PGC
PUBLISHING

Camus, F., 2005 - The Andean Porphyry Systems; *in Porter, T.M. (Ed.), Super Porphyry Copper & Gold Deposits: A Global Perspective*; PGC Publishing, Adelaide, v. 1, pp 45-63.

THE ANDEAN PORPHYRY SYSTEMS

Francisco Camus

Codelco-Chile, Santiago, Chile

Abstract - The Chilean Andes comprise the most richly endowed copper province on Earth. A total resource (including production) of about 490 million tonnes of fine copper has been identified in more than 63 porphyry copper deposits and numerous prospects.

Andean porphyry deposits occur along five metallogenic belts that extend from central Chile to southern Perú and northwest Argentina. They formed between the Early-Late Cretaceous and Pliocene. Within these belts the deposits occur in clusters associated with multiphase plutonic complexes. This relationship is particularly prevalent in the Late Eocene-Oligocene belt, the most prolific of all. The time span between the oldest and youngest belt corresponds to the period in which contractional tectonism of the Andean cycle was established and developed from Late Cretaceous to Recent.

The five porphyry belts reflect Andean tectonomagmatic evolution, with progressive eastern migration of volcanism and plutonism with time. Arc migration correlates with discrete and transient periods of increased convergence velocity and convergence angle. These periods coincide with the strongest deformation events that in turn correlated with the temporal development of each one of the five porphyry belts. These events resulted in regional uplift, shortening, and crustal thickening which in turn produced syn-orogenic erosion.

Porphyry copper emplacement occurred syn-tectonically and the resultant multiphase intrusive complexes have variable compositions ranging from granodiorite to tonalite, monzonite and quartz monzonite evolving in all cases from intermediate composition pre-mineral phases to more felsic intra-mineral phases. A reversal to more mafic magmatism has been reported locally.

Alteration and mineralisation processes evolved from early magmatic stages dominated by high-temperature fluids to late stages dominated by low or moderate-temperature hydrothermal fluids with magmatic and meteoric components.

Supergene modifications such as oxidation, leaching and secondary enrichment have been very important in developing the high-grade copper orebodies that are presently being profitably mined in the Andes. Lateral migration of copper-bearing solutions has developed proximal exotic deposits.

Introduction

Chile and southern Perú contain one of the largest copper concentrations on Earth. A total resource (including production) of about 500 million tonnes of fine copper has been identified in 63 porphyry copper deposits (Fig. 1). If 10 million tonnes of contained fine copper is taken to be the minimum tonnage required to classify porphyry copper deposit as a giant ore deposit, then this part of the Andean cordillera contains eleven of the 20 giant porphyries along the Circum-Pacific belt. Among them are the three largest of all, El Teniente, Río Blanco-Los Bronces and Chuquicamata (Fig. 1), all containing resources plus production above 50 million tonnes of fine copper. El Teniente is the largest of all with 94.4 million tonnes of fine copper (resources plus production). Currently Chile produces about 4.94 million tonnes of fine copper annually, which represents around 37% of global production.

The presence of so many large copper porphyries has intrigued researchers throughout the 20th century. Exploration efforts, with the discovery of about 12 world-class porphyry copper deposits in the last 25 years, have enhanced interest in understanding the Andean geological evolution and metallogenesis. The geological processes that are common factors in controlling the emplacement of these ore bodies along the porphyry copper belts located in the Domeyko cordillera and in the Andes of central Chile have been the subject of research by numerous individuals in Chile and elsewhere. As a consequence, during the last 15 years, the understanding of the tectonomagmatic evolution of the Chilean porphyry copper systems has greatly progressed. The results of these efforts have been communicated widely at international conferences, technical journals and special publications (e.g., Sillitoe and Camus, 1991; Camus *et al.*, 1996; Skinner, 1999; Camus, 2003).

This paper is an updated and revised version of "The Andean Porphyry Systems" by Camus, F. 2002, first published in Cooke, D.R. and Pongratz, J. (Eds.) Giant Ore Deposits: Characteristics, genesis and exploration, CODES Special Publication 4, p. 5-22, June 2002.

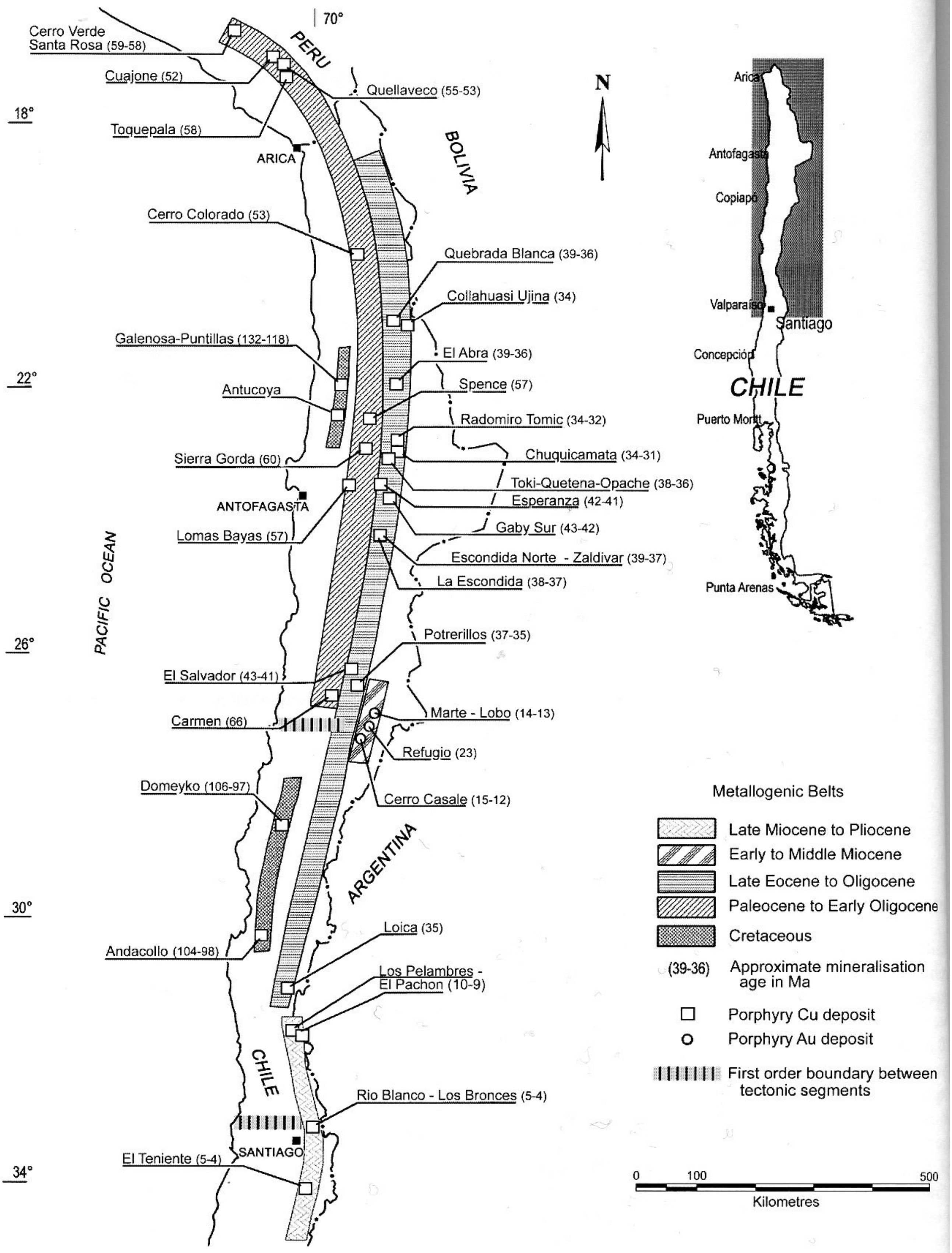

Figure 1: ***Location of Andean porphyry copper metallogenic belts.*** The principal porphyry copper and gold deposits and prospects a shown together with ages in million years (Ma).

The Andean Porphyry Deposits

In the central Andes, porphyry copper-molybdenum and gold-rich porphyry deposits occur in seven temporally discrete, roughly parallel north-trending metallogenic belts that extend from central Chile and NW Argentina to southern Perú. Of the seven belts, six occur in Chile and their time spans are as follow: Late Palaeozoic-Triassic (239-195 Ma); Cretaceous (132-73 Ma); Paleocene-Early Eocene (65-50 Ma); Late Eocene-Oligocene (43-31 Ma); Upper Oligocene to Middle Miocene (23-12 Ma); and Late Miocene-Pliocene (12-4 Ma). Most of the porphyry copper mineralisation occurs in the three youngest belts which are located in northern and central Chile (Fig. 1).

Copper, molybdenum and gold endowments in the Chilean porphyries are greatest in the youngest systems. Fig. 2 shows a rather gradual increase of the abundances of these three metals with respect to time, with the Late Eocene-Oligocene and Late Miocene-Pliocene being the most important periods of copper-molybdenum-gold deposition. The increase in copper and molybdenum deposition from the Cretaceous relative to the Late Miocene-Pliocene is almost 39 and 66 times respectively, whereas gold increases approximately five times. This significant increase in metal content can also be recognised at the level of individual belts. In the Late Eocene-Oligocene belt, three separate porphyry sub-stages can be differentiated with different time spans (Fig. 3): Early (43-41 Ma), Intermediate (39-36 Ma) and Late (34-31 Ma). The latter sub-stage shows the largest copper-molybdenum concentration and most of this large volume of metals is concentrated in only three deposits (Rosario, Chuquicamata and Radomiro Tomic, Fig. 3). The same situation occurs in the Late Miocene-Pliocene belt, where three porphyries account for more than 180 Mt of contained fine copper (Los Pelambres, Río Blanco-Los Bronces and El Teniente; Figs. 1 and 2).

Geological Framework

The Chilean porphyry deposits are associated with the geologic and metallogenic evolution of the Andean cordillera of Chile and neighbouring Argentina. Mesozoic and Cenozoic sedimentation, magmatism and tectonic deformation have dominated this region, and are superimposed on a Palaeozoic basement. This complex history is the result of three tectonic cycles developed during the Early Palaeozoic (Famatinian cycle), Late Palaeozoic (Gondwana cycle) and the Mesozoic-Cenozoic (Andean cycle; Mpodozis and Ramos, 1990). Collision, subduction and accretion of allochthonous terranes characterised the Early and Late Palaeozoic cycles (Bahlburg and Hervé,

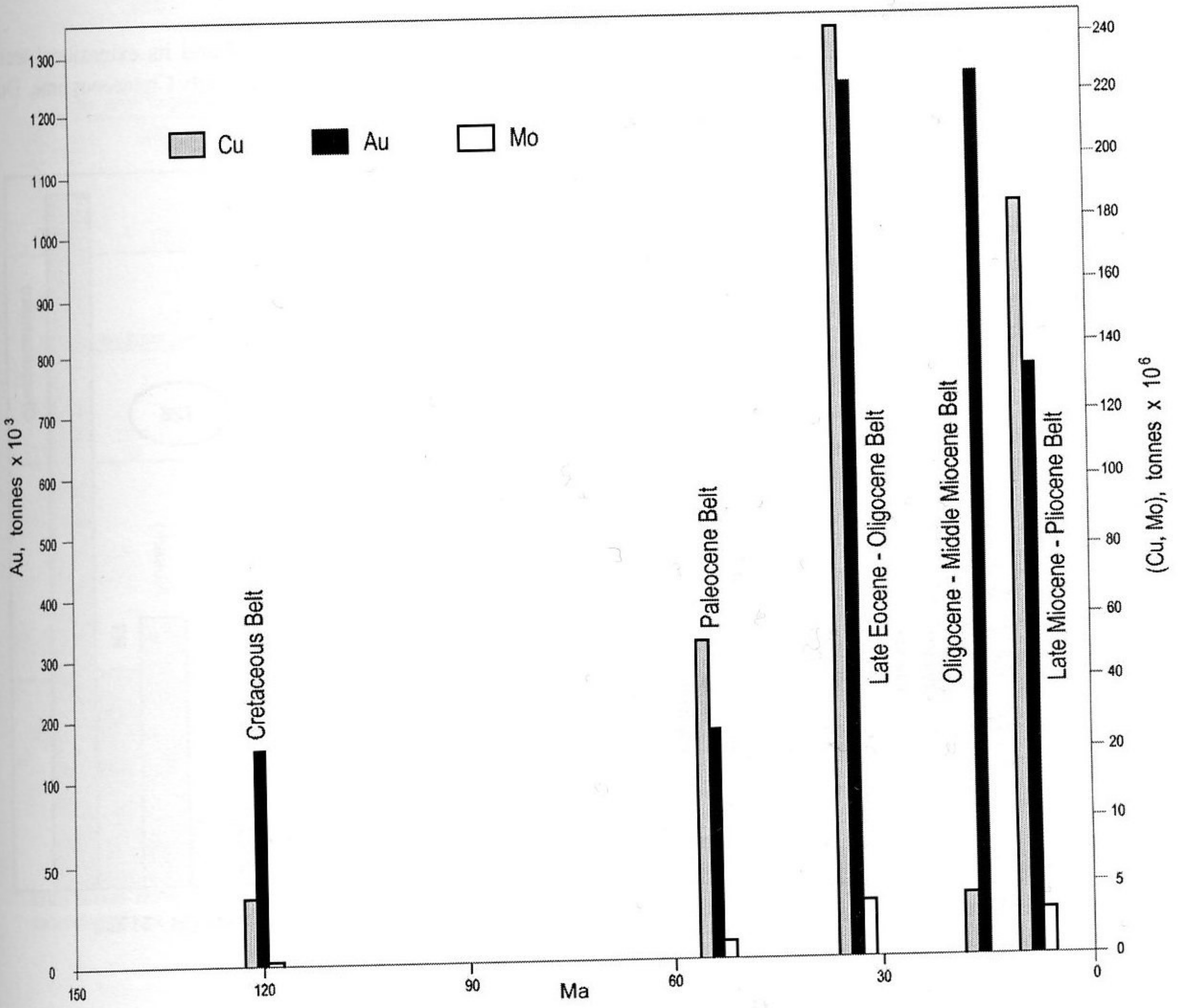

Figure 2: ***Diagram showing copper, molybdenum and gold distribution with time.*** The five metallogenic belts are shown with the respective tonnage expressed in tonnes of metal.

1997). In contrast, the Andean cycle lacks evidence of collision of major terranes. Its evolution is more related to subduction, with the initial development of a back-arc basin which evolved into a continental arc at the end of the Early Cretaceous. The emplacement and distribution of the porphyry copper-molybdenum, copper-gold and gold systems is closely associated with the geological events that took place during the evolution and development of the Gondwana and the Andean tectonic cycles, the latter being the most productive in terms of metal deposition (Fig. 2).

Geological Characteristics of the Tectonic Cycles

The Gondwana Cycle (Carboniferous to Middle Triassic)

The Gondwana tectonic cycle was characterised by an arc-related subduction accretionary complex that extended along the Chilean coastal region south of 25°S latitude from Late Devonian to Early Jurassic (Mpodozis and Ramos, 1990). Complex sequences of "I" and "S" type granitoids and related volcanic rocks of rhyolitic composition were emplaced along Chile and Argentina to the east of the accretionary complex. These rocks have been interpreted as products of anatexis within the framework of a period of extensional tectonics or as the result of the felsic differentiation of a calc-alkaline subduction-related assemblage (Mpodozis and Ramos, 1990; Mpodozis and Kay, 1992).

Several stages of compressional deformation have bee recognised in Argentina. Associated with thes deformational stages, two groups of porphyry copp occurrences can be recognised in Argentina (Sillitoe, 197 and in northern Chile (Fig. 4). The oldest group occurrences crops out principally in Argentina and cove the period 295-266 Ma. The youngest group (239-195 M has only been recognised in northern Chile. These tw groups can be correlated with similar groups in easte Australia (Horton, 1978). None of them are of econom significance in South America today.

The Andean Cycle (Mesozoic to Cenozoic)

The Andean cycle is the most important tectonic event th occurred along the western margin of Gondwana. commenced during the upper Triassic, when a maj palaeogeographic change took place and the La Palaeozoic magmatic arc shifted westward to a new positi near the present Chilean coast (Mpodozis and Ramo 1990). A complex series of interconnected extensio ensialic basins, most of them of half-graben type, form behind the arc during the Jurassic-Early Cretaceous. T arc was built on the Palaeozoic accretionary prism northern and central Chile, whereas the basement of t back-arc basins was the Late Palaeozoic magmatic b (Mpodozis and Ramos, 1990).

The back-arc basin system and its extensional tecto framework were active until Early Cretaceous time. Duri

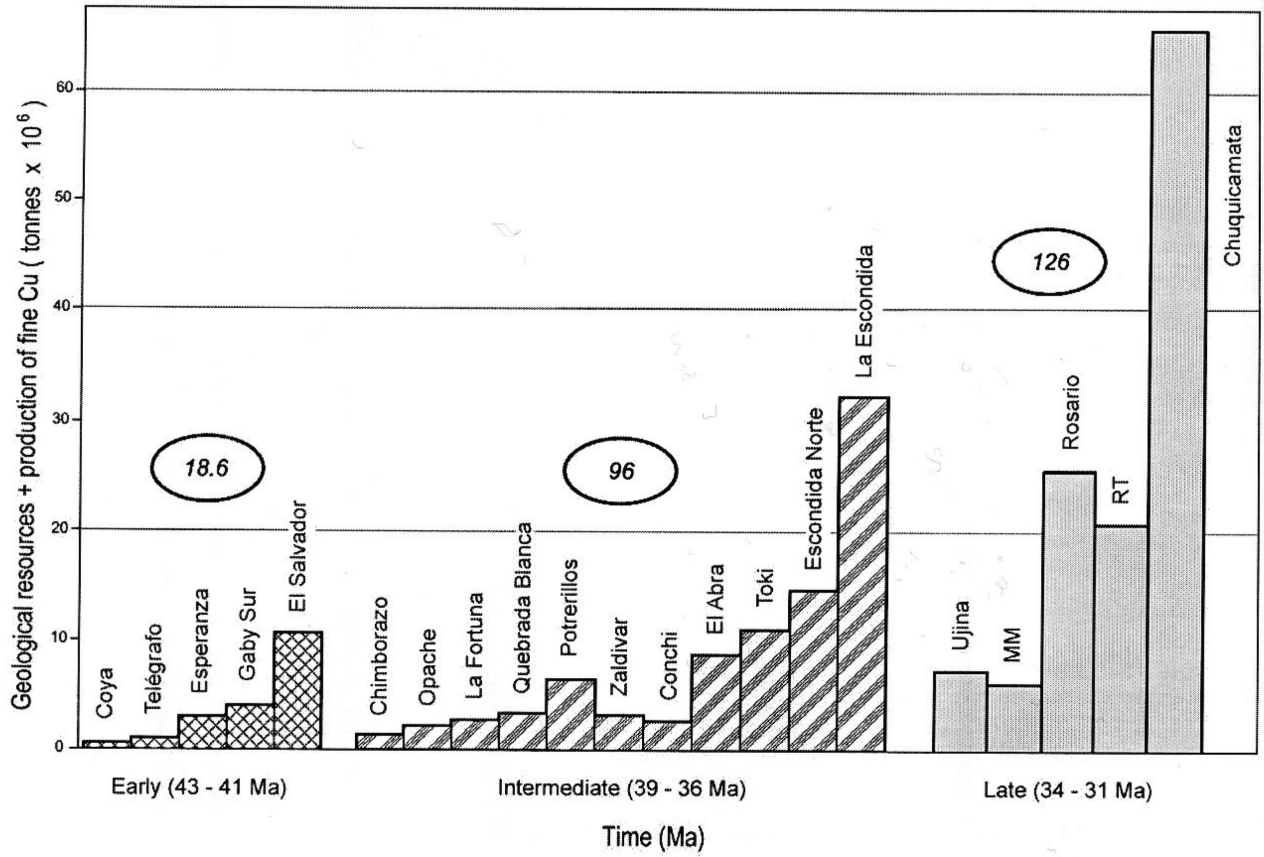

Figure 3: ***Geological resources + production for the three stages into which the Late Eocene-Oligocene porphyry copper belt has been subdivided.*** Figures in circles correspond to million tonnes of fine copper.

the Late Cretaceous, the basins were inverted as a consequence of a major contractional deformation event related to the opening of the Atlantic Ocean (~ 130-135 Ma). They were then overprinted by a series of continental magmatic arcs that have migrated eastward with time. Arc magmatism has dominated the Andean evolution during the Upper Cretaceous and the Cenozoic.

The Jurassic-Cretaceous back-arc system was not continuous, and varied from ensialic to marginal basins. Consequently, the Late Cretaceous contractional event resulted in different styles of tectonic deformation (Mpodozis and Ramos, 1990), which in turn significantly influenced the metallogenic processes that developed during this cycle, especially those related to emplacement

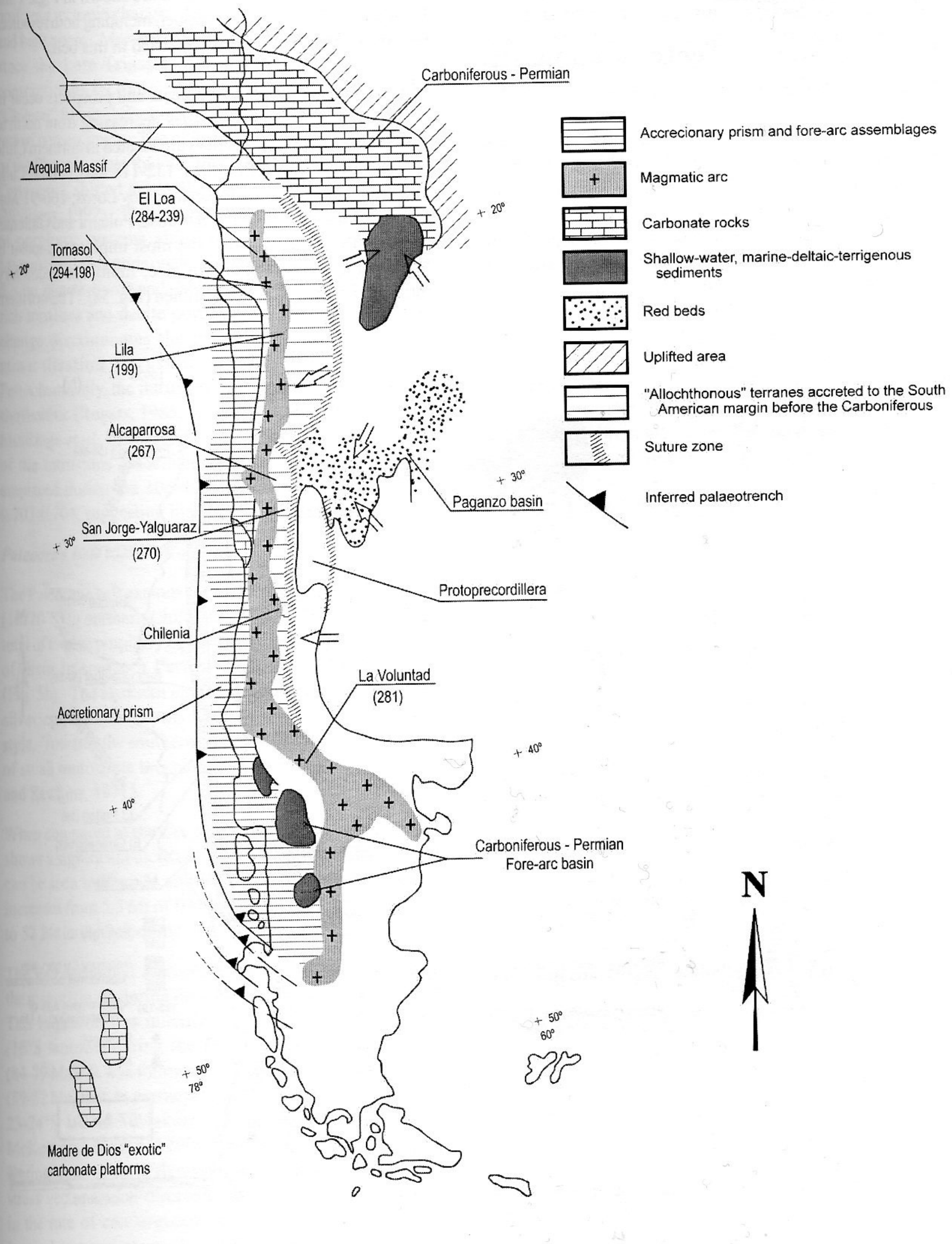

Figure 4: ***Location of the porphyry prospects along the Late Palaeozoic palaeogeography*** (modified after Mpodozis and Ramos, 1990).

of porphyry-style mineralisation. The largest and most important copper-molybdenum deposits of porphyry-style present along the Andean belt were formed during the contractional stage of this tectonic cycle, in addition to the more significant porphyry-gold occurrences. In contrast, during the extensional early stages of the Andean cycle, the formation of stratabound copper, copper-silver, IOCG deposits and magnetite-apatite iron oxide orebodies, characterised metallogenesis.

Meso-Cenozoic Tectonomagmatic Evolution of Porphyry Systems

Porphyry copper-molybdenum and porphyry gold deposits formed within the Andes since the Carboniferous, but those emplaced during the Andean tectonic cycles are the best preserved. They occur along five metallogenic belts (Fig. 1) that show similar geological features suggestive of a common genetic origin. These characteristics are described separately for each belt.

Cretaceous Belt (132-73 Ma)

Towards the final stages of the evolution of the Jurassi Early Cretaceous magmatic arc, porphyry-sty mineralisation developed within what are now the easte flanks of the Coastal Range, between 22°-36°S (Fig. 5 This porphyry copper belt extends for 1500 km with a to of ten deposits and prospects having been discovered date, selected examples of which are shown in Figs. 1 a 5a. A total of 5.5 Mt of fine copper, including both resour and production, have been identified in this belt.

The Cretaceous porphyry deposits and prospects occur three discrete clusters, with ages decreasing from north south (Fig. 5a). These clusters are located in northern Ch (Antucoya, Galenosa-Puntillas; 132-118 Ma); central Ch (Andacollo, Domeyko, Pajonales, Los Loros; 106-91 M Fig. 5a) and southern Chile (San José, Polcura and Gallet 90-73 Ma). Economically, the most important deposit Andacollo, where a medium size, immature seconda enrichment blanket is being mined (Fig. 5a). The northe

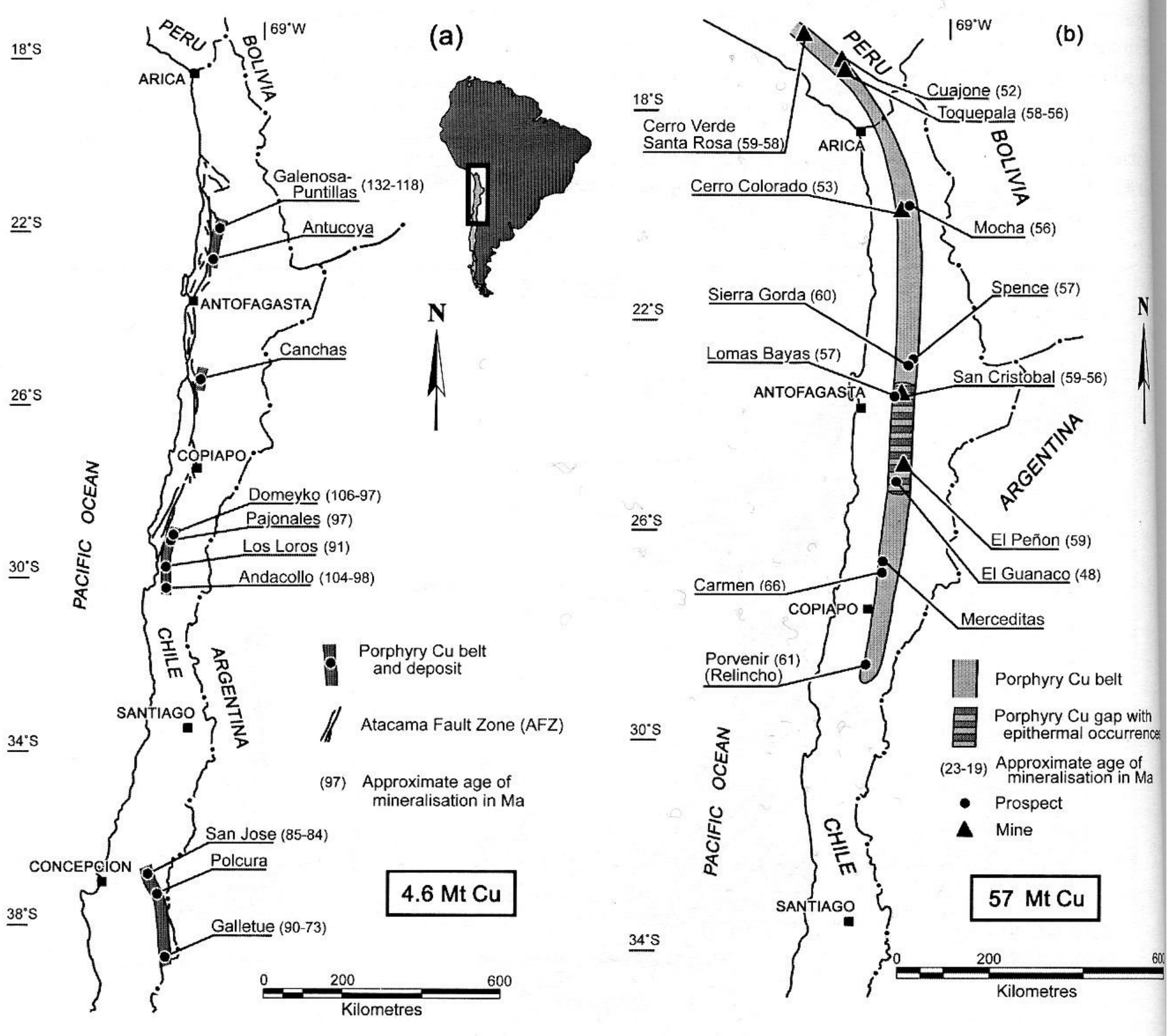

Figure 5: ***Location of the Andean tectonic cycle porphyry belts - (a) Cretaceous belt, and (b) Paleocene belt.*** The figures in the rectangles are million tonnes of fine copper.

Chile cluster was localised by some of the eastern strands of the Atacama Fault System (AFS) a 1000 km long trench-linked strike-slip fault system (Figure 5a) that was active from Early Jurassic to Early Cretaceous (Brown *et al.*, 1993). The northern Chile Cretaceous porphyries consist essentially of oxide copper mineralisation.

Within the framework of the tectonomagmatic evolution of the Andes, the Cretaceous belt formed at a time of profound tectonic change. An extensional tectonic regime and high angle "Mariana-type" subduction had dominated since the Late Triassic. This was transformed to a contractional tectonic regime and development of a "Chilean" type subduction zone, due to an increase in the rate of convergence. The oblique NW convergence vector of the Phoenix plate that dominated from Jurassic to Early Cretaceous, shifted gradually to a more orthogonal vector (Williams, 1992). This change favoured the emplacement of porphyry systems along reactivated normal faults. Magmatism also underwent a change, from intermediate diorite, quartz diorite and gabbro to more alkaline and silica rich tonalites and dacite porphyries. This compositional change discriminates the pre-mineralisation and syn-mineralisation intrusions in the Cretaceous belt. Petrochemically, the intrusions are high K calc-alkaline to shoshonitic (Rogers, 1985; Williams, 1992). According to Munizaga *et al.*, (1985), initial Sr isotopic ratios for some of the intrusions associated with the porphyry systems emplaced during the 106-97 Ma time span vary between 0.703-0.704, suggesting limited crustal contamination.

Paleocene Belt (65-50 Ma)

The Paleocene belt extends for 1500 km from southern Perú (16°20'S) to northern Chile (29°30'S). Along its length, a total of twelve porphyry deposits and prospects occur, four of them in southern Perú and the remainder in Chile (Fig. 5b). The southern end of the belt contains six gold-silver epithermal systems of high and low sulphidation style. Towards the southern end of the belt, several groups of small tourmaline breccia pipes are recognised (Sillitoe and Sawkins, 1971).

When compared to the Cretaceous belt, the Paleocene belt shows a significant increase in copper content (Fig. 2). As can be seen in Figs. 5a and 5b, the total contained copper increases from 5.5 Mt of fine copper in the Cretaceous belt to 52 Mt in the Paleocene belt.

The Paleocene belt represents the eastward migration of the magmatic arc during the Late Cretaceous to Paleocene. This migration was initially developed in southern Perú (16°S latitude) during the Peruvian compressive phase (84-79 Ma). It was followed by the Incaic I tectonic phase (59-52 Ma) that, in northern Chile, extended south to about 23-24°S latitude (Maksaev, 1979; Noble *et al.*, 1985; McKee and Noble, 1990; Benavides-Cáceres, 1999). During most of the Paleocene, the principal compressive stress vector was E-directed, associated with an increase in the rate of convergence (>15 cm/year) related to the Incaic I tectonic phase (Pardo-Casas and Molnar, 1987). According to Williams (1992) mineralisation in this belt commenced at 65-60 Ma with the emplacement of several epithermal deposits (San Cristóbal, El Peñón and Guanaco). Porphyry style mineralisation developed only at the end of this period at Lomas Bayas and Sierra Gorda (Fig. 5b).

The main copper mineralising stage of the Paleocene belt occurs within the 60-55 Ma interval, coincident with the development of major structural systems such as the Incapuquio and Micalaco Faults in southern Perú. The Incapuquio and Micalaco Faults are very complex and show sinistral/transcurrent, normal and dextral/reverse movements that have been traced for more than 140 km and probably controlled the emplacement of the Toquepala, Cuajone and Quellaveco porphyry cluster (Zweng and Clark, 1995). In northern Chile, during this same time period, the porphyries of Cerro Colorado, Mocha and Spence were emplaced, in addition to the low sulphidation epithermal systems of San Cristobal and El Peñón. To the north of Mocha and south of Toquepala, the belt is concealed beneath thick sequences of Late Oligocene to Miocene ignimbrite sheets (Tosdal *et al.*, 1984).

From about 24°S latitude and during the 55-48 Ma time span, no porphyry deposits were developed and metallogenesis was dominated by high and low sulphidation epithermal systems (Puig *et al.*, 1988; Fig. 5b). It is important to note that most of these deposits occur in association with volcanic centres and calderas (Puig *et al.*, 1988; Cornejo and Mpodozis, 1996). This period coincides with decreased convergence rates favouring extensional tectonics, and contrasts with the preceding compressional regime that resulted from decoupling between plates.

During the Paleocene, magmatism along the Chilean section of the belt is characterised by the presence of multiphase intrusions with compositions varying from gabbro, granodiorite, quartz diorite, quartz monzonite and diorite, with granodiorite being the predominant plutonic rock (Williams, 1992). These rocks are cal-alkaline, meta-aluminous, low in Fe and high K (Williams, 1992). REE patterns indicate low La/Yb ratios (3.2-7.5) and negative Eu anomalies, indicating a low pressure fractionating mineralogy dominated by plagioclase, olivine and pyroxene in a magma source equilibrated with a thinner crust (<40 km; Williams, 1992). An exception is the granodiorite porphyry associated with the Cerro Verde-Santa Rosa (Fig. 5b) deposit, where La/Yb ratios of 20-22 have been determined (Le Bel, 1995).

Late Eocene-Oligocene Belt (43-31 Ma)

The Late Eocene-Oligocene belt contains one of the largest concentrations of copper in the world. Thirty three porphyry copper-molybdenum and porphyry copper deposits and prospects have been identified to date, containing ~241 Mt of fine copper (Fig. 6). The largest deposits are Chuquicamata (66.4 Mt fine Cu) and La Escondida (32.5 Mt fine Cu; Table 1). As shown in Fig. 6, porphyry systems in this belt occur in clusters of more than two to four deposits which are associated with large multiphase plutonic complexes. The belt extends for more than 1400 km along the Cordillera Domeyko in northern Chile and can be traced from the border with Perú (18°S latitude) to 31°S (Fig. 6). Recently, it has been extended into southern Perú to approximately latitudes 13°30' S where significant skarn and porphyry copper systems have been recognised (Perelló *et al.*, 2003b).

The Domeyko Cordillera is the end product of contractional deformation processes that began in the Late Cretaceous (70 Ma) and continued for more than 40 Ma. In the Late Cretaceous the Nazca plate began to move towards the South American plate and a gradual increase in the rate of convergence resulted in slab flattening (Skewes and Stern, 1995; James and Sacks, 1999). According to Pardo-Casas and Molnar (1987) the most rapid convergence (>15 cm/year) occurred between 50 and 42 Ma (Incaic cycle) and since 26 Ma (Quechua cycle). In between these periods, average rates were 5-5.5 ±3 cm/year. These periods of rapid convergence coincide with the culmination and development of the Domeyko Fault Zone (DFZ), which hosts six giant porphyry copper deposits. The DFZ (Fig. 6) is a narrow (~50 km wide and 1000 km long) fold and fault belt consisting of a complex segmented systems of first, second and third order *en echelon* faults showing different origins and histories, that has affected volcanic, sedimentary and plutonic rocks. The age of these rocks range from Palaeozoic to Recent (Cornejo *et al.*, 1997; Mpodozis *et al.*, 1993; Mpodozis *et al.*, 1994; Cornejo and Mpodozis, 1996; Tomlinson and Blanco, 1997a, 1997b; Reutter *et al.*, 1996; Tomlinson *et al.*, 2001).

As a consequence of the tectonic inversion of the Tarapacá basin, and the DFZ development, uplift, shortening and crustal thickening occurred along most of the Cordillera Domeyko (Mpodozis and Ramos, 1990; Cornejo *et al.*, 1993; Kley and Monaldi, 1998). The structural and magmatic evolution and the development of the DFZ along the Cordillera de Domeyko belt were not simultaneous. Consequently, three main stages of porphyry emplacement can be recognised along this belt: a) early (43-41 Ma); b) intermediate (39-36 Ma); and c) late (34-31 Ma) (Figs. 3 and 6). As can be seen in Fig. 3, the copper content gradually increases towards the late stage. Gold, by contrast, shows the highest content in the intermediate stage. The porphyry-related intrusions were emplaced syn-tectonically, probably through the mechanism proposed by Skarmeta and Castelli (1997). The Cobre porphyry in Potrerillos (Figs. 1 and 6) is an excellent example of a mineralised syn-tectonic intrusion (Tomlinson, 1994).

Magmatism within the different porphyry stages consists of porphyritic and epizonal, relatively small felsic intrusive bodies that were emplaced between 1.5-2.5 km beneath the surface. They formed stocks and elongated tabular bodies controlled in morphology by the dominant structural patterns, and are part of major multiphase intrusive complexes that include pre, intra and post-mineral phases. The age difference between the pre and post mineral phases varies from 1 to 5 Ma. The largest known multiphase intrusive complex is the Los Picos-Fortuna Granodiorite, with ~200 km^2 of surface exposure and as much as five intrusive phases. Of these, the felsic phases are associated with four porphyry deposits (Toki, Opache, Quetena and Genoveva, Fig. 6). Petrographically these complexes have variable compositions between granodiorite, monzonite and quartz monzonite, and show clear fractionation trends, fr intermediate pre-mineral, to more felsic intra-mine phases higher in SiO_2 and K_2O, although reversals to m mafic magmatism have occurred locally (Cornejo et 1997).

Petrochemically these rocks are calc-alkaline, me aluminous, with high to moderate K, high Fe_2O_3/FeO rat indicating highly oxidised magmas, and they belong to "I" type, magnetite series. Their REE patterns show str fractionation with high La/Yb ratios (> 20-25). This d suggests the presence of high-pressure, hydrated magn with amphibole and/or garnet in the magma source an thicker continental crust (> 45 Km; Gustafson, 1979, Lop 1982, Ishihara *et al.*, 1984, Zentilli *et al.*, 1995, Corn *et al.*, 1997).

Early-Middle Miocene (Maricunga) Belt (23-12 Ma)

The Early-Middle Miocene Maricunga belt contains ri gold-rich porphyry systems (Vila and Sillitoe, 1991). To identified gold resources are ~1300 tonnes occurri essentially in four deposits (Marte, Lobo, Cerro Casale a Refugio; Fig 7).

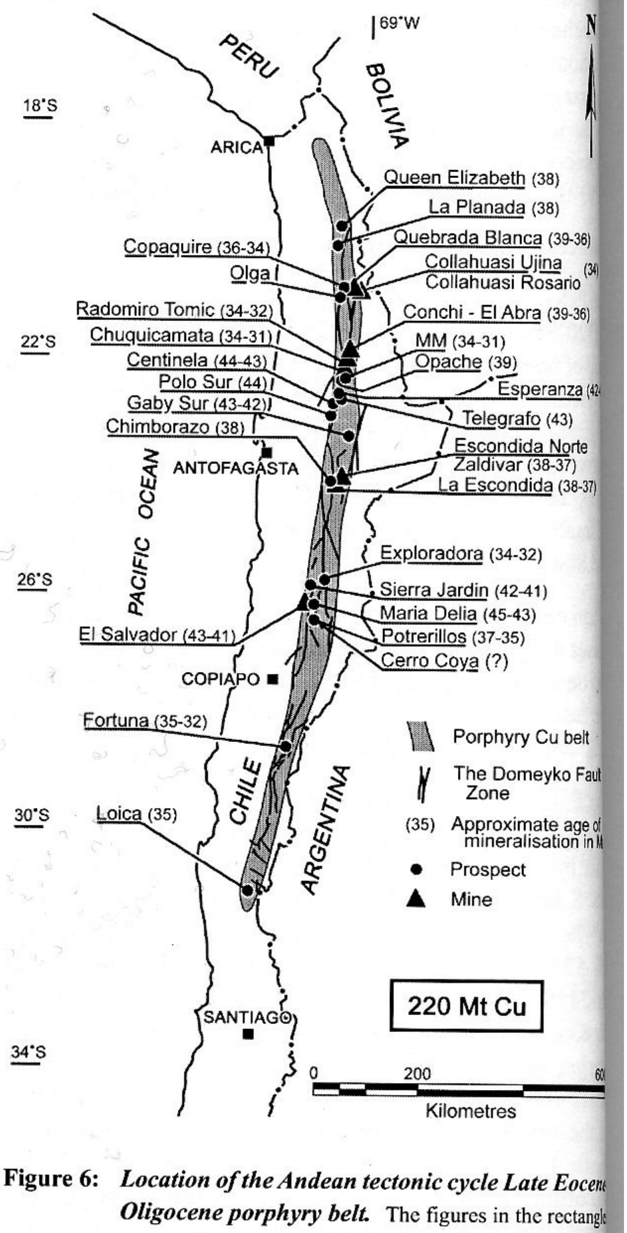

Figure 6: ***Location of the Andean tectonic cycle Late Eocene Oligocene porphyry belt.*** The figures in the rectangle are million tonnes of fine copper or tonnes of gold.

The belt extends north-south for ~200 km (26°-28°S) along the western boundary of the Puna plateau in the Atacama region of northern Chile (Figs. 1 and 7). It is dominated by the presence of a series of volcanic centres and internally drained saline basins.

From a tectonic point of view, the Maricunga belt formed after migration of the magmatic arc eastwards from the Late Eocene-Oligocene belt to its present position, in response to the Incaic and Quechua tectonic cycles. The Maricunga belt is now situated within the present-day active volcanic arc of the Central Andes, lying in the transition zone between the steep and shallow dipping segments of the Wadati-Benioff zone (Kay *et al.*, 1994; Mpodozis *et al.*, 1995).

The Maricunga belt is composed of series of stratovolcanos, dome fields and pyroclastic rocks, lava flows and ignimbrite sheets that overlie a continental basement. The basement is composed of Mesozoic sedimentary sequences, and Palaeozoic plutons and coeval volcanics. The Maricunga belt developed as a result of the contractional deformation regime initiated at about 26 Ma (Quechua cycle; Kay *et al.*, 1994; Mpodozis *et al.*, 1995). Porphyry gold mineralisation occurs in two sub-belts: western (25-20 Ma) and eastern (14-12.5 Ma) (Sillitoe *et al.*, 1991). The Refugio and Santa Cecilia porphyry gold systems occur within the western sub-belt, while the Marte, Lobo and Cerro Casale gold-rich porphyries were emplaced along the eastern sub-belt (Fig. 7). In addition to the gold-rich porphyries, several high sulphidation gold-silver epithermal systems also occur, such as La Coipa, Esperanza, and La Pepa (Fig. 7). Multiphase intrusive complexes associated with mineralisation comprise dark-coloured diorite that is predominantly porphyritic, together with microdiorite and

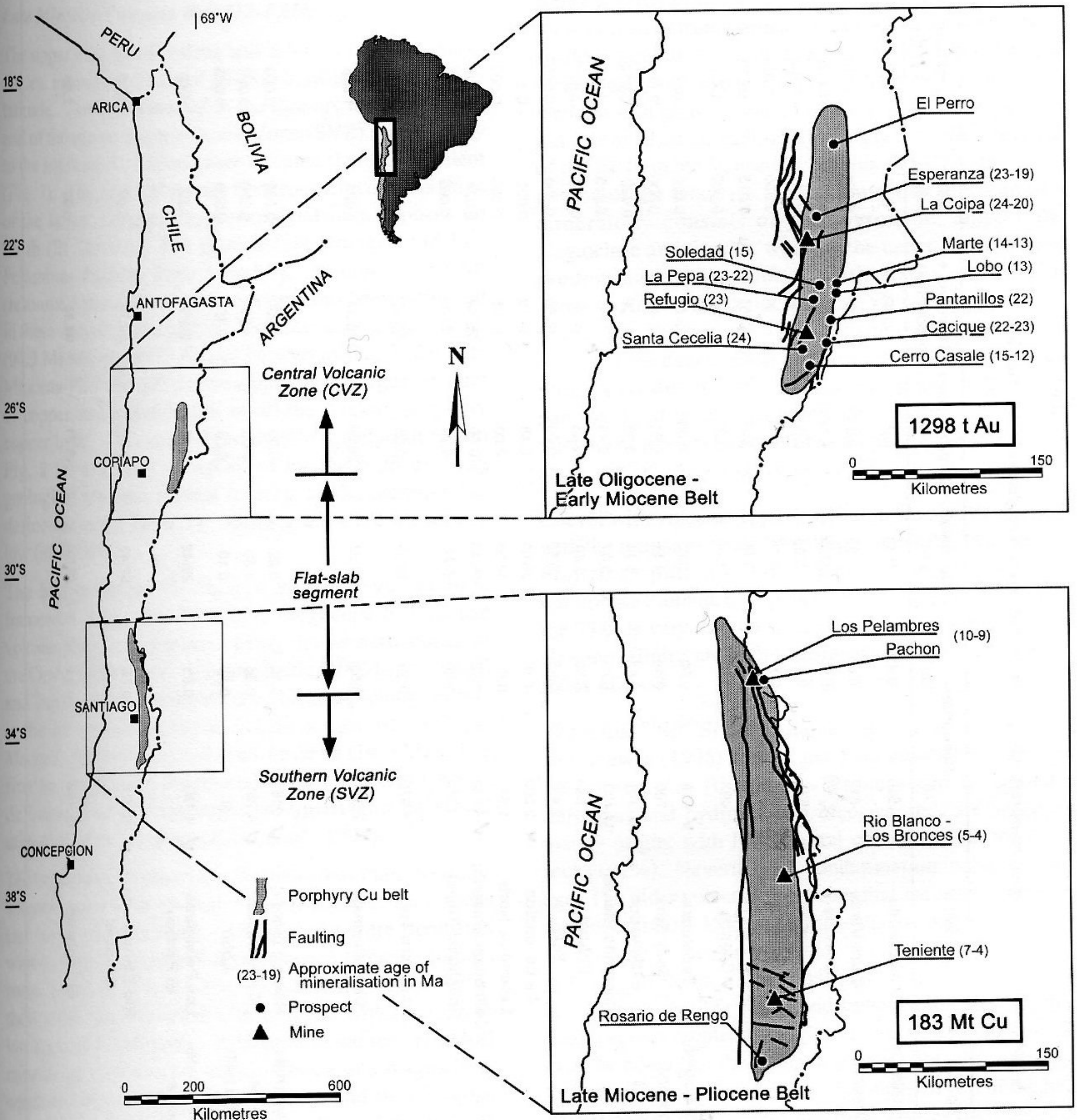

Figure 7: ***Location of the Andean tectonic cycle Late Oligocene to Late Pliocene porphyry belts.*** The figures in the rectangles are million tonnes of fine copper or tonnes of gold.

Table 1: ***Copper, molybdenum, gold resources, and production of selected Andean porphyry deposits***

Belt	Deposit	Resources Mt	Resources Cu, %	Cu metal Mt	Cu production Mt	Resouces + production	Mo %	Mo metal %	Au g/t	Contained Au tonnes	Selected references
(a) Cretaceous	Andacollo	540	0.45	2.43	0.00	2.43	0.01	0.05	0.25	135	Reyes, 1991
(b) Paleocene	Cerro Verde	810	0.66	5.35	0.61	5.96	0.021	0.170	0.000	0	Le Bel, 1995
	Cuajone	2,170	0.60	13.02	4.12	17.14	0.030	0.651	0.000	0	Concha y Valle, 1999
	Quellaveco	965	0.63	6.08	0.00	6.08	0.017	0.164	0.000	0	Candiotti de los Ríos, 1995
	Toquepala	691	0.74	5.11	4.80	9.91	0.030	0.207	0.000	0	Zweng y Clark, 1995
	Cerro Colorado	194	1.00	1.94	0.57	2.51	0.015	0.029	0.000	0	Unpublished data
	Spence	497	0.92	4.57	0.00	4.57	0.000	0.000	0.180	89	Unpublished data
(c) Late Eocene-Oligocene	Esperanza	514	0.60	3.08	0.00	3.08	0.000	0.000	0.260	134	Perelló et al., 2003a
	Gaby Sur	700	0.49	3.43	0.00	3.43	0.000	0.000	0.000	0	Aguilar et al., 2003
	El Salvador	974	0.63	6.14	5.15	11.29	0.022	0.214	0.100	97	Gustafson and Hunt, 1975
	Quebrada Blanca	400	0.83	3.32	0.48	3.80	0.015	0.060	0.100	40	Hunt and Bratt, 1983
	El Abra	1,544	0.55	8.49	0.85	9.34	0.005	0.077	0.000	0	Ambrus, 1977; Gerwe et al., 2003
	Toki	2,411	0.45	10.85	0.00	10.85	0.000	0.000	0.000	0	Rivera and Pardo, 2003
	La Escondida	2,262	1.15	26.01	6.48	32.49	0.021	0.475	0.100	226	Ojeda, 1990; Padilla et al., 2001
	Escondida Norte	1,615	0.87	14.05	0.00	14.05	0.000	0.000	0.000	0	Williams, 2003
	Collahuasi (Rosario)	3,108	0.82	25.49	0.00	25.49	0.024	0.746	0.010	31	Munchmeyer, 1984;
	Collahuasi (Ujina)	636	1.06	6.74	0.94	7.68	0.000	0.000	0.000	0	Dick et al., 1994; Lee, 1994 Bisso et al., 1998
	Radomiro Tomic	4,970	0.39	19.38	0.55	19.93	0.015	0.746	0.000	0	Cuadra and Rojas, 2001; Lorca et al., 2003
	Chuquicamata	7,521	0.55	41.37	25.00	66.37	0.024	1.805	0.040	301	Ambrus, 1979; Soto, 1979; Zentilli et al., 1995; Ossandón et al., 2001
(d) Early-middle Miocene (Maricunga belt)	Refugio (Verde)	216	0.10	0.22	0.00	0.22	0.000	0.000	0.88	190	Muntean and Einaudi, 2001
	Cerro Casale	1,285	0.35	4.50	0.00	4.50	0.000	0.000	0.70	900	Vila and Sillitoe, 1991
	Lobo	80	0.12	0.10	0.00	0.10	0.000	0.000	1.60	128	Vila and Sillitoe, 1991
(e) Late Miocene-Pliocene	Los Pelambres-El Pachón	4,193	0.63	26.42	0.46	26.88	0.02	0.67	0.02	84	Sillitoe, 1973; Skewes and Atkinson, 1985 Atkinson et al., 1996
	Río Blanco/ Los Bronces	6,991	0.75	52.43	4.30	56.73	0.02	1.26	0.04	245	Warnaars et al., 1984 Serrano et al., 1996 Vargas et al., 1999
	El Teniente	12,482	0.63	78.64	15.71	94.35	0.02	2.50	0.04	437	Howell and Molloy, 1960; Camus, 1975; Skewes et al., 2002

quartz diorite. A typical feature of these intrusive complexes is the presence of post-mineral dacite porphyry plugs (Vila and Sillitoe, 1991).

REE patterns versus age, reported by Mpodozis *et al.*, (1995), indicate increasing La/Yb ratios with decreasing age of volcano-plutonic products. La/Yb ratios of <20 occur in igneous rocks of 26-21 Ma, increasing to 60-80 in rocks of the youngest volcanic event (6-5 Ma). According to Mpodozis *et al.*, (1995) this trend indicates a gradual increase in crustal thickness from 45 km at 26 Ma to >45 km at 5 Ma, with the highest La/Yb ratios reflecting a residual mineralogy dominated by garnet, typical of high pressure environments (Kay *et al.*, 1991). During the two-mineralisation periods of 26-21 Ma and 14-12 Ma, La/Yb ratios are very similar (22-15), consistent with magmas dominated by intermediate pressure conditions and with hydrated amphibole as the residual mineralogical phase.

Late Miocene-Pliocene Belt (12-4 Ma)

The upper Miocene-Pliocene belt is located in the Central Andes, extending for about 400 km between 32°S to 35°S latitude. The belt is located in the fore-arc of the northern end of the active South Volcanic Zone (SVZ) immediately to the south of the Chilean non-volcanic flat-slab segment (Fig. 7). The upper Miocene-Pliocene belt contains three of the largest porphyry copper-molybdenum deposits on Earth (El Teniente, Río Blanco-Los Bronces and Los Pelambres-Pachón, Figs. 1 and 7). A total of 183 Mt (resource + production) of fine copper has been estimated in these deposits, of which El Teniente is the largest of all (94.3 Mt fine copper). As can be seen in Fig. 2, the Late Miocene-Pliocene belt contains the second largest amount of copper and molybdenum of all the Andean porphyry copper belts. The relatively high gold tonnage shown in Fig. 2 for this belt is explained by the high existing geological resource present in each of the deposits that define the belt (Table 1). Gold grades are uniformly low (<0.04 g/t).

The belt is currently situated within a geotectonic framework dominated by a Late Oligocene to Pliocene volcano-plutonic arc located along the western slopes of the Cordillera Principal. Kay and Kurtz (1995) and Castelli and Iriarte (1998) subdivide the volcano-plutonic events in the arc into three stages. These stages are a) Coya-Machalí, b) Farellones and c) El Teniente (10-3 Ma). The first two stages are dominated by strong contractional deformational events, regional uplift and eastward migration of the arc front (Kurtz *et al.*, 1997).

The Coya-Machalí stage (a) is dominated by mafic to silicic volcanic flows with intercalations of volcaniclastic rocks and lacustrine sediments. These rocks were deposited within an approximately N-S extensional volcano-plutonic basin, bound by N-S trending normal faults. Chemically, these rocks are associated with magmas with medium to low K_2O and 47-67% SiO_2. REE patterns indicate a residual mineralogy with olivine, orthopyroxene and plagioclase, which suggests low-pressure conditions and an anhydrous environment (Kay and Kurtz, 1995). Crustal thickness is estimated by these workers to have been 30 to 35 km, with subduction angles of >25°.

In the El Teniente and Río Blanco-Los Bronces regions, from 20-16 Ma, the volcanic and volcaniclastic units in the El Teniente and Río Blanco-Los Bronces regions were subject to a gradual process of contractional deformation which resulted in inversion of extensional faults, folding, uplift and crustal thickening. Erosion rates are inferred to have been relatively low, of the order of 550 m/Ma (Kurtz *et al.*, 1997). Towards the end of the deformation event, plutonism was initiated with the intrusion of the La Obra pluton (19.6 Ma, Kay and Kurtz, 1995) and the initial phases of the Río Blanco-San Francisco plutonic complex (20-13 Ma, Rivera and Navarro, 1996).

After the Middle Miocene deformation event, volcanism was renewed with the deposition of the Farellones stage. This resulted in the deposition of more than 2000 m of andesitic to rhyodacitic lavas and pyroclastic rocks from a series of stratovolcanos and calderas located along the active arc (Rivano *et al.*, 1990). In the El Teniente region, a transitional volcanic series was deposited that varies from an older tholeiitic (bottom) to a younger calc-alkaline (top) series (Kay and Kurtz, 1995). Chemically, they have medium to high K_2O and 50 to 75% SiO_2. REE patterns indicate residual mineralogical changes from the lower part of the El Teniente Volcanic Complex (TVC) to the upper portion of the sequence. In the lower part, the dominant mineralogy consists of clinopyroxene, amphibole, plagioclase and titanite, whereas the upper portions have predominantly amphibole, with lesser amounts of clinopyroxene and plagioclase. La/Yb ratios vary from 4 in the lower sections to 13.2 in the upper sections of the TVC. These data suggest changes from medium to high-pressure conditions under a hydrated regime. In the lower part, oxidised conditions dominate. The inferred crustal thickness varies between 35 to 40 km and the subduction angle is >25° (Kay and Kurtz, 1995).

Coeval with volcanic episodes, plutonism also developed, with the intrusion of the late phases of the Río Blanco-San Francisco pluton (13-7.4 Ma) and the El Teniente multiphase Plutonic Complex (TPC; 12-7 Ma). Chemically the TPC is very similar to the TVC. Rocks are of calc-alkaline affinity, are high K, have 59-70% SiO_2 and La/Yb ratios of 8-22.

The initial $^{87}Sr/^{86}Sr$ ratios and initial ε_{Nd} reported by Stern and Skewes (1995) for the magmas associated with Los Pelambres, Río Blanco-Los Bronces and El Teniente intrusions and hydrothermal breccias, indicate an upper mantle origin, with little crustal contamination for these rocks (<2%). Nevertheless, contamination increases with age. The older volcanic sequences that are associated with thinner crust (30-35 km), i.e. those that belong to the Coya-Machalí stage, have lower initial $^{87}Sr/^{86}Sr$ ratios and higher initial ε_{Nd}. In contrast, the Farellones stage shows relatively high initial $^{87}Sr/^{86}Sr$ ratios and lower initial ε_{Nd}. In this case magmas erupted through a thicker crust (~40 km). It must be noted that these increases were not uniform along the belt. They occurred first in the northern part of the belt (Río Blanco-Los Bronces), and then continued to the south (Stern and Skewes, 1995). Stage (c) began as a consequence of a substantial increase in convergence rate between the

Nazca and South American plates, together with a flattening of the angle of subduction (Kay *et al.,* 1991). As a result, an important increase in the active contractional stress regime produces a new structural tectonic inversion with the reactivation of the old extensional faults. The basin morphology was also inverted and the rates of erosion increased substantially to figures in the order of ~3 km/Ma (Kurtz *et al.,* 1997). Faults such as El Fierro and Pocuro represent the eastern and western limits respectively of the uplifted blocks (Castelli and Iriarte, 1998). Due to this dramatic uplift, crust was gradually thickened to ~50 km (Stern and Skewes, 1995).

The final phase of magmatic activity was the Teniente stage (Stage 3). Concurrent with contractional deformation, multiphase syntectonic magmatism and porphyry copper-molybdenum emplacement occurred, controlled by NE and NNE to NNW structural systems. The intrusions associated with copper mineralisation vary in composition from quartz diorite to dacite porphyry. These rocks have high SiO_2 (>65%) and very high La/Yb ratios (20-60; Kay and Kurtz, 1995, Stern and Skewes, 1995, Skewes, 1998). REE patterns with high La/Yb ratios are consistent with a residual mineralogy rich in garnet, which represents a high-pressure hydrous mineralogy.

Based on their petrochemical and petrologic data, Kay and Kurtz (1995) showed how the evolution of the volcanic and plutonic rocks of the El Teniente region related to the evolution of the prevailing tectonic environment. Volcano-magmatic evolution follows a progression from low K, tholeiitic sequences during the Coya-Machalí stage to high K, calc-alkaline trends during the Farellones and Teniente stages. Together with this evolution of volcanic rock compositions, there has been a shift from a residual mineralogy dominated by pyroxene to one dominated by amphibole. This trend has been documented by the REE patterns, especially the La/Yb ratios. The older andesitic lavas (Coya-Machalí stage) have low La/Yb ratios (2-6), whereas the younger lavas (Farellones stage) tend to have higher values (4-22). Finally, the intrusive episodes are characterised by very large La/Yb ratios (20-62). This is interpreted to indicate low pressure, anhydrous mineralogical assemblages in the older volcanic sequences, and medium pressure, hydrous and oxidising to drier, higher pressure mineral assemblages in the younger sequences (Kay and Kurtz, 1995).

Alteration and Mineralisation Styles

Porphyry copper mineralisation and alteration are related to the most felsic phases within multiphase intrusive complexes. This is a common theme repeated throughout the Andean porphyry copper belts. Each of these felsic phases may be related to an individual porphyry copper deposit, resulting in the clustering of deposits that characterises parts of the Andean copper belt. The alteration and mineralisation processes that occurred in the individual porphyry systems evolved from early stages dominated by high-temperature, late magmatic oxidised fluids to late stages dominated by low or moderate-temperature more reduced hydrothermal fluids with magmatic and meteoric components.

Formation of each deposit and their associated metallog belts were controlled by the Andean cordill tectonomagmatic evolution. However, distinctions o between belts in terms of alteration and mineralis features, particularly when comparing the copp molybdenum and copper-gold systems. In the porph copper-molybdenum and copper deposits, the follow alteration stages are present: late magmatic (potassic propylitic), transitional, main hydrothermal phyllic and hydrothermal advanced argillic. An intermediate arg stage is also recognised locally. In the porphyry g deposits, the dominant stages are late magmatic (potas chloritic), intermediate argillic, advanced argillic and minor proportions, phyllic.

All the alteration-mineralisation stages display g vertical zonation from deep potassic alteration thro phyllic of varied morphology to superimposed advan argillic lithocaps. The overall resultant architectur dependent on the structural setting of the system as wel the amount of telescoping that occurred.

These different alteration-mineralisation stages are pres from the Cretaceous to the Late Miocene-Pliocene be The best deposits preserved are those systems that bel to the Late Miocene-Pliocene belt which are the least ero of all, whereas the Cretaceous belt, due to extensive eros show basically only the potassic stage and the roots phyllic alteration. Even within a belt, the systems sh different levels of erosion, and consequently differ alteration-mineralisation exposures in response to development of different structural blocks along the that have been affected by different degrees of uplift a erosion.

Porphyry Copper-Molybdenum Systems

Almost all of the copper and molybdenum in these depos was introduced during the earliest stages of magmat hydrothermal activity, at low-sulphidation states (hi Cu/S ratios) in association with K silicate alteration. T alteration assemblage consists of K feldspar, biotite a anhydrite, which have replaced plagioclase and maf minerals. Additionally, these minerals are present in qua veins of "A" and "EB" types (Gustafson and Quiroga, 19 Gustafson and Hunt, 1975). Rutile and magnetite occ locally in minor proportions. In the deeper parts of so of these deposits, secondary albite, actinolite and magneti have been recognised (Gustafson and Quiroga, 1995).

About 70-80% of the copper mineralisation occurs bornite and chalcopyrite. These two sulphides coexist wi quartz in "A" veins, structures which are typicall discontinuous, "wispy" and wormy with no alteration halo Other veins are "EB" veins, which contain biotite wi variable proportions of albite, K feldspar, chlori actinolite, anhydrite and green sericite. They locally hav albite alteration halos.

The potassic alteration assemblage grades outwards fro the core of the deposits to a peripheral propylitic alterati zone. This lower temperature alteration zone consists chlorite, epidote, calcite and pyrite. It is essentially barre although chalcopyrite is present in minor quantities immediately adjacent to the potassic zone.

A second major phase of magmatic-hydrothermal activity (the transitional stage) occurs after the porphyry intrusions have crystallised and temperature and pressure conditions have decreased. This stage marks the transition from early, high-temperature magmatic-hydrothermal activity, which is dominated by magmatic fluids, and the late hydrothermal stage, which is associated with low to moderate-temperature fluids that have magmatic and meteoric fluid components.

"B" type planar, continuous quartz veins with narrow sericite halos and central sutures are typical of the transitional stage. The presence of sericite halos is interpreted to be an indication of retrograde effects produced by the incorporation of meteoric fluids into the system (Gustafson and Hunt, 1975; Skewes and Atkinson, 1985). The transitional stage produces the bulk of the molybdenum resource, together with some copper within the "B" veins. The transitional stage generally occurs in the upper parts of the intrusions and tends to be focussed on the central portion of the systems, forming a core within the orebodies. In some porphyry copper-molybdenum deposits, the transitional stage is represented by chlorite-bearing intermediate argillic alteration. Examples where intermediate argillic alteration is associated with molybdenite and a second phase of chalcopyrite deposition include La Escondida (Padilla *et al.*, 2001), La Fortuna (Perelló *et al.*, 1996) and Escondida Norte (Williams, 2003).

The main hydrothermal stage, also known as the phyllic or quartz-sericite alteration stage, is developed under conditions of high sulphur fugacity, relatively low oxygen fugacity and low K^+/H^+ ratios (i.e. acidic conditions). This stage is characterised by quartz, sericite and pyrite, with minor amounts of chalcopyrite, bornite, enargite, sphalerite and galena. Quartz occurs with pyrite as "D" type veins (terminology from Gustafson and Hunt, 1975), with 1-2 cm wide halos of sericite and rare chlorite. Locally "D" veins can contain anhydrite, tourmaline and minor carbonates. If the process of hydrothermal alteration is sufficiently pervasive, the rock can be transformed almost completely into quartz and sericite (e.g., Chuquicamata; Ossandón *et al.*, 2001).

One the most important characteristics of the phyllic alteration zone at many Andean porphyry deposits is that it is telescoped downwards into the potassic-altered core as a result of structural controls. As a consequence, the early K silicate alteration can be strongly overprinted by the phyllic phase, producing a typical telescoping effect due to the breaking of the brittle transition (Fournier, 1999). Chuquicamata, La Escondida and Rosario are examples where this has occurred (Ojeda, 1990; Lindsay *et al.*, 1995; Masterman *et al.*, 2004).

The Andean porphyries include numerous deposits where hydrothermal breccias are associated with phyllic alteration (e.g., Rio Blanco-Los Bronces, El Teniente). This is another example of the interaction of magmatic fluids, exsolved from intrusions, with deeply circulating meteoric waters during the main stage of hydrothermal alteration (Sillitoe, 1985).

During the main hydrothermal stage, some copper mineralisation has been added to at least a few of the deposits (e.g., El Teniente, Chuquicamata) but generally at relatively low levels compared with the earlier stages. Part of this may be copper remobilised from earlier-formed veins.

The last stage of hydrothermal activity is represented by low-temperature advanced argillic alteration assemblages with low- sulphidation states (high Cu/S ratios). These zones are located in the upper parts of the porphyry systems, forming what is known as the lithocap of the deposit (Sillitoe, 1995), and are only preserved in some systems.

The lithocaps consist of quartz, alunite, kaolinite, dickite, sericite, pyrophyllite and diaspore. Other minerals present are zunyite, dumortierite and topaz. Sulphide minerals are typically pyrite and marcasite and sulphosalts include enargite, luzonite and tennantite-tetrahedrite. There are also minor amounts of covellite, bornite and hypogene chalcocite. All of these minerals occur as massive sulphide veins and they can enhance significantly the overall copper grades of the deposits. These assemblages can also be telescoped into the potassic core of the porphyry deposits by structural activity (eg., Chuquicamata, Mansa Mina, Rosario).

Porphyry Gold-(Copper) Systems

The early stages of alteration in the gold-rich porphyry systems are similar in many ways to the copper-molybdenum porphyries. One significant difference is the high iron oxide content in porphyry gold systems (locally >10-vol%), suggestive of high fO_2/fS_2 conditions (Sillitoe and Gappe, 1984; Perelló and Cabello, 1989; Vila and Sillitoe, 1991). Generally the early stage alteration assemblages in the gold-(copper) systems are composed of magnetite, K feldspar and oligoclase. In some cases the assemblage is chlorite, magnetite and albite. "A" type quartz veins occur, but not with the abundance seen in the copper-molybdenum porphyries.

The transitional alteration stage, as described for the porphyry copper-molybdenum systems, is not recognised in the Andean porphyry gold systems. However, a hydrothermal stage known as intermediate argillic alteration (or sericite-clay-chlorite: SCC, by the terminology of Sillitoe and Gappe, 1984), is recognised. This alteration assemblage consists mainly of chlorite, sericite, illite, smectite and minor calcite. Magnetite, pyrite, specularite and minor chalcopyrite are also present (Sillitoe, 1993; Vila and Sillitoe, 1991). Intermediate argillic stage alteration locally obliterates earlier K silicate alteration assemblages, and is in turn overprinted by the advanced argillic lithocap (Muntean & Einaudi, 2001), which is of similar extent in the upper part of these system as in the porphyry copper-molybdenum deposits. Phyllic alteration is also present, but it is not widely developed.

Breccias and Related Phenomena

Together with the alteration and mineralisation processes, brecciation phenomena are distinct in many Andean porphyry deposits, especially in those that belong to the

Paleocene, Upper Eocene-Oligocene, and most notably the Pliocene belt.

Magmatic-hydrothermal breccias are closely related to porphyry emplacement at El Abra, Quebrada Blanca, El Salvador, Gaby Sur, Los Pelambres, El Teniente and Rio Blanco-Los Bronces. They typically formed due to multiple brecciation events, which occurred from the late magmatic stage to the hydrothermal stages. At Los Pelambres (Atkinson *et al.,* 1996), El Teniente (Skewes *et al.,* 2002), and specially Río Blanco-Los Bronces (Vargas *et al.,* 1999), the late magmatic alteration-mineralisation, transitional and main hydrothermal stages are represented by the magmatic and hydrothermal breccias that accumulate between 2% and 50% of the copper and molybdenum mineralisation.

At Río Blanco-Los Bronces the magmatic-hydrothermal breccias have been cemented at depth by biotite, anhydrite and K feldspar followed by tourmaline, magnetite, and specularite toward the surface. Mineralisation shows a zonation with chalcopyrite-bornite and molybdenite at depth, diminishing gradually toward the surface (Vargas, *et al.,* 1999). The main hydrothermal stage represented by sericite dominates the upper portions of the breccia bodies. Similar situations are observed at El Teniente and Los Pelambres (Skewes *et al.,* 2002; Atkinson *et al.,* 1996).

Phreatomagmatic breccias, generally barren, are present in the Pliocene porphyry belt at Rio Blanco-Los Bronces and El Teniente. These latter breccias are very large in terms of dimensions and structural expression when compared with the magmatic-hydrothermal breccias. At El Teniente, the Braden Breccia is a well-defined funnel-shaped breccia pipe (Howell and Molloy, 1960; Camus, 1975). Its surface diameter is 1300 m (at 3000 m a.s.l.), which decreases to 650 m at 2000 m a.s.l.. Overall, the Braden Breccia has a vertical extent of about 1800 m. The origin of the Pliocene phreatomagmatic breccias has been linked to the very high rate of uplift and exhumation of the central Chile porphyry province (Skewes and Stern, 1995).

Supergene Modification

Very important supergene modifications such as oxidation, copper leaching and secondary copper enrichment affected the Andean porphyry deposits. These processes, among others, explain why many of the orebodies are so rich and economically viable. The supergene processes have occurred in response to global climatic changes, beginning in the Oligocene with desertification of the Atacama region and a drop in the regional ground water table. The coupling of these globally driven climate changes with tectonic uplift, synorogenic erosion, exhumation and subsequent geomorphological landscape evolution has produced the ideal environment for development of supergene copper oxide and sulphide deposits (Alpers and Brimhall, 1988; Cuadra and Rojas, 2001). Supergene enrichment processes occurred in northern Chile from about 34 Ma to about 14 Ma (Sillitoe and McKee, 1996). In central Chile, these processes started around 3 Ma and are still developing today. Consequently, the Pliocene porphyry belt only contains incipient supergene enrichment, in stark contrast to the Eocene-Oligocene belt.

Secondary leaching and oxidation result in downward percolation of copper enriched solutions during ore deposit weathering. Cycles of leaching and redeposition of copper result in the cumulative development of chalcocite enrichment blankets. Lateral migration of these copper bearing solutions, controlled by local hydraulic gradients result in the generation of major exotic copper deposits like Sagasca, Huinquintipa, Mina Sur, El Tesoro and Damiana (Sillitoe and McKee, 1996; Munchmeyer, 1996

Synthesis

The tectonomagmatic evolution discussed in this paper and the characteristics of the alteration and mineralisation of the different porphyry systems allows us to identify a series of common geological events that are typical of the porphyry belts developed during the Gondwana and Andean cycles. These events occurred in all belts and a description of them follows.

Porphyry systems in the Andes were developed within a contractional tectonic regime. This tectonism caused inversion of the Upper Triassic to Early Cretaceous extensional back-arc basins that had developed along the western margin of Gondwana. The basins were deformed and uplifted by reactivation of basin-bounding normal extensional faults.

The porphyry belts are the expression of a tectonomagmatic evolution marked by the eastern migration of volcanism and plutonism. This migration correlates with the shift from high angle "Mariana" type subduction that lasted from the Jurassic to Lower Cretaceous, to a compressional gently dipping "Chilean" type subduction system that predominated thereafter. During the latter interval, there have been discrete and transient periods of increased convergence velocity and convergence angle. These periods coincide with the strongest deformation events which in turn can be correlated with the temporal development of each magmatic belt, particularly those associated with the giant porphyry systems. These periods do not appear to have been uniform throughout the belts.

The end result of the deformation events is a series of *en echelon* north-trending thrust, reverse and minor strike slip fault systems, and north-trending folds. One of the most important fault trends recognised along the porphyry belt is the Domeyko Fault System that extends for more than 1000 km along the Domeyko cordillera in northern Chile (Fig. 6). This system has been active since the Late Eocene and coincides closely with the Eocene-Oligocene belt of porphyry systems.

Regional uplift, shortening and crustal thickening occurred as a consequence of tectonic shortening along most of the cordillera in northern and central Chile. The very significant uplift resulted in syn-orogenic erosion that can be observed along the western slopes and plains of the Andean range that now lies at over 3000 to 4000 m elevation. The erosion rate diminished with time as the climate changed, beginning in the Oligocene, to produce, by middle Miocene, the hyper-arid conditions of the modern Atacama desert. In central Chile, the processes of uplift and exhumation are still occurring.

Multiphase intrusions and associated porphyries, appear to be emplaced syn-tectonically along faults. No volcanism has been identified that is contemporaneous with mineralised porphyry intrusions. The existing volcanic centres and calderas are pre or post tectonic events, even though some were the controlling loci for the emplacement of particular porphyry systems.

Petrographically, the granitoid and porphyry complexes, where exposed, have variable compositions that range from granodiorite to tonalite, monzonite and quartz monzonite. In almost all cases, these rocks show clear fractionation trends from intermediate composition pre-mineral phases to more felsic intra-mineral phases higher in SiO_2 and K_2O contents. Petrochemically, these rocks are calc-alkaline, metaluminous, have high to moderate K, high Fe_2O_3/FeO ratios (indicating highly oxidised magmas) and all belong to the I-type, magnetite series. Their REE patterns show strong fractionation with high La/Yb ratios (>20-25), which is suggestive of the presence of high pressure, hydrated magmas with amphibole and/or garnet at the magma source, typical of contractional tectonic regimes and thick continental crust (>45 km). These trends are consistent with contractional deformation and progressive trapping of the magmas at greater depth due to uplift, shortening and crustal thickening.

References

Aguilar, A., Gomez, M. and Pérez, P., 2003 – Discovery and geology of the undeveloped Codelco's Gaby copper deposit. (Abs.) *Congreso Geológico Chileno, 10th*, Concepción, 2003, CD-ROM, 1p.

Alpers, C. N. and Brimhall, G.H., 1988 - Middle Miocene climatic change in the Atacama desert, northern Chile: evidence from supergene mineralization at La Escondida. *Geological Society of America Bulletin,* v. 100, pp. 1640-1656.

Ambrus, J., 1977 - Geology of El Abra porphyry copper deposit, Chile. *Economic Geology*, v. 72, pp. 1062-1085.

Ambrus, J., 1979 - Emplazamiento y mineralización de los pórfidos cupríferos de Chile Ph.D. thesis, *Universidad de Salamanca*, 308p.

Atkinson, W.W., Souviron, A., Vehrs, T.I. and Faunes, A., 1996 - Geology and mineral zoning of the Los Pelambres porphyry copper deposit, Chile; *in* Camus, F., Sillitoe, R.H. and Petersen, R., (Eds.), Andean copper deposits: new discoveries, mineralization, styles and metallogeny, *Society of Economic Geologists,* Special Publication 5, pp. 131-156.

Bahlburg, H. and Hervé, F., 1997 - Geodynamic evolution and tectonostratigraphic terranes of northwestern Argentina and northern Chile. *Geological Society of America Bulletin*, v. 109, (7), pp. 869-884.

Benavides-Cáceres, V., 1999 - Orogenic evolution of the Peruvian Andes: the Andean cycle; *in* Skinner, B.J., (ed.), Geology and ore deposits of the Central Andes, *Society of Economic Geologists* Special Publication 7, pp. 61-107.

Bisso, C., Durán, M. and Gonzáles, A., 1998 - Geology of the Ujina and Rosario copper porphyry deposits, Collahuasi district, Chile; *in* Porter T.M., (ed.), Porphyry and hydrothermal copper & gold deposits: a global perspective, *PGC Publishing,* Adelaide, pp. 133-148.

Brown, M., Diaz, F. and Grocott, J., 1993 - Displacement history of the Atacama fault system 25°00'S-27°00'S, northern Chile. *Geological Society of America Bulletin*, v. 105, pp. 1165-1174.

Camus, F., 1975 - Geology of the El Teniente orebody with emphasis on wall-rock alteration. *Economic Geology*, v. 70, pp. 1341-1372.

Camus, F., 2003 - Geología de los sistemas porfíricos en los Andes de Chile. *Servicio Nacional de Geología y Minería,* Santiago, 267p.

Camus, F., Sillitoe, R.H. and Petersen, R., (Eds.), 1996 - Andean Copper Deposits: new discoveries, mineralization, styles and metallogeny. *Society of Economic Geologists,* Special Publication 5, 198p.

Candiotti de los Ríos, H., 1995 – geología y análisis de datos cuantitativos del yacimiento de pórfido de cobre Quellaveco. *Sociedad Geológica del Perú, Volumen Jubilar Alberto Benavides*, pp. 33-46.

Castelli, J. C. and Iriarte, S., 1998 - Exploración básica generativa entre los ríos Maipo y El Yeso. *Gerencia de Exploraciones, Codelco-Chile*, Unpublished report, 40p.

Concha, O., y Valle, J., 1999 - Prospección, exploración y desarrollo del yacimiento de Cuajote. *in ProExplo'99, Congreso Internacional de Prospectores y Exploradores, 1st,* Lima, pp. 117-143.

Cornejo, P., Mpodozis, C., Ramírez, C.F. and Tomlinson A.J., 1993 - Estudio geológico de la región de Potrerillos y El Salvador (26° - 27° Lat.S). *Servicio Nacional de Geología y Minería-Codelco-Chile*, Unpublished report, 258p.

Cornejo, P. and Mpodozis, C., 1996 - Geología de la región de Sierra Exploradora (25°-26° S). *Servicio Nacional de Geología y Minería, Codelco-Chile*, Unpublished report, 330p.

Cornejo, P., Tosdal, R. M., Mpodozis, C., Tomlinson, A.J., Rivera, O. and Fanning, C.M., 1997 - El Salvador, Chile porphyry copper deposit revisited: geologic and geochronologic framework. *International Geology Review*, v. 39, pp. 22-54.

Cuadra, P. and Rojas, G., 2001 - Oxide mineralization at the Radomiro Tomic porphyry copper deposit, northern Chile. *Economic Geology*, v. 96, pp. 387-400.

Dick, L.A., Chávez Jr., W.X., Gonzáles, A. and Bisso, C., 1994 - Geologic setting and mineralogy of the Cu-Ag-(As) Rosario vein system, Collahuasi district, Chile. *Society of Economic Geologists Newsletter*, v. 19, (1), pp. 6-11.

Fournier, R.O., 1999 - Hydrothermal processes related to movement of fluid from plastic into brittle rock in the magmatic-epithermal environment.

Economic Geology, v. 94, pp. 1193-1211.

Gerwe, J., Latorre, J.J. and Barrett, L., 2003 – El Abra porphyry copper deposit, northern Chile – update. (abs.) *Congreso Geológico Chileno, 10th*, Concepción, 2003, CD-ROM, 1p.

Gustafson, L.B., 1979 - Porphyry copper deposits and calc-alkaline volcanism. *in* McElhinny, M.W., (ed.), The Earth: Its origin, structure and evolution, *Academic Press* London, pp. 427-468.

Gustafson, L.B. and Hunt, J.P., 1975 - The porphyry copper deposit at El Salvador, Chile. *Economic Geology*, v. 70, pp. 857-912.

Gustafson, L.B. and Quiroga, J., 1995 - Patterns of mineralization and alteration below the porphyry copper orebody at El Salvador, Chile. *Economic Geology*, v. 90, pp. 2-16.

Horton, D.J., 1978 - Porphyry-type copper-molybdenum mineralization belts in eastern Queensland, Australia. *Economic Geology*, v. 73, pp. 904-921.

Howell, F.H. and Molloy, J.S., 1960 - Geology of the Braden orebody, Chile, South America. *Economic Geology*, v. 55, pp. 863-905.

Hunt, J.P. and Bratt, J.A., 1983 - Quebrada Blanca, Chile, an enriched porphyry copper deposit. *Mining Engineering*, v. 35, pp. 636-644.

Ishihara, S., Ulriksen, C., Sato, K., Terashima, S., Sato, T. and Endo, Y., 1984 - Plutonic rocks of north-central Chile. *Bulletin of the Geological Survey of Japan*, v. 35, (11), pp. 503-536.

James, D.E. and Sacks, I.S., 1999 – Cenozoic formation of the central Andes: A geophysical perspective. *in* Skinner, B.J., (ed.), Geology and ore deposits of the Central Andes. *Society of Economic Geologists*, Special Publication No 7, pp. 1-25.

Kay, S.M., Mpodozis, C., Ramos, V. and Munizaga, F., 1991 - Magma source variations for mid-Tertiary magmatic rocks associated with a shallowing subduction zone and a thickening crust in the Central Andes (28°-33°S). *in* Hamon, R.S., and Rapela, C.W., (eds.), Andean Magmatism and its tectonic setting. *Geological Society of America, Special Paper*, v. 265, pp. 113-137.

Kay, S.M., Mpodozis, C., Tittler, A. and Cornejo, P., 1994 - Tertiary magmatic evolution of the Maricunga mineral belt in Chile. *International Geology Review*, v. 36, pp. 1079-1112.

Kay, S.M. and Kurtz, A.C., 1995 - Magmatic and tectonic characterization of the El Teniente region. *Codelco-Chile, División El Teniente*, Unpublished report, 180p.

Kley, J. and Monaldi, C.R., 1998 - Tectonic shortening and crustal thickness in the central Andes: how good is the correlation. *Geology*, v. 26, (8), pp. 723-726.

Kurtz, A.C., Kay, S.M., Charrier, R. and Farrar, E., 1997 - Geochronology of Miocene plutons and exhumation history of the El Teniente region, Central Chile (34-35°S). *Revista Geológica de Chile*, v. 24, (1), pp. 73-90.

Le Bel, L.M., 1985 – Mineralization in the Arequipa segment: the porphyry-Cu deposit of Cerro Verde/Santa Rosa. *in* Pitcher, W.S., Atherto[n], M.P., Cobbing, E.J., and Beckinsale, R.D., (eds.) Magmatism at a plate edge: The Peruvian Andes *Blackie and Son*, Glasgow, pp 250-260.

Lee, A.W., 1994 - Evolution of the Rosario copper molybdenum porphyry deposit and associated copper-silver vein system, Collahuasi district region, northern Chile. Msc. thesis, *Queen's University*, Kingston, Ontario, 75p.

Lindsay, D.D., Zentilli, M. and Rojas de la Rivera, J., 19[..] – Evolution of an active ductile to brittle she[ar] system controlling the mineralization at the Chuquicamata porphyry copper deposit northern Chile. *International Geology Review* v. 37, pp. 945-958.

López-Escobar, L., 1982 - Características geoquímicas [de] rocas ígeneas asociadas con pórfidos cuprífer[os] chilenos. *Revista Geológica de Chile*, v. [..] pp. 3-19.

Lorca, G., Rojas, G., and Valdés, R., 2003 – Oxi[de] mineralization in the Radomiro Tomic - Chuq[uicamata] Norte orebody. (abs.), *Congreso Geológico Chileno, 10th*, Concepción, 2003, CD-ROM, 1[p].

Maksaev, V., 1979 - Las fases tectónicas Incaica y Quech[ua] en la cordillera de los Andes del norte de Chil[e]. *Congreso Geológico Chileno 2°, Santiago* Actas, v. 1, pp. B63-B77.

Masterman, G., Cooke, D.R., Berry, R.F., Clark, A., Archibald, D., Mathur, R., and Durán, M., 200[.] $^{40}Ar/^{39}Ar$ and Re/Os Geochronology of Porphyry Copper-Molybdenum Deposits and Related Copper-Silver Veins in the Collahuasi District Northern Chile: *Economic Geology*, v. 9[.] pp. 673-690.

McKee, E.H. and Noble, D.C., 1990 - Cenozoic tecton[ic] events, magmatic pulses, and base-and precious metal mineralization in the central Andes. i[n] Ericksen, G.E., Cañas, M.T., Reinemund, J. (eds.), Geology of the Andes and its relation [to] hydrocarbon and mineral resources, *Circum-pacific Council for Energy and Mineral Resources, Earth Science Series*, v. 1[1] pp. 189-194.

Mpodozis, C. and Ramos, V., 1990 - The Andes of Chile and Argentina. *in* Ericksen, G.E., Cañas, M.T. Reinemund, J., (eds.), Geology of the Andes and its relation to hydrocarbon and mineral resources, *Circum-pacific Council for Energy and Mineral Resources,* Earth Science Series v. 11, pp. 59-90.

Mpodozis, C. and Kay, S.M., 1992 - Late Paleozoic t[o] Triassic evolution of the Gondwana margin Evidence from the Chilean Frontal Cordillera batholiths. *Geological Society of America Bulletin*, v. 104, pp. 999-1014.

Mpodozis, C., Marinovic, C. and Smoje, I., 1993 - Estudi[o] geológico-estructural de la cordillera de Domeyko entre Sierra Limón Verde y Sierra Mariposas, Región de Antofagasta. *Servicio Nacional de Geología y Minería*, unpublished report, 231p.

Mpodozis, C., Tomlinson, A. and Cornejo, P., 1994 - Acerca del control estructural de los intrusivos eocenos y pórfidos cupríferos de la región de Potrerillos-El Salvador. *Congreso Geológico Chileno 7th*, Concepción, Actas, v. 2, pp. 1596-1600.

Mpodozis, C., Cornejo, P., Kay, S.M. and Titler, A., 1995 - La franja de Maricunga: Síntesis de la evolución del frente volcánico Oligoceno-Mioceno de la zona sur de los Andes Centrales. *Revista Geológica de Chile*, v. 22, pp. 273-313.

Munchmeyer, C., 1984 - Proyecto Collahuasi, geología del distrito de Collahuasi y del pórfido cuprífero Rosario. *Compañía Minera Doña Inés de Collahuasi*, Unpublished report, 120p.

Munchmeyer, C., 1996 - Exotic deposits – products of lateral migration of supergene solutions from porphyry copper deposits. *in* Camus, F., Sillitoe, R.H. and Petersen, R., (Eds.), Andean copper deposits: new discoveries, mineralization, styles and metallogeny, *Society of Economic Geologists* Special Publication N°5, pp. 43-58.

Muntean, J. L. and Einaudi, M. T., 2001 - Porphyry-epithermal transition: Maricunga belt, northern Chile; *Economic Geology*, v. 96, pp. 743-772.

Munizaga, F., Huete, C. and Hervé, F., 1985. - Geocronología K-Ar y razones iniciales Sr87/Sr86 de la franja Pacífica de desarrollos hidrotermales; *Congreso Geológico Chileno 4th*, Antofagasta, Actas, 3, pp. 357-379.

Noble, D.C., Sébrier, M., Mégard, F. and McKee, E.H., 1985 - Demonstration of two pulses of Paleogene deformation in the Andes of Perú. *Earth and Planetary Science Letters*, v. 73, pp. 345-349.

Ojeda, J.M., 1990 - Geology of the Escondida porphyry copper deposit, II Region, Chile. *in Pacific Rim Congress 90,* Gold Coast, Queensland, 1990, Proceedings, v. 2, pp. 473-483.

Ossandón G., Fréraut, R., Gustafson, L.B., Lindsay, D.D. and Zentilli, M., 2001 - Geology of the Chuquicamata mine: a progress report. *Economic Geology*, v. 96, pp. 249-270.

Padilla, R.A., Titley, S.R. and Pimentel, F., 2001 - Geology of the Escondida porphyry copper deposit, Antofagasta region, Chile. *Economic Geology*, v. 96, pp. 307-324.

Pardo-Casas, F. and Molnar, P., 1987 - Relative motion of the Nazca (Farallón) and South American plates since late Cretaceous time. *Tectonics*, v. 6, pp 233-248.

Perelló, J. and Cabello, J., 1989 - Pórfidos cupríferos ricos en oro; una revisión. *Revista Geológica de Chile*, v. 16, 1, pp 73-92.

Perelló, J., Brockway, H. and Martin, R., 2003a - The porphyry Cu-Au deposit at Esperanza, Antofagasta region, northern Chile. (abs.), *Congreso Geológico Chileno, 10th*, Concepción, 2003, CD-ROM, 1p.

Perelló, J., Carlotto, V., Zárate, A., Ramos, P., Posso, H., Neyra, C., Caballero, A., Fuster, N. and Muhr, R., 2003b - Porphyry-style alteration and mineralization of the middle Eocene to early Oligocene Andahuaylas-Yauri belt, Cuzco region, Perú. *Economic Geology*, v. 98, pp. 1575-1605.

Puig, A., Díaz, S. and Cuitiño, L., 1988 - Sistemas hidrotermales asociados a calderas en el arco volcánico Paleógeno de la región de Antofagasta, Chile. Distritos Cachinal de la Sierra y El Soldado. *Revista Geológica de Chile*, v. 15, pp. 57-82.

Reyes, M., 1991 - The Andacollo strata-bound gold deposit, Chile, and its position in a porphyry copper-gold system. *Economic Geology*, v. 86, pp. 1301-1316.

Rivano, S., Godoy, E., Vergara, M. and Villaroel, R., 1990 - Redefinición de la Formación Farellones en la cordillera de los Andes de Chile Central (32-34°S). *Revista Geológica de Chile*, v. 17, (2), pp. 205-214.

Rivera, O. and Navarro, H.M., 1996 - Estudio geológico distrital de la división Andina de Codelco-Chile, 2ª etapa. *Codelco-Chile, Gerencia de Planificación y Tecnología Minera*, Unpublished report, 169p.

Rivera, S. and Pardo, R., 2003 - Discovery and geology of the Toki porphyry copper deposis, Chuquicamata district, northern Chile. (abs.), *Congreso Geológico Chileno, 10th*, Concepción, 2003, CD-ROM, 1p.

Rogers, G., 1985 - A geochemical traverse across the northern Andes. Ph.D. thesis, *The Open University, London*, 333p.

Reutter, K.J., Scheuber, E. and Chong, G., 1996 - The Precordilleran fault system of Chuquicamata, northern Chile: Evidence for reversals along arc-parallel strike-slip faults. *Tectonophysics*, v. 259, pp. 213-228.

Serrano, L., Vargas, R., Stambuk, V., Aguilar, C., Galeb, M., Holgrem, C., Contreras, A., Godoy, S., Vela, I., Skewes, M.A. and Stern, C.R., 1996 - The Late Miocene to Early Pliocene Río Blanco-Los Bronces copper deposit, central Chilean Andes. *in* Camus, F., Sillitoe, R.H. and Petersen, R., (eds.), Andean copper deposits: new discoveries, mineralization, styles and metallogeny, *Society of Economic Geologists* Special Publication N°5, pp. 119-130.

Sillitoe, R.H., 1973 - Geology of the Los Pelambres porphyry copper deposit, Chile. *Economic Geology*, v. 68, pp. 1-10.

Sillitoe, R.H., 1977 - Permo-Carboniferous, upper Cretaceous, and Miocene porphyry copper-type mineralization in the Argentinean Andes. *Economic Geology*, v. 72, pp. 99-109.

Sillitoe, R.H., 1985 - Ore-related breccias in volcanoplutonic arcs. *Economic Geology*, 80, pp 1467-1514.

Sillitoe, R.H., 1993 - Gold-rich porphyry copper deposits: geological model and exploration implications. *in* Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., and Duke, J.M., (Eds.), Mineral Deposit Modeling, *Geological Association of Canada*

Special Paper 40, pp 465-478.

Sillitoe, R.H., 1995 - Exploration of porphyry copper lithocaps. *Pacific Rim Congress, Auckland, 1995, Proceedings, Australian Institute of Mining and Metallurgy*, Melbourne, pp. 527-532.

Sillitoe, R.H. and Sawkins, F.J., 1971 - Geologic, mineralogic, and fluid inclusion studies relating to the origin of copper-bearing tourmaline breccia pipes, Chile. *Economic Geology*, v. 66, pp. 1028-1041.

Sillitoe, R.H. and Gappe, I.M., 1984 - Philippine porphyry copper deposits: geologic setting and characteristics. *United Nations Technical Support for Regional Offshore Prospecting in East Asia,* Technical Publication 14, 89p.

Sillitoe, R.H. and Camus, F., (eds.), 1991 - A special issue devoted to gold deposits in the Chilean Andes. *Economic Geology*, v. 86, pp. 1153-1345.

Sillitoe, R.H., McKee, E.H. and Vila, T., 1991 - Reconnaissance K-Ar geochronology of the Maricunga gold-silver belt, northern Chile. *Economic Geology*, v. 86, pp. 1261-1270.

Sillitoe, R.H. and McKee, E.H., 1996 - Age of supergene oxidation and enrichment in the chilean porphyry copper province. *Economic Geology*, v. 91, pp. 164-179.

Skarmeta, J., y J.C. and Castelli, 1997 - Intrusión sintectónica del granito de las Torres del Paine, Andes patagónicos de Chile. *Revista Geológica de Chile*, v. 24, (1), pp. 55-72.

Skewes, M.A., 1998 - Química de intrusivos ácidos del yacimiento El Teniente. *Codelco-Chile División El Teniente*, Unpublished report, 22p.

Skewes, M.A. and Atkinson, Jr. W.W., 1985 - Petrology of the early-formed hydrothermal veins within the central potassic alteration zone of Los Pelambres porphyry copper deposit, Chile. *Revista Geológica de Chile*, v. 25-26, pp. 39-56.

Skewes, M.A. and Stern, C,R., 1995 - Genesis of the giant late Miocene to Pliocene copper deposits of central Chile in the context of Andean magmatic and tectonic evolution. *International Geology Review*, v. 37, pp. 893-909.

Skewes, M.A., Arévalo, A.G., Floody, R., Zuñiga, P. and Stern, C.R., 2002 - The giant El Teniente breccia deposit: hypogene copper distribution and emplacement. *in* Goldfarb, R.J., and Nielsen, R.L., (Ed.s), Integrated methods for discovery: Global exploration in the twenty-first century. *Society of Economic Geologists,* Special Publication 9, pp. 299-332.

Skinner, B.J., (Ed.), 1999 - Geology and ore deposits of the Central Andes. *Society of Economic Geologists,* Special Publication no. 7, 351p.

Soto, H.M., 1979 - Alteración y mineralización primaria en Chuquicamata. PhD thesis, *Universidad de Salamanca*, 242p.

Stern, C.R. and Skewes, M.A., 1995 - Miocene to present magmatic evolution at the northern end of the Andean southern volcanic zone, Central, Chi *Revista Geológica de Chile*, v. 22, (pp. 261-272.

Tomlinson, A.J., 1994 - Relaciones entre el pórfi cuprífero y la falla inversa de la mina d Potrerillos: un caso de intrusión sintectóni *Congreso Geológico Chileno 7°,* Concepci Actas, 2, pp. 1629-1633.

Tomlinson, A.J. and Blanco, N., 1997a - Structu evolution and displacement history of the we fault system, Precordillera, Chile: Part synmineral history. *Congreso Geológico Chile 8th*, Antofagasta, Actas, 3, pp. 1873-1877.

Tomlinson, A.J. and Blanco, N., 1997b - Structu evolution and displacement history of the we fault system, Precordillera, Chile: Part postmineral history. *Congreso Geológi Chileno 8th*, Antofagasta, Actas, pp. 1878-1882.

Tomlinson, A.J., Blanco, N., Maksaev, V., Dilles, J.H Grunder, A.L. and Ladino, M., 2001 - Geolog de la precordillera andina de Quebrada Blan – Chuquicamata, regiones I y II (20°30' – 22° S). *Servicio Nacional de Geología y Miner Codelco Chile*, 444p.

Tosdal R.M., Clark, A.H. and Farrar, E., 1984 - Cenozo polyphase lanscape and tectonic evolution of t Cordillera Occidental, southernmost Per *Geological Society of America, Bulletin*, v. 9 (11), pp. 1318-1332.

Vargas, R., Gustafson, L.B., Vukasovic, M., Tidy, E. a Skewes, M. A., 1999 - Ore breccias in the R Blanco-Los Bronces porphyry copper depos *in* Skinner, B.J., Geology and ore deposits o the central Andes, *Society of Economi Geologists,* Special Publication no. pp 281-297.

Vila, T. and Sillitoe, R.H., 1991 - Gold-rich porphy systems in the Maricunga belt, northern Chi *Economic Geology*, v. 86, pp. 1238-1260.

Warnaars, F., Holmgren, C. and Barassi, S., 1985 - Porphy copper and tourmaline breccias at Los Bronce Río Blanco, Chile. *Economic Geology*, v. 8 pp. 1544-1565.

Williams, W.C., 1992 - Magmatic and structural contro in mineralization in the Paleocene magmatic a between 22°40' and 23°45' south latitud Antofagasta, II Region, Chile. Ph.D. thesi *University of Arizona,* Tucson, 182p.

Williams, M.J., 2003 - Geology and mineral resources o Escondida Norte deposit, Region II, Chil (Abs.), *Congreso Geológico Chileno, 10* Concepción, 2003, CD-ROM, 1p.

Zentilli, M., Graves, M., Lindsay, D., Ossandón, G. a Camus, F., 1995 - Recurrent mineralization i the Chuquicamata porphyry copper system restrictions on genesis from mineralogica geochronological and isotopic studies. In Clar A.H., (Ed.), Giant Ores Deposits II. Controls o the scale of orogenic magmatic-hydrotherma mineralization, Department of Geologica

Sciences, *Queen's University,* Kingston, Ontario, 1995, Proceedings, pp. 90-113.

Zweng, P.L. and Clark, A.H., 1995 - Hypogene evolution of the Toquepala porphyry copper-molybdenum deposit, Moquegua, southeastern Perú. in Pierce, F.W., and Bolm, J.G., (Ed.s), Porphyry copper deposits of the American Cordillera, *Arizona Geological Digest*, v. 20, pp. 566-612.