate alteration that affected the andesites, Escondida stock and the two rhyolites. Its distribution is controlled by the main fault zones, and by the contacts between the rhyolites and the intruded rocks. The alteration is defined by pyrophyllite, alunite and quartz, the presence of banded quartz veins and abundant sulphides.

The mineral assemblages encountered within this stage, commenced with *substage C-a* comprising quartz-pyrite-enargite, followed by *substage C-b* of bornite-chalcopyrite-pyrite, then *substage C-c* of sphalerite-pyrite, and locally developed *substage C-d* containing pyrite-molybdenite. Padilla *et al.*, (2001) note that each of these substages largely includes the re-opening of veins mineralised during the previous substages to emplace a new layer. They further added, that not all of the *stage C* veins carried the full paragenetic assemblage, although all contain pyrite. At the margins of the veins there are bands of fine grained (up to 500 μm) sugary quartz and fine grained, semi-translucent quartz (<70μm) that are <10 to 100 mm thick.

Beyond the walls of these veins, finely disseminated pyrite is found within the pervasive acid-sulphate alteration. All of the preceding were deposited in association with sericite and pyrophyllite, but in the absence of alunite. The terminal advanced argillic phase is *substage C-e,* marked by pyrite-alunite, in veins that are locally brecciated and cemented with alunite (Padilla *et al.,* 2001; Padilla *et al.,* 2004).

Where *stage C* veining intersects veins containing copper mineralisation emplaced during an earlier stage, the copper grade is normally enhanced to be from 0.6 to >1% Cu and the pyrite:chalcopyrite ratios are >5:1 (Padilla *et al.,* 2001; Padilla *et al.,* 2004). *Stage C* veins have been compared to the D-type veins of Gustafson and Hunt (1975) (Ojeda, 1990).

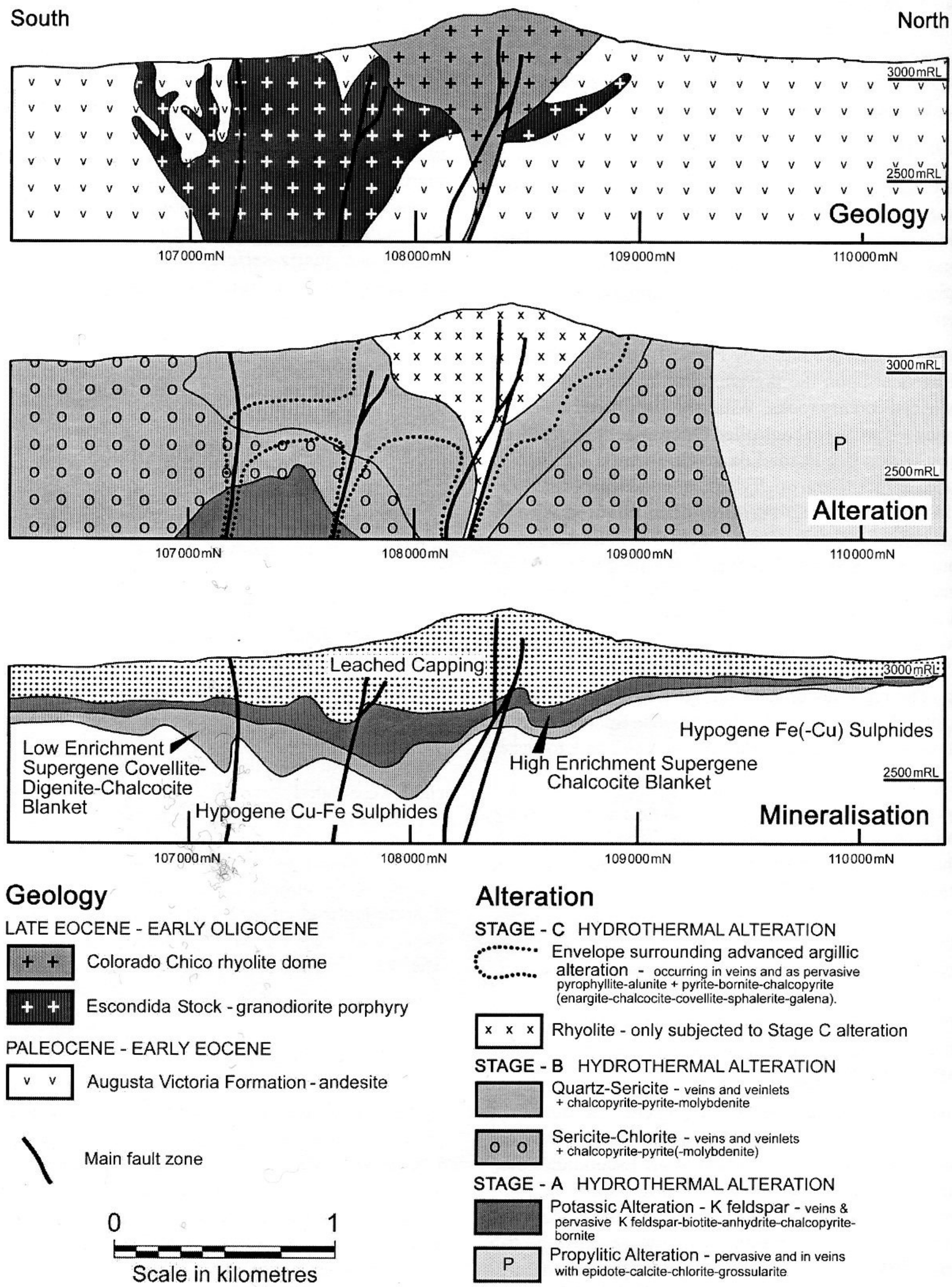

Figure 5: ***Geology, alteration and mineralisation on section 16 450 mE of the Escondida deposit.***
See Figs. 3 and 4 for location of the section. Modified after Padilla *et al.,* (2001).

Chronology and Paragenesis

Field relationships show that the *stage A* alteration and mineralisation, overprints the Colorado Grande and Escondida intrusives of the Escondida stock. The ages of the intrusives and the *stage A* alteration are in the approximate range of 38 to 37.5 Ma. The older limit of emplacement of the Colorado Chico rhyolite overlaps with the younger age of the Colorado Grande porphyritic granodiorite, suggesting the system evolved over a relatively short time frame. However, *stage B* hydrothermal activity is shown by field relationships to post date *stage A*, but to predate intrusion of the Colorado Chico rhyolite dome (Padilla *et al.*, 2004).

Dating ($^{40}Ar/^{39}Ar$) of alunite samples from polymetallic veins cutting the Colorado Chico rhyolite dome has provided ages of 35.7 ±0.3 and 35.2 ±0.3 Ma, while Re-Os dating of molybdenite of *substage C-d* yielded an age of 33.7 ±0.3 Ma indicating that *stage C* represented a separate hydrothermal event at the Escondida deposit. *Stage A* biotite from veins apparently reheated by the Colorado Chico rhyolite dome returned a $^{40}Ar/^{39}Ar$ age close to 36 Ma. The emplacement of the Cerro Sureste rhyolite has not been unequivocally dated, with ages of 34.7 ±1.7 Ma and others suggesting a date of between 36 and 34 Ma, suggesting it may be contemporaneous with the Colorado Chico rhyolite and the first pulse of *stage C* hydrothermal activity. However, the oldest ages of the late barren rhyodacite that cut the Cerro Sureste rhyolite overlap with the upper ages of the molybdenite, suggesting emplacement near 34 Ma (Padilla *et al.*, 2004).

Hypogene copper grades associated with *stage A* potassic alteration, with little input from *stages B* and *C*, are typically <0.3% Cu. However, in areas of intense chlorite-sericite and quartz-sericite overprint, grades are, on average, between 0.4 and 0.6% Cu, and locally where *stage C* veins cut earlier stage mineralisation, the hypogene grades may reach 1% Cu (Padilla *et al.*, 2004).

Isotopic data indicate that *stages A* and *B* alteration and mineralisation was related to progressively evolving magmatic hydrothermal fluids, and that *stage B* introduced new copper, rather than redistributing *stage A* metal. Isotopic data also suggests the progressive introduction of meteoric water to the hydrothermal system from the end of *stage B* and through *stage C*. The same data indicates that the early phases of *stage C*, particularly the pre-alunite pyrite-enargite and sphalerite-pyrite substages, involved leaching and redeposition of metal from the earlier stages of mineralisation. However, the isotope data from galena in alunite bearing veins imply both leaching of earlier sulphides and the addition of sulphide from outside of the system. It is therefore considered that the emplacement of the post-Escondida stock rhyolitic magmas and the younger copper-barren rhyodacite dykes may have promoted *stage C* hydrothermal activity and advanced argillic alteration through the circulation of heated meteoric water and leaching of earlier *stage A* and *B* sulphides. For full data and discussion supporting this paragenesis and these conclusions, see Padilla *et al.*, (2004).

Supergene Mineralisation

The Escondida deposit has a thick, areally extensive, and well developed supergene sulphide enrichment blanket, with an average grade of more than 1.1% Cu, based on a 0.3% Cu cutoff. In 1999, this blanket accounted for 65% of the total resource at Escondida. This enrichment blanket is overlain by a leached cap with associated zones of oxide ore and perched/residual supergene sulphide blankets (Padilla *et al.*, 2001).

The major Domeyko Fault (West Fissure) Zone structures were reactivated after deposition of the hypogene mineralisation to downthrow a block between the Portezuelo and Panadero faults (Figs. 3 and 4) containing the core of the hypogene orebody. Uplift, erosion, oxidation and lowering of the water table in an arid climate led to the development of a downward migrating leached cap and underlying supergene sulphide enrichment blanket between 18.0 and 14.7 Ma, possibly principally controlled by reactivation of the NW trending set of faults (Ojeda, 1990).

Supergene Enrichment Blanket

The supergene enrichment blanket has dimensions of approximately 4.5 x 1 km, and varies from a few metres to 500 m in thickness (Figs. 3 and 5), with the long axis oriented NW, parallel to the main direction of cross faulting (Ojeda, 1990). The upper horizon of the blanket is sub-horizontal, offset vertically in several places across fault zones, while the lower limit is irregular, making the thickness variable (Padilla *et al.*, 2001). Highs and depressions in the base of the blanket tend to be elongated parallel to the same NW fault trend, although secondary north-south and east-west elongations of highs and lows are also observed (Ojeda, 1990). Depressions in the base of the blanket are also related to fault associated fracturing, influencing the downward access of meteoric water. In general, grades within the blanket vary from 0.3% to >2% Cu, and in places may exceed 3.5% Cu. The high grade enrichment ore resource averages over 1.1% Cu, with substantial additional tonnages of lower grade 0.6 to 0.7% Cu (Padilla *et al.*, 2001; BHP Billiton, 2003).

Enrichment ore has been defined by the presence of chalcocite and covellite equal to, or greater than, 10% of the total contained sulphides (Ojeda, 1990). Sulphides occur as disseminations and in veins and include chalcocite, covellite, and minor digenite and idaite, replacing grains of bornite, chalcopyrite and pyrite. Chalcocite is found throughout the full thickness of the blanket, with the upper portion of the zone of strong enrichment being dominated by whitish grey chalcocite, probably mostly djurleite. Covellite and digenite appear near the middle and increase in volume downward. As the abundance of supergene digenite(-anilite) increases downwards, chalcocite(-djurleite) rims on pyrite decrease in thickness.

The generalised zonation of sulphides from hypogene ore at the base of the blanket to the top is as follows: chalcopyrite → covellite → digenite(-anilite) → djurleite(-chalcocite) (Alpers and Brimhall, 1989).

Alpers and Brimhall, (1989) noted that *supergene alteration* at Escondida has resulted in the development of kaolinite, gypsum and alunite from the destruction of feldspars, chlorite, biotite and anhydrite. They add that supergene kaolinite is rare to absent from the zones of original pervasive advanced argillic alteration and the mixed quartz-sericite and advanced argillic assemblages, but increases in depth in the mixed quartz-sericite - potassic zones, probably as a result of the absence of the feldspars, chlorite and biotite that kaolinite replaces due to hypogene alteration. They also reported that supergene kaolinite alteration and dissolution of hypogene anhydrite persisted to depths several hundred metres below the top of the enriched sulphide blanket, and well below the base of strong copper enrichment. The influence of these supergene processes persisted into zones of only poorly enriched protore, which have never-the-less, experienced measurable changes to characteristics, such as mineralogy, density and porosity. Supergene alunite is distributed throughout the advanced argillic and quartz-sericite zones. It occurs as cryptocrystalline veins and fracture coatings up to 10 mm thick, and as fine grained disseminations, and persists to 50 m below the top of the enriched sulphide blanket. Supergene alunite has been extensively replaced by jarosite within the leached cap (Alpers and Brimhall, 1989).

The zone of highest grade and thickness of enriched ore corresponds to the interval of highest hypogene grade, associated with the greatest intensity of hypogene stockwork mineralisation. This zone is located within the downthrown block between the Portezuelo and Panadero faults, where strong quartz-sericite and advanced argillic events overprint early potassic alteration (Ojeda, 1990; Padilla *et al.*, 2001). In this interval, chalcocite reaches 7 to 8% of the rock volume, and accounts for 90% of the copper sulphides (Ojeda, 1990). The chalcocite(-djurleite) has virtually replaced all of the hypogene chalcopyrite and bornite as well as some of the pyrite. The content of pyrite is very variable through the profile due to the presence of pyritic veining (Alpers and Brimhall, 1989).

Leached Cap

The supergene sulphide enrichment blanket at Escondida is overlain by a thick zone of leaching, the upper limit of which is essentially the current land surface, below a thin cover of superficial gravels. Its base varies from a few metres below the surface to depths of more than 200 m over the main supergene enrichment blanket. The peaks of the higher hills prior to mining were originally more than 350 m above the enrichment blanket. The leached capping, as currently exposed, represents an earlier supergene enriched blanket which has been leached as uplift, oxidation and leaching progressed and the zone of enrichment moved correspondingly downwards. Strong leaching of the preceding hypogene and supergene copper sulphide mineralisation has left residual values of <100 to 600 ppm Cu and 10 to 480 ppm Mo in the capping, within a porous rock devoid of hypogene sulphides, but containing variable amounts of limonite in their place. The composition of the limonite has a good correlation with the supergene grades and thicknesses of the underlying supergene blanket. Hematite generally predominates above the thicker and higher grade central sections of the enrichment blanket, indicating leaching from an earlier chalcocite enrichment blanket. Jarosite is the principal oxide over the thinner zones of lower grade, which are found mostly on the margins of the blanket, overlying the pyritic fringe of the hypogene mineralised system. Goethite overlies the oxide ores in the western part of the deposit (Alpers and Brimhall, 1989; Ojeda, 1990; Padilla *et al.*, 2001)

A study of the limonite of the leached cap allows the reconstruction of the earlier, now leached enrichment blanket. This former blanket contained a number of restricted zones of >1.5% Cu, with a cumulative surface area of <0.2 km^2. By comparison, the area averaging >1.5% Cu in the current enrichment blanket is more than 2.0 km^2, emphasising the process of cumulative downward enrichment, from the original lower grade hypogene mineralisation, through progressive stages of supergene enrichment and leaching (Alpers and Brimhall, 1989).

The leached capping at Escondida, like many developed over porphyry copper mineralisation in the central, most arid portion of the Atacama desert, have been subjected to *superleaching*. This process involves significant modification by the remobilisation of quartz and other rock constituents, and the removal of limonite from relict sulphide cavities. The process is believed to be related to the cyclic migration of the salts abundant in the upper 1 to 3 m of the soil profile in that part of the Atacama desert. These salts are apparently transported by capillary action in the soil and the upper parts of weathered bedrock, being dissolved and then re-precipitated. The crystallisation within fissures and cavities causes a fracturing of the rock mass, much like "ice-wedging", the modification of these openings, and the "plucking" of limonite after sulphides. The salt dissolution is also believed to promote chemical modification of the rocks involved. In the leached cap at Escondida, this process is interpreted to have resulted in the destruction of much of the surface evidence of hematitic "live limonite", which is diagnostic of leached chalcocite (Lowell, 1991).

Perched Enriched Sulphide Lenses

Intervals of perched or residual supergene sulphide mineralisation have been encountered within the leached cap, and are the result of incomplete leaching of the earlier supergene blanket. Thicknesses encountered in drill holes vary from 0.1 to 30 m and usually correspond to enriched thick *stage C* massive sulphide veins or to fault zones above the current sulphide blanket (Ojeda, 1990).

Oxide Ore

A NW oriented 1500 x 200 m zone of copper oxide ore was developed on the southwestern margin of the Escondida stock (Fig. 3), over a thickness of 50 to 200 m. Grades vary from 0.2 to 1.5% Cu (Padilla *et al.*, 2001), although the current oxide reserve grade is 0.65% Cu (BHP Billiton, 2003). The "oxide" mineralisation comprises a grouping of non-sulphide minerals, predominantly oxides, silicates, sulphates and carbonates which include brochantite, antlerite, atacamite, chrysocolla, 'copper-wad' and tenorite. It occurs mainly along fractures within andesites which have been subjected to hypogene biotite and chlorite-sericite alteration, although it also occur in lesser volumes over zones of hypogene K feldspar alteration within the Escondida stock (Padilla *et al.*, 2001; Ojeda, 1990). This mineralisation is characterised by the absence of sulphides and occurs within the zone of oxidation above the supergene sulphide enrichment blanket normally occupied by the leached cap (Padilla e*t al.*, 2001; Ojeda, 1990).

Discovery

The discovery drill hole that cut the Escondida deposit in March 1981 was the culmination of the "Atacama Project", first proposed to senior management of Utah International Inc. and Getty Oil Co. by J D Lowell in July 1978 (Lowell, 1991).

The aim of the Atacama Project was to conduct a grass roots exploration program for supergene enriched porphyry copper deposits in areas of outcrop and shallow cover in the Pre-Andean Range of northern Chile, localised over a 500 km interval between Calama (Chuquicamata) and Inca del Oro (just SW of El Salvador). The joint venture was negotiated and signed in January 1979 and work commenced soon after under the management of Lowell, who reported to a management committee representing the partners (Lowell, 1991; Ortiz 1995).

The project was based on the premise that porphyry copper deposits are accompanied by predictable, concentric, zonal patterns in which the outer propylitic zone may cover an area of up to a hundred times that of the orebody it surrounds. It was also recognised that this target could be further enlarged, as many porphyry deposits are surrounded by a halo of peripheral polymetallic occurrences and deposits that form clusters (defined as 2 or more occurrences per square mile). This expanded the target area by a factor of several times. The concept was that, while the deposit may be concealed under cover, the peripheral alteration and polymetallic halo might be mapped, or detected in cheap, shallow, air-core scout drilling, and the predictive vectors followed to ore. In addition, the leached cap over a supergene enriched deposit would most likely be soft, recessive and concealed by younger cover. Within the project area there was, what was considered, a favourable mix of around 50% pre-mineral outcrop in which to search for halos, and 50% pre-mineral rocks sub-cropping below relatively shallow post-mineral gravels and volcanics in which a concealed deposit might lie (Lowell, 1991).

Initial work on the project included assembly of data, and both aerial and ground reconnaissance, using joint venture staff and local consulting geologists. The project proceeded with concurrent regional and local programs. The regional work comprised a geochemical survey over the entire interval targeted by the project, involving the collection of stream sediment samples (sieved to -80 mesh) at 1 km intervals along three parallel longitudinal traverses, each extending over the whole north-south length of the 30 km wide target porphyry belt. This produced some 1400 samples during 1979, each of which was assayed for Cu, Mo and Zn. Thresholds were established at 80 ppm Cu, 10 ppm Mo and 100 ppm Zn. Concurrently with the geochemical survey, a regional geological map was prepared from existing data and new reconnaissance mapping. Some 30 anomalies were delineated from the geochemistry, while other targets were identified and followed up based on known mineralisation, existing data and the previous experience of the project team (Lowell, 1991; Ortiz 1995).

The 30 regional geochemical anomalies were followed up by another 670 stream sediment and soil samples, as well as a study of float in sampled water courses. After elimination of "cultural" anomalies (due to contamination from smelters, mine dumps, known workings, etc.), 10 anomalies remained, one of which was the Escondida district. As anomalies were identified by the regional work, they were progressively followed up by district and prospect scale investigations. To give protection to the better anomalies, approximately 1 million hectares of titles were pegged, one of which enclosed the Escondida deposit (Lowell, 1991).

One of the prospects visited on the basis of previous experience of project staff was the Escondida district. A field visit in August 1979, prior to the results of the regional geochemistry, recognised the following favourable characteristics: i). the presence of a large, well-zoned porphyry copper system with an extensive phyllic zone, surrounded by strong propylitic alteration; ii). skarn mineralisation and peripheral polymetallic vein occurrences; iii). a well developed leached capping, hosted by sericitised, alunitised and silicified quartz-feldspar porphyry, could be recognised on two hills, surrounded by post-mineral cover; iv). while limonite was very sparse in much of the capping, in about 20% of samples there was evidence of limonite after chalcocite. As with many of the other occurrences considered, following the field visit, a grid was established and 313 leached cap and shallow soil geochemical samples were collected on a 50x100 m grid. The grid covered an 1800x1300 m area of the leached cap, above the northwestern half of the Escondida supergene sulphide enrichment blanket. Copper values ranged from 10 to 660 ppm, 30% of which were >100 ppm and 9% >200 ppm. Molybdenum values varied from 1 to 480 ppm, with two samples yielding 3000 ppm. Of these, 40% were >20 ppm and 13% were >50 ppm Mo, the latter being regarded as highly anomalous (Lowell, 1991; Ortiz 1995).

Soon after the August 1979 visit, data from the regional geochemical sampling also pointed to the Escondida district, and was followed up with a further 50 stream sediment samples over a larger area within the district. This follow-up indicated stream sediment anomalies of 10 to 22 ppm Mo in 7 samples over an area of 20 km^2, 80 to 585 ppm Cu in 19 samples over an area of 45 km^2, and 100 to 325 ppm Zn in 21 samples forming a halo around the Cu and Mo anomalous zones. These samples confirmed the significance of the district, which would have attracted attention equally on the basis of either the regional geochemistry or from the field inspection based on previous knowledge (Lowell, 1991).

The area defined by the Cu, Mo and Zn stream sediment geochemical anomalism at Escondida appears to broadly coincide with the outline of the propylitic alteration zone shown on Fig. 2. A halo of Zn persisted to the outer margin of that alteration, surrounding the less extensive copper anomaly that took in the Escondida and southern Zaldivar deposits, while a molybdenum high was centred on Escondida (Lowell, 1991; Ortiz 1995). For plots of the results, see either of these two references.

The first drilling on the project was commenced in September 1979, nine months after the start of the project, to test for the primary source of an exotic copper target, elsewhere in the project area, not at Escondida. In fact some 16 200 m of drilling had been completed on 4 different targets in the first two years of the Atacama Project, prior to the discovery of Escondida (Ortiz 1995).

Following the field visits and follow-up sampling in late 1979, leached cap samples were studied by an expert consultant and a geological map was prepared over the Escondida-Zaldivar district during 1980. The leached capping study did not appreciate the possibility of superleaching (see the *"Leached Cap"* section above), and concluded that the samples studied contained insufficient of the limonite characteristic of cappings associated with underlying blankets of high grade supergene chalcocite to be of significance. The study also concluded that the existence of broad areas of pervasive silicification, scarcity of quartz veinlets and the presence of alunite suggested the area was probably in the roof zone above a porphyry Cu-Mo deposit, with higher grade most likely at a depth of around 1 km (Lowell, 1991; Ortiz 1995).

The district scale mapping established the essential geological and structural framework of the district, although it overestimated the extent of the Tertiary intrusives, including some in the Zaldivar area now known to be highly altered Palaeozoic rhyolitic volcanics. The distribution of silicate alteration was also delineated and shown to cover an area of 80 km^2, comprising an outer 2 to 3 km wide propylitic halo, which at Escondida, surrounded a 9 x 5 km nucleus of phyllic, phyllic-argillic and siliceous alteration, with a marginal block of biotite altered andesite on the northwestern edge. To the north, at Zaldivar the alteration was less intense. The mapping suggested the centre of the mineralised system lay under the alluvial cover between Escondida and Zaldivar, bounded by zones of phyllic alteration found at each of these two centres. The mapping also showed that, with the exception of some fracture coatings of exotic copper minerals (chrysocolla) in a fresh diorite dyke, virtually all outcrop at Escondida was devoid of copper mineralisation. Copper sulphates were found at 200 to 300 mm depths in some isolated pits, and turquoise was occasionally noted in the southwestern part of the area. In addition, apart from a few shallow pits related to supergene aluminium sulphate mining, no historical workings were recorded at the time of discovery (Lowell, 1991; Ortiz 1995).

By early 1981, Escondida was under secure title and was scheduled for drill testing, although it was not the top priority prospect at that stage on the Atacama Project. Two targets areas within the district were selected for drilling. The first was the gravel covered interval between the phyllic zones at Escondida and at Zaldivar, with 5 drill holes at 1 km spacings planned on two lines. The second was the area of geochemical anomalism and scattered occurrences of good leached capping at Cerro Colorado, located over the northwestern section of the Escondida stock and supergene sulphide enrichment blanket as now known. Four holes at 500 m spacings were planned in this area, from the NE to SW, to test for a supergene sulphide enrichment blanket. While the 1980 expert study of the leached capping advised against the probability of such a blanket, the project team's emerging understanding of superleaching persuaded them to still test the possibility (Lowell, 1991; Ortiz 1995).

Air core drilling of the first target was commenced in March 1981, with 5 holes to depths of 150 to 180 m which intersected andesites and porphyries with only weak phyllic and propylitic alteration, several percent pyrite and, in two holes, 0.2% and 0.25% Cu in the primary zone. The four holes into the second target, over Escondida were drilled to depths of 300 to 450 m for a total of 1376 m, from March 13 to 21, 1981. The first, RDH-6, on the northern slopes of the Cerro Colorado, intersected 241 m of strongly leached capping before passing through 51 m of supergene chalcocite averaging 1.51% Cu, underlain by an additional 0.68% Cu enrichment zone and into a high pyrite:chalcopyrite primary zone. The second hole, RDH-7, on the southern slopes of the hill passed through 137 m of leached cap, and then into 73 m of secondary chalcocite averaging 0.68% Cu, 55 m at 1.52% Cu and 37 m of 0.68% Cu. Hole RDH-8 was further south again and over the best of the surface leached capping indications. It detected a 22 m thick interval of copper oxides assaying 0.8% Cu and an underlying 25 m of 0.67% supergene copper sulphide. The final hole in this program, between RDH-6 and 7, and a little further east, penetrated 365 m of intensely leached capping, before intersecting 91 m of supergene sulphides averaging 1.30% Cu (Lowell, 1991; Ortiz 1995).

Drilling continued, extending the limits of the supergene blanket, culminating in hole RDH-61 encountering 250 m of 3% Cu in late 1981. Some 86 drill holes and 117 480 m of drilling was required for deposit delineation, and ore reserves estimation was completed at the end of 1983 with a figure of 1.7 Gt @ 1.59% Cu using a 0.7% Cu cut-off. The development of the mine was announced in July 1988 and construction commenced soon after. The first production from the concentrator was in December 1990.

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The manuscript of this paper was submitted to the authors of the key papers that were the main sources of information on the regional setting, district geology and the ore deposit itself for their review. This was done to ensure it accurately summarised, and did not misrepresent their work and conclusions. No objection or advice of any necessary changes was received.

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