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CHILEAN STRATA-BOUND Cu- (Ag) DEPOSITS: AN OVERVIEW

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Abstract - Strata-bound Cu- (Ag) deposits, long known as 'Chilean manto-type', occur along the Coastal Cordillera of northern Chile (22°-30°S) hosted by Jurassic and Lower Cretaceous volcanic and volcano-sedimentary rocks. These deposits are typical of the first stage of Andean evolution characterised by an extensional setting of the arc magmatism along the active margin of South America. Strata-bound Cu- (Ag) deposits were formed during two metallogenic epochs in the Late Jurassic and uppermost Early Cretaceous. The mineralisation took place at the time of structurally controlled emplacement of batholiths within the Mesozoic volcanic and sedimentary strata. The volcanic-hosted strata-bound Cu- (Ag) deposits invariably occur distal, but peripheral to coeval batholiths emplaced within tilted Mesozoic strata. The prevalent view that these deposits have an inherent genetic relationship with hydrothermal fluid derivation from subvolcanic stocks and dykes is contended here, because these minor intrusions are largely barren and this hypothesis does not fit well with Sr, Os and Pb isotopic data that call for crustal contribution of these elements. The strata-bound Cu- (Ag) mineralisation appears to be produced by fluids of mixed origin that were mobilised within permeable levels and structural weakness zones of the Mesozoic arc-related volcano-sedimentary sequence during the emplacement of shallow granodioritic batholiths under transtensional regimes. These hydrothermal fluids deposited copper and subordinate silver when reacted with organic matter, pyrite and/or cooled away from their heat sources. Although strata-bound Cu- (Ag) mineralisation took place during the same Cretaceous metallogenic event that formed the magnetite-apatite bodies, and Fe-oxide-Cu-Au deposits along the present Coastal Cordillera, the conceivable relationships with these other types of deposits are hampered by the inconclusive debate about the origin of the Chilean Fe-oxide deposits. However, the available data strongly suggest that the Fe oxide-rich deposits are metasomatic in origin and genetically related to contact zones of Lower Cretaceous dioritic batholiths, whereas the iron-poor volcanic-hosted Cu- (Ag) stratabound deposits constitute distal mineralisation peripheral to Upper Jurassic of Lower Cretaceous granodioritic batholiths.

Introduction

Strata-bound copper deposits with subordinate silver, long known as 'Chilean Manto-type', occur along the Coastal Cordillera of northern Chile hosted by Jurassic and Lower Cretaceous volcanic and volcano-sedimentary rocks. These Mesozoic strata-bound deposits historically were the second source of Chilean copper production after Cenozoic porphyry copper deposits, but have recently been displaced to third place by the exploitation of large Lower Cretaceous Fe-oxide-Cu-Au deposits (eg. Candelaria and Manto Verde mines; Marschik et al., 2000, Vila et al., 1996, Zamora and Castillo, 2001).

Two groups of significant strata-bound Cu- (Ag) occur in Chile: (a) from 22° to 26° lat. S hosted by a Jurassic volcanic sequence (La Negra Formation) and (b) from 30° to 34° lat. S hosted by Lower Cretaceous volcanic and volcano-sedimentary rocks. Although a group of Lower Cretaceous Fe-oxide-Cu-Au strata-bound deposits in the Punta del Cobre district (~27°30' S) have traditionally been included in the manto-type in Chile (eg. Camus, 1980, 1985), the present review excludes them, being exclusively focused on the Fe-poor volcanic-hosted strata-bound copper deposits with subordinate silver that are hosted by Mesozoic andesitic-basaltic volcanic sequences along the Coastal Cordillera of northern Chile. For lack of space, this paper does not discuss Cu- (Ag)±(Hg) mantos hosted by Cenozoic rhyolitic ignimbrites such as: Jardin, Amolanas, Venado, Elisa de Bordo (Camus, 1985, Lortie and Clark, 1987, Mayer and Fontboté, 1990, Jurgeit and Fontboté, 1990). These relatively small deposits represent a different metallogenic problem altogether.

Volumes and Grades

The largest strata-bound Cu- (Ag) deposit of the Jurassic group is Mantos Blancos in the Coastal Cordillera of Antofagasta in northern Chile, where 120 mt (million metric tons or tonnes) of ore were extracted during the period 1960-1995 producing 1 643 715 tonnes of copper. In 1995 the

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Editors note: The Chilean strata-bound Cu-(Ag), or "Manto" deposits, particularly Mantos Blancos and El Soldado, have been included within the Iron Oxide Copper-Gold (IOCG) family by many authors in the existing literature. Others however, have argued a contrary view. Consequently, these two renowned authorities on this group of deposits were invited to contribute a paper describing the characteristics of the "Chilean Mantos", and then on the basis of their observations to discuss whether they are members of the IOCG family and their relationship to the ores of the family within the same belt.

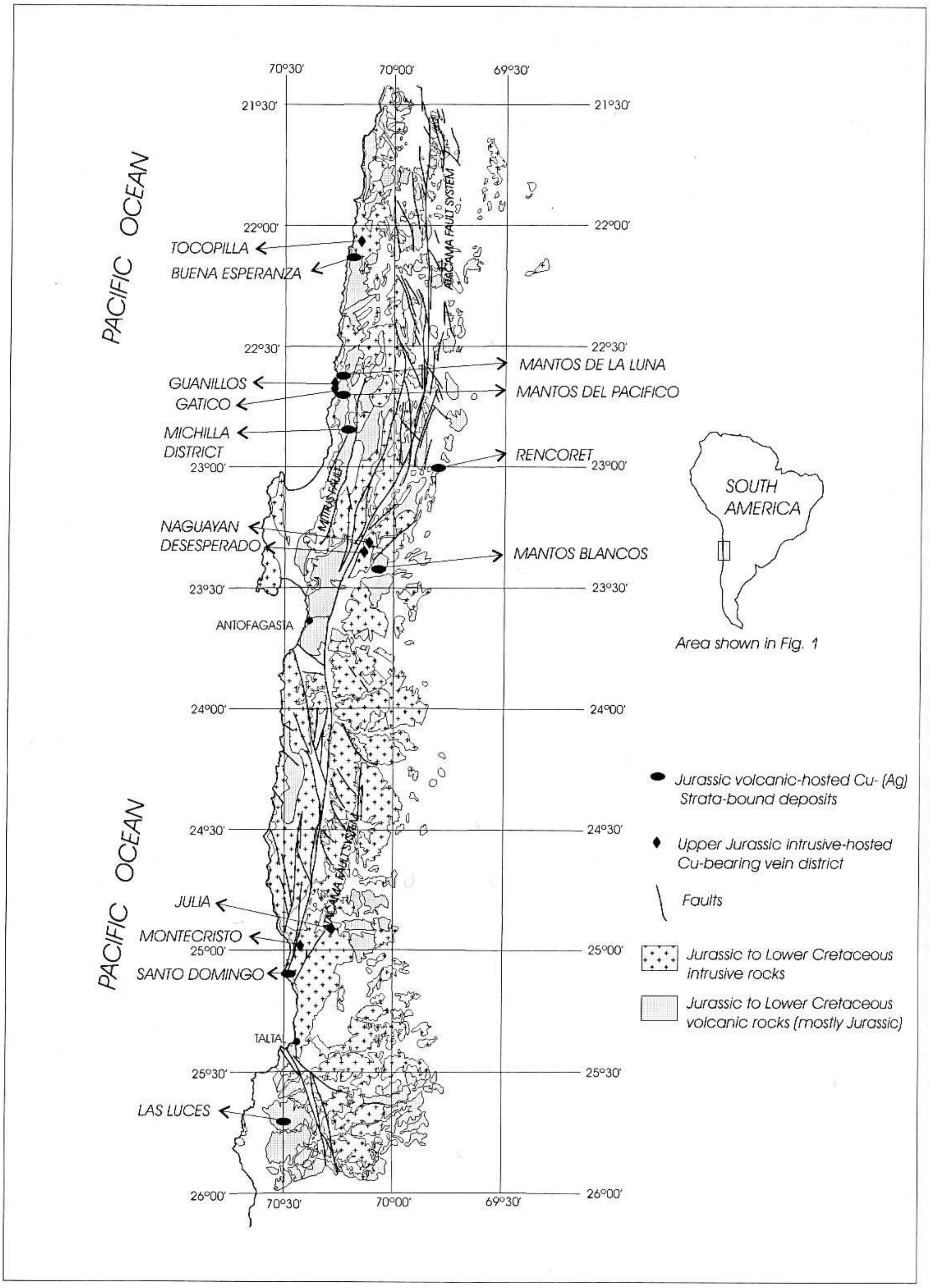


Figure 1: Upper Jurassic volcanic-hosted Cu-(Ag) strata-bound deposits and Cu-bearing vein districts hosted by Upper Jurassic intrusives in the Coastal Cordillera of northern Chile from 22° to 26°S. Simplified geology after Boric et al., 1990.

remaining reserves amounted to 43 mt of oxide ore at 0.86% Cu and 62 mt of sulphide ore at 1.18% Cu and 12 g/t Ag (Pizarro, 1997). The second in volume is the Mantos de la Luna deposit that has measured resources of 40.5 mt at 1.39% Cu plus inferred resources of 6 mt at 1.4% Cu (Minería Chilena, 2001). The other Jurassic deposits are smaller, although the reserves and production of some commonly total some millions of tonnes of ore at 1 to 3.8% Cu and 8 to 25 g/t Ag. The most significant deposits are Susana and Juarez in the Michilla district, and Santo Domingo, with other examples such as Buena Esperanza and Mantos del Pacifico (Fig. 1). The largest strata-bound Cu- (Ag) deposit hosted by Lower Cretaceous volcanic rocks is El Soldado in the Coastal Cordillera of central Chile, whose production plus ore reserves amounts to over 200 mt at 1.35% Cu. The second in volume of the Lower Cretaceous group is Lo Aguirre (now exhausted), located immediately west of Santiago city, where 11.1 mt at 2.14% Cu were exploited. Lower Cretaceous volcano-clastic rocks in central Chile host another group of relatively small strata-bound Cu- (Ag) deposits. Typical examples are: Talcuna (Boric, 1985) and Cerro Negro (Elgueta et al., 1990). At Cerro Negro 6 mt of ores at 1-3% Cu and 31 g/t Ag were exploited, whereas the average tonnage of other deposits is about 2 mt at 1.7% Cu and 25 g/t Ag (Camus, 1990).

Geological Setting of the Strata-bound Cu-(Ag) Mineralisation

The Andean Cordillera in northern Chile (18º-34º Lat. S) is a section of the Central Andes that has long been regarded a classic example of a "simple" orogen developed along a convergent plate margin (eg. Dewey and Bird, 1970, James, 1971). This is a non-collisional orogen formed over a long-lived, currently active, subduction system, whose distinctive feature is the occurrence of a great volume of igneous rocks generated throughout its geologic history. Therefore the Andes have been referred to as a "magmatic mountain range" (Zeil, 1979) or a "volcano-plutonic orogen" (Sillitoe, 1976). Most of the rich metallic ore deposits of the Andes are of hydrothermal origin. They have an inherent and temporal relationship to the magmatic arc activity, and they are believed to derive most of their metallic content from underlying subduction-related processes (eg. Sillitoe, 1972, 1974, 1976, Clark and Zentilli, 1972, Clark et al., 1976, Maksaev, 1990, Maksaev and Zentilli, 1999). Successive supra-subduction volcano-plutonic arcs were developed since the Early Jurassic on the western continental margin of South America in response to plate convergence with an east-dipping Benioff zone. The magmatic front systematically shifted position inland as geological time progressed, the eastward change of position of the arc system followed periods of crustal thickening by compressive deformation, so that tectonism also migrated inland with time (Boric et al., 1990).

Two major stages are recognised in the geological evolution of the Andes in the northern half of Chile: 1). from the Jurassic to the end of the Early Cretaceous, when a magmatic arc-system flanked to the east by a sedimentary marine back-arc basin developed within an extensional tectonic setting, and, 2). since the Late Cretaceous to the present, when arc-systems developed on a continental environment within an overall compressive tectonic setting. Fold and thrust belts were locally developed eastward from the arc systems during the second stage.

Strata-bound Cu-(Ag) mineralisation was conspicuous during the first extensional stage of Andean evolution in Chile, whereas porphyry copper deposits strongly dominated during the second. These two major stages in the geological evolution of the north Chilean Andes reveal a major change of geodynamic conditions on the active continental margin during orogen formation that was also reflected in Andean metallogeny.

Most of the Andean Cordillera of the northern half of Chile was built above a basement that corresponds to an accretionary prism and arc system related to a pre-existing subduction regime on the border of the Gondwana super-continent during the Late Paleozoic to Early Triassic (Mpodozis and Ramos, 1990). The main N-S orientation of the Andean structures in northern Chile are oblique relative to the largely NNW to NW-trending fabric of the Upper Paleozoic basement rocks (eg. Tosdal and Richards, 2001). A 2500 km long belt that extends from northern Chile to southern Argentina and consists of rhyolitic ignimbrites and andesites several thousand metres thick, known as the Choiyoi Formation, represents the Upper Carboniferous to Lower Triassic arc system. The striking abundance of felsic rocks of this pre-Andean belt has been taken to represent either crustal anatexis-related processes during an extensional stage or as calc-alkaline subduction-related differentiated felsic rocks (Mpodozis and Ramos, 1990).

The Late Paleozoic–Early Triassic accretionary prism and magmatic arc system were replaced during Middle to Late Triassic time by a palaeogeography dominated by a number of NW-trending fault-bounded isolated basins or grabens (Charrier, 1979, Suarez and Bell, 1993, Ramos and Aleman, 2000). The formation of these grabens is believed to be related to extensional tectonics that preceded the fragmentation of the Gondwana super-continent (Mpodozis and Ramos, 1990). The Middle-Upper Triassic basins were filled by continental red-beds and lacustrine sediments, but also by marine sedimentary deposits along the present Coastal and Domeyko Cordilleras of northern Chile, and by local basaltic and rhyolitic bimodal volcanic rocks (Mpodozis and Cornejo, 1997; Ramos and Aleman, 2000). Subduction-related igneous activity resumed in the Early Jurassic some 100 to 150 km west from the former position of the Late Paleozoic–Early Triassic magmatic arc, while the area formerly occupied by the Late Paleozoic arc subsided to originate the Jurassic back-arc marine basin that persisted during the Early Cretaceous.

During the Jurassic and Early Cretaceous a subduction-related magmatic arc system was established along the whole length of the present Coastal Cordillera of northern Chile. It is now represented in northernmost Chile (21º-26ºS) by a thick basaltic to andesitic volcanic pile (>7000 m thick) of calc-alkaline to K-rich calc-alkaline nature, with initial stages of tholeiitic affinity (Rogers and Hawkesworth, 1989, Pichowiak, et al., 1990). The volcanic strata were episodically intruded by a number of Jurassic and Lower Cretaceous calc-alkaline dioritic to granodioritic batholiths, many smaller intrusions and conspicuous dyke swarms (eg. Marinovic et al., 1995, Dallmeyer et al., 1996). Numerous Cu-bearing vein districts occur within Upper Jurassic batholiths (Boric et al., 1990). Most of the Jurassic - Lower Cretaceous volcanic rocks of the Coastal Cordillera of northernmost Chile were erupted in subaerial conditions, although minor marine fossiliferous calcareous sedimentary intercalations and local pillow lavas attest a persistent depositional environment more or less at sea level (Ferraris and Di Biase, 1978, Naranjo and Puig, 1984, Marinovic et al., 1995, Gröschke et al., 1988; Bogdanic et al., 1994). The extrusion of this volcanic sequence had to be accompanied by considerable crustal subsidence probably related to the extensional tectonic setting of the whole arc system (Dallmeyer et al., 1996). The fact that a thick Jurassic-Lower Cretaceous volcanic pile was deposited without significant relief building indicates that magmatic

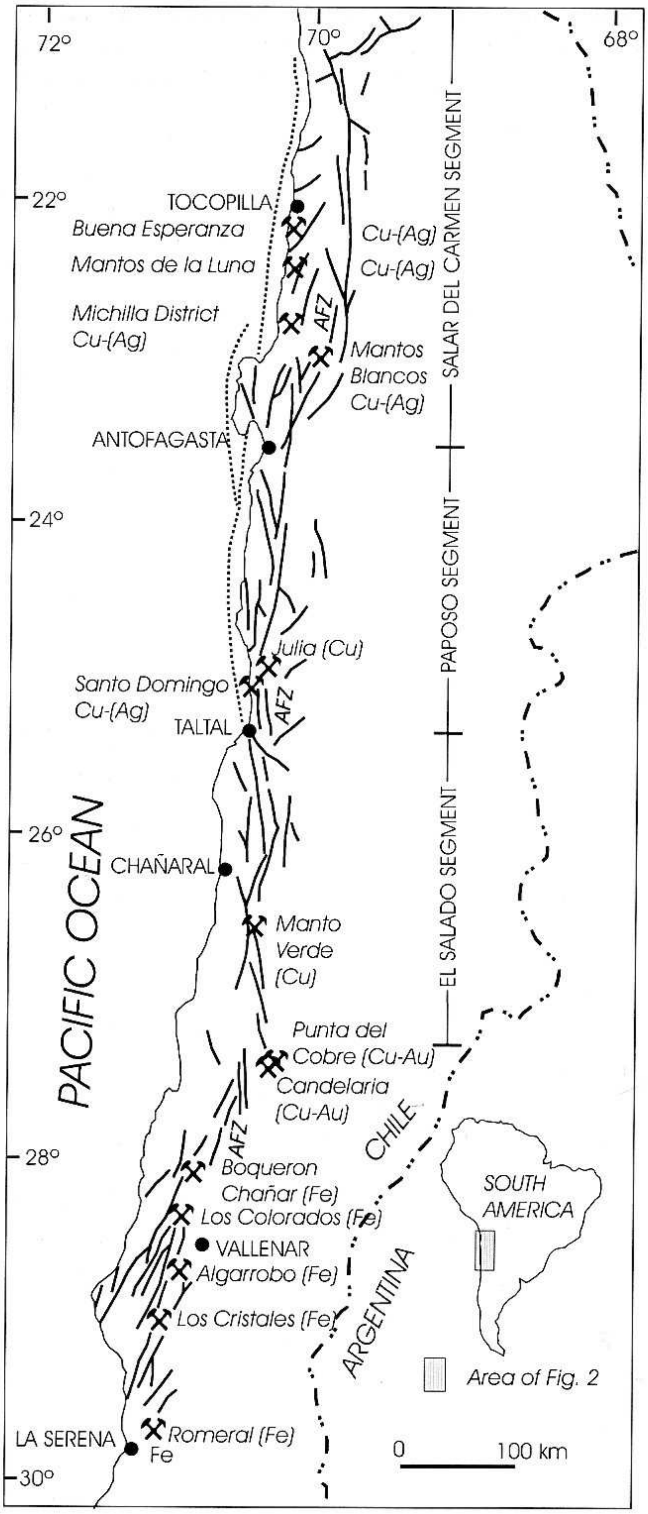


Figure 2: Major faults of the sinistral Atacama Fault Zone (AFZ) along the Coastal Cordillera of northern Chile, modified after Brown et al. (1993) and Vila et al. (1996). Main Fe, Cu-Au, and Cu-(Ag) deposits within the domain of the fault zone are shown.

arc evolution was accompanied by crustal thinning that accommodated steady subsidence. Foliated intrusions and mylonites along the Coastal Cordillera of the Antofagasta area (23°-26° Lat. S) indicate changes of stress regime with local transpressive conditions during the Jurassic and transtension during the Early Cretaceous (Gonzalez, 1999). These foliated intrusions and mylonites are related to the Atacama Fault Zone that is a major trench-linked sinistral strike-slip fault system that extends more than 1000 km along the Coastal Cordillera of northern Chile from latitude 20° to 30° S (Fig. 2). This fault system developed through the Jurassic-Early Cretaceous as an intra-arc regional structure related to oblique subduction of the Aluk (Phoenix) plate relative to the South American continent (Boric et al., 1990, Scheuber and Andriessen, 1990; Scheuber and Gonzalez, 1999).

The development of the Jurassic to Early Cretaceous magmatic arc along the present Coastal Cordillera was accompanied by subsidence and formation of a back-arc basin system farther east in the area now occupied by the Intermediate Depression and Domeyko Cordillera (Tarapaca Basin, Mpodozis and Ramos, 1990). In northern Chile (21°-27°S) the back-arc basin sequences are preserved as a belt of marine and continental sedimentary rocks exposed 70 to 110 km east of the coeval magmatic arc (Reutter and Scheuber, 1988, Ardill et al., 1998). In addition, local continental and marine sedimentation took place during the Early Cretaceous within the domain of the magmatic related sinistral to pull-apart basins (eg. El Way basin; Maksaev, 1990).

In the Coastal Cordillera of north-central Chile (~30°-34°S) the subsiding Jurassic to Lower Cretaceous magmatic arc is represented by a >10 000 m thick sequence of mafic lavas intercalated with marine clastic and carbonate rocks. This volcano-sedimentary sequence is thought to be deposited over thinned crust (Vergara et al., 1995; Aguirre et al., 1999). Episodic emplacement of plutonic complexes also took place during arc development in central Chile. The intrusion of large Aptian-Albian (upper-Early Cretaceous) granodioritic to dioritic batholiths (K-Ar 118-96 Ma; Rivano et al., 1993, Rivano and Sepulveda, 1991, Dallmeyer et al., 1996) appear to be particularly relevant to copper mineralisation. Iron, copper and gold occur within and on the periphery of these batholiths that were emplaced along extensional or sinistral transtensional faults within the Lower Cretaceous section of the volcanic-sedimentary sequence: eg. the Illapel Super-unit along the Manquegua and associated faults (Rivano y Sepulveda, 1991) and the La Borracha Plutonic Complex within the domain of the Atacama Fault Zone (Dallmeyer et al., 1996). In detail the Aptian-Albian batholiths are composed of a number of individual plutons that conform to relatively narrow N-S-trending belts indicating that batholiths largely expanded by episodic injection of magma batches that were emplaced along transtensional faults within the Lower Cretaceous volcanic-sedimentary pile and older intrusions. This is consistent with emplacement models postulated for Mesozoic plutonic complexes along the Coastal Cordillera of the Copiapo region (26°-29°S) of Chile (eg. Dallmeyer et al., 1996, Wilson and Grocott, 1999). Tilting of the Jurassic-Lower Cretaceous sequence also appears to be related to Aptian-Albian sinistral transtensional tectonics along the Coastal Cordillera of central Chile (~30°-34°S).

On the other hand, Tithonian-Neocomian (Late Jurassic to Early Cretaceous) marine limestones that outcrop in the High Andes between 32°-34°S attest that a marine platform developed to the east of the extensional magmatic arc in central Chile (Aconcagua Platform of Mpodozis and Ramos, 1990).

Tectonic inversion took place during the Cenomanian to Santonian (lower Late Cretaceous) as result of compressive deformation pulses that affected the whole Central Andes. This included contraction and emergence of the of the arc and back-arc basin system (Megard, 1987, Coira et al., 1982, Mpodozis and Ramos, 1990, Ladino et al., 1999, Tomlinson et al., 2001). The igneous activity along the former Jurassic - Lower Cretaceous magmatic arc ceased at the onset of compression and subsequently a new magmatic arc was developed some 50 km eastward from the previous location. Subsequent Late Cretaceous and Cenozoic volcanic activity in the Andes of northern Chile took place exclusively in a subaerial environment, with further episodes of crustal shortening/thickening by compressive deformation events.

The tectonic inversion of the former Jurassic to Lower Cretaceous marine back-arc basin domain, waning of the igneous activity along the westernmost section of the South American continental border and the establishment of a new magmatic arc farther inland are major Late Cretaceous palaeogeographic changes that have been interpreted as an adjustment of the active continental margin of South American from a Mariana type (extensional) to a Chilean (compressive) type of subduction (Davidson and Mpodozis, 1991). These significant geological and tectonic changes correlate with a rapid separation between Africa and South America, with the latter overriding the oceanic plate to the west (Ramos and Aleman, 2000).

The stratigraphic position and geochronological data indicate that the Chilean volcanic-hosted strata-bound Cu-(Ag) deposits were generated during the Late Jurassic and uppermost Early Cretaceous. The overall extensional tectonic setting, crustal thinning, active subsidence, extensional tilting of the volcano-sedimentary strata and episodic batholith emplacement within these strata during the development of the Jurassic - Lower Cretaceous magmatic arc are singular to this early stage of Andean evolution in Chile. However, it appears that distinct periods of transtensional tectonics facilitated shallow emplacement of batholitic masses, provided structural weakness zones for hydrothermal fluid circulation, and modified the hydraulic regime within the permeable strata of tilted volcano-sedimentary strata. The concurrence of these specific factors and probably other still unknown ingredients may account for the occurrence of two discrete periods of strata-bound Cu-(Ag) mineralisation.

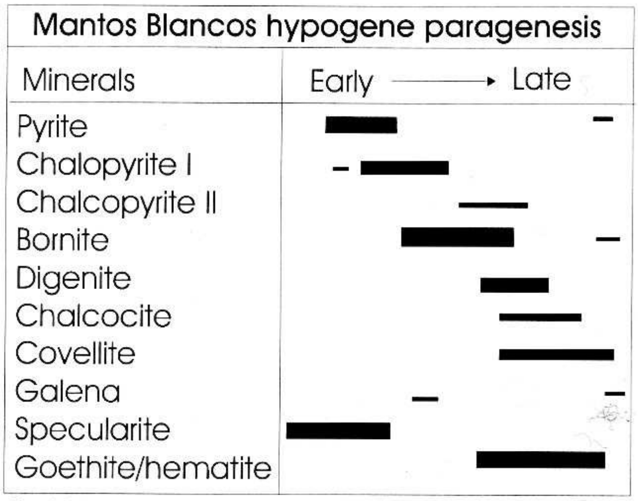
Jurassic Volcanic-hosted Strata-bound Cu-(Ag) Deposits

The strata-bound Cu-(Ag) deposits of the Jurassic belt are distributed along the Coastal Cordillera of northern Chile between 22°-26°S (Fig. 1). They are primarily hosted by mafic Jurassic basaltic to andesitic porphyritic lavas or breccia bodies, although the largest deposit of this group Mantos Blancos is hosted by a bimodal suite of rhyolitic and andesitic rocks, with some ore-grade mineralisation also occurring within dacitic and andesitic sills and dykes (Chavez, 1985). Strata-bound Cu-(Ag) deposits often occur near gabbroic, dioritic or andesitic subvolcanic intrusive bodies, such as dykes, sills, stocks, or volcanic necks, but these intrusives are largely un-mineralised and some post-date copper mineralisation (eg. at Buena Esperanza, Susana, and Santo Domingo; Palacios, et al., 1986, Espinoza et al., 1996). These subvolcanic intrusives have been interpreted as feeder conduits of the Jurassic volcanism (Palacios and Definis, 1981, 1981b, Espinoza, 1981, Espinoza et al., 1996).

The strata-bound Cu-(Ag) deposits have long been known as "Chilean Manto-type", because initial mining exploited the stratiform sections of the deposits (referred to as "mantos" by miners). However, the complete orebodies are commonly composite, including stratiform, lenticular, pipe, and irregular forms, that are either concordant or discordant to the bedding of the host Jurassic volcanic strata. Mantos Blancos for example includes at least four main lenticular disseminated and fracture-filling sulphide orebodies (Sorpresa, Aida, Nora, and Marina) forming an overall, slightly unconformable, sub-horizontal tabular ore deposit (Chavez, 1985). The thicknesses of mineralised zones at Mantos Blancos range from 150 to 350 m and the deposit extends irregularly over an area of 2.6x1.2 km. At Buena Esperanza and Susana copper sulphides cement the matrix of a central breccia pipe and are also disseminated in a number of conformable stratiform orebodies ("mantos") around the breccia pipes (Palacios, 1990; Espinoza et al., 1996). The stratiform orebodies (2 to 25 m thick) are commonly restricted to the amygdaloidal and brecciated sections of the Jurassic lava flows while minor veins occur along local faults and fractures (Palacios and Definis, 1981, 1981b, Dreyer and Soto, 1985). The main hypogene sulphides are chalcocite and bornite, minor chalcopyrite, and at times covellite and digenite. Hypogene gangue minerals are quartz, hematite, pyrite, chlorite, albite, and calcite. Minor magnetite occurs as dissemination within mineralised rocks, but is mostly replaced by hematite or maghemite. At Mantos Blancos, where specularite occurs, it is early in the paragenesis and mostly concentrated within a barren andesite flow that overlies the orebody, whereas a fine reddish hematite dissemination occurs within mineralised rocks. A lateral hypogene zonation has been described at Mantos Blancos and Santo Domingo that includes copper-rich cores dominated by chalcocite-bornite-digenite surrounded by a peripheral halo of bornite-chalcopyrite or chalcopyrite alone, and an external halo (mostly uneconomic) of chalcopyrite-pyrite (Chavez, 1985, Definis, 1985). The hydrothermal alteration assemblage of albite - chlorite - hematite - quartz - calcite - epidote - sphene - scapolite - anatase - minor sericite is associated with ore minerals in these strata-bound Cu- (Ag) deposits, with the primary textures of the volcanic rocks being preserved (Losert, 1973, Chavez, 1984, 1985, Palacios, 1986, 1990). This local alteration appears to be superimposed upon a regional low grade alteration/ metamorphism of the volcanic sequence characterised by a chlorite-calcite-epidote-zeolite-prehnite-pumpellyite assemblage, with little or no alteration contrast macroscopically visible between mineralised and barren volcanic country rocks. The hydrothermal alteration is particularly pervasive in Mantos Blancos, where lithogeochemistry shows significant metasomatism of the host rocks with addition of Na, Fe and Mg (Chavez, 1985).

Paragenetic studies of these strata-bound Cu-(Ag) deposits have shown that pyrite-chalcopyrite-bornite and minor magnetite were deposited first, followed by subordinate amounts of hypogene chalcocite-covellite-digenite accompanied by hematite (Fig. 3). This sequence indicates a gradual increase in the proportion of copper in the sulphides, and probably a decrease of sulphur activity in the mineralising fluids with time (Chavez, 1985, Losert, 1974, Wolf et al., 1990; Trista, 2001). The paragenetic sequence is characterised by the successive hypogene replacement of iron rich sulphides (pyrite, chalcopyrite) by copper-rich sulphides (bornite, chalcocite, covellite, digenite) which may account for iron release and formation of hypogene hematite associated with the copper sulphides (Chavez, 1984).

Two phase, liquid-rich fluid inclusions in quartz and calcite with sulphides from Mantos Blancos have yielded homogenisation temperatures in the 225°-400°C range (mostly concentrated within 284°-355°C) and salinities from 8 to 17 wt.% NaCl equivalent (Collao, 1993). Fluid inclusions in gypsum from the same deposit have lower homogenisation temperatures in the 112°-225°C range and lower saline content (3-10 wt.% NaCl equivalent). Pressure estimations from the fluid inclusion data range from 145 to 222 bars in hydrostatic conditions (Collao, 1993). At the Buena Esperanza deposit saline fluid inclusions (up to 35 wt.% NaCl equivalent) in calcite that contains copper sulphides have produced homogenisation temperatures ranging from 65° to 195°C, whereas fluid inclusion in quartz-filled amygdules yielded homogenisation temperatures between 130°C and 235°C; minimum formation pressures were estimated at about 285-315 bars (Nisterenko et al., 1973). However, Palacios (1990) reported higher fluid inclusion homogenisation temperatures (440°-500°C) of hyper-saline (52-59 wt.% NaCl eq.) fluid inclusions in hydrothermal quartz from the vicinity of the central gabbroic stock of Buena Esperanza, which was regarded as the mineralising fluid source by this author. Two phase, liquid-rich fluid inclusions in quartz from the Buena Vista deposit (Michilla District) have yielded homogenisation temperatures ranging from 214° to 360°C (mostly concentrated within 220°-300°C) and salinities from 16 to 21 wt.% NaCl equivalent; a trapping pressure of 90 bars was estimated for an average homogenisation temperature of 270°C and hydrostatic pressure conditions (Trista, 2001). Although the last author estimated that the fluid at Buena Vista was trapped close to the boiling point, no evidences of boiling of hydrothermal fluids were observed by any of the above mentioned authors. The limited data available for the formation conditions of the Jurassic strata-bound Cu- (Ag) deposits suggests that saline fluids, at moderate temperatures, within a depth range of about 1000 to 3000 m deposited metals within the Jurassic volcanic pile assuming hydrostatic pressure conditions. This estimate of depth of emplacement for the Jurassic strata-bound Cu-(Ag) deposits is consistent with independent estimations of unroofing based on apatite fission track data (<2 km assuming a palaeo-geothermal gradient of 30°C/km) from Jurassic and Cretaceous intrusions along the Coastal Cordillera of the northern section of the Antofagasta Region (Maksaev, 1990, 2000, Andriessen, 2000).



Bar thickness indicate the relative abundance of the minerals. (After Chavez, 1985)

Figure 3: Paragenetic sequence of hypogene minerals in Mantos Blancos volcanic-hosted Cu-(Ag) strata-bound deposit. After Chavez (1985).

Sparse and imprecise K-Ar and Rb-Sr minimum radiometric dates indicate that the main strata-bound deposits hosted by Jurassic volcanic rocks of northern Chile were formed at about 150-140 Ma (Boric et al., 1990, Venegas et al., 1991, Tassinari et al., 1993, Vivallo and Henriquez, 1998). This radiometric age range is younger than the volcanic host rocks that have been dated by Rb-Sr and K-Ar methods in the 186-165 Ma range, but overlapping with ^{40}Ar-^{39}Ar, Rb-Sr and K-Ar ages of granodioritic batholiths that intrude the volcanic sequence along the coastal area (age compilation in Vivallo and Henriquez, 1998). Minor stocks and dykes spatially related to the strata-bound Cu-(Ag) deposits have minimum K-Ar ages ranging between 154 and 133 Ma, except for the gabbroic stock at Buena Esperanza that have yielded a K-Ar age of 168 ± 5 Ma in plagioclase (Boric et al., 1990).

On the other hand, numerous iron oxide and copper bearing veins are hosted by the Upper Jurassic dioritic to granodioritic batholiths that are emplaced within the same Jurassic volcanic sequence that hosts strata-bound Cu-(Ag) deposits along the Coastal Cordillera. The most significant occur at the Tocopilla, Gatico, Desesperado, Julia and Montecristo districts (Fig. 1). These vein districts were of primary economic importance in the second half of the 19th Century and early 20th Century when most of the Chilean copper production came from veins, but most are long abandoned. The largest vein deposits are Minita-Despreciada (Tocopilla District), Toldo-Velarde (Gatico District), and Julia-Reventon (Julia District). These are mostly NE-trending, steeply-dipping veins (though some veins strike WNW, E-W and N-S), from 750 to 2000 m long, 1 to 12 m wide and about 370 to 670 m of known vertical extent. Copper ores concentrate in rich pockets along these structures, separated by low grade or barren sections. The hypogene paragenetic sequence of the largest veins is tourmaline-actinolite-quartz-magnetite-hematite-pyrite-chalcopyrite-bornite-calcite (Ferraris et al., 1973, Boric et al., 1990). Strong silicification, argillic alteration and chloritisation occur within these copper bearing veins, and extends some metres into their intrusive wall rocks. The hypogene minerals fill fractures and openings, either as irregular and discontinuous veinlets or massive pockets with banded textures, or as fine dissemination. The structure of the Cu-bearing veins is regular and continuous within the intrusive bodies, but quite irregular and discontinuous when the veins extend into the intruded volcanic rocks, as at the Naguayán - Desesperado district (Boric et al., 1990), although a transition from these magnetite and copper bearing veins to strata-bound Cu-(Ag) mineralisation has not been observed. Cu-bearing veins from the Tocopilla and Guanillos Districts contain hyper-saline fluid inclusions (48-68 wt.% NaCl eq.) with homogenisation temperatures from 320° to 540°C, but mostly between 380°-420°C (Trista, 2001). The characteristics of this type of magnetite and copper-bearing veins indicate that they are high to moderate temperature mesothermal deposits (Ruiz et al., 1965, Ferraris et al., 1973, Boric et al., 1990, Vivallo and Henriquez, 1998, Trista, 2001). They are genetically related to the emplacement and cooling of Upper Jurassic Batholiths (K-Ar and ^{40}Ar-^{39}Ar ages ranging from 167 to 140 Ma, Maksaev, 1990).

The apparent time and space relationships between the Jurassic volcanic-hosted Cu-(Ag) strata-bound deposits and the mesothermal Cu-bearing veins hosted by plutonic rocks, plus geochemical and isotopic comparisons led Vivallo and Henriquez (1998) to postulate that the batholith-hosted, iron-rich, Cu-bearing veins were the deep feeder structures of the hydrothermal fluids that originated the strata-bound deposits within the Jurassic volcanic strata. Although this hypothesis cannot be discarded, these two types of deposits were formed in rather different pressure and temperature conditions, their timing of formation is poorly constrained, and there are no direct field relationships between them (Trista, 2001).

Most of the strata-bound Cu-(Ag) deposits of the Jurassic belt have an upper oxidised zone that extends to a maximum depth of 250 m. The degree of supergene oxidation is variable; some deposits comprise almost exclusively oxidised copper ores (eg. Mantos de la Luna, Juarez), whereas others are completely composed of hypogene sulphides (eg. Buena Esperanza). When present, the boundary between the supergene and hypogene ores is gradual, so that some deposits include a zone with a mixture of copper sulphides and oxidised minerals (eg. Susana, Santo Domingo). The oxidised ores include mainly atacamite, minor chrysocolla, malachite, and rare cuprite and native copper; the oxidised rocks show profuse goethite and hematite stains on fracture surfaces. Copper grades are similar in the oxidised upper section and the underlying hypogene sulphide zone of the deposits, so that no significant Cu transport occurred during the supergene oxidation (largely *in situ* oxidation). Only the largest deposits such as Mantos Blancos and Susana have local enriched pockets with supergene chalcocite group minerals and covellite (Astudillo, 1984, Chavez, 1985, Wolf et al., 1990).

The poor development of secondary enrichment within the Jurassic strata-bound Cu-(Ag) deposits could be explained by the insufficiency of hypogene pyrite to release supergene acid solutions under oxidation, and the profuse occurrence of calcite gangue that may have readily neutralised any supergene acid solutions precluding the leaching of metallic cations from the oxidised zone.

Lower Cretaceous Strata-bound Cu-(Ag) Deposits

Lower Cretaceous volcanic rocks with marine sedimentary intercalations form a N-S-trending belt in north central Chile that is located about 30 to 60 km east from the Pacific coast. Significant volcanic-hosted strata-bound Cu-(Ag) deposits occur within this belt, particularly in central Chile (eg. El Soldado, Lo Aguirre) (Fig. 4). In addition, there is a distinct group of strata-bound Cu-(Ag) deposits within

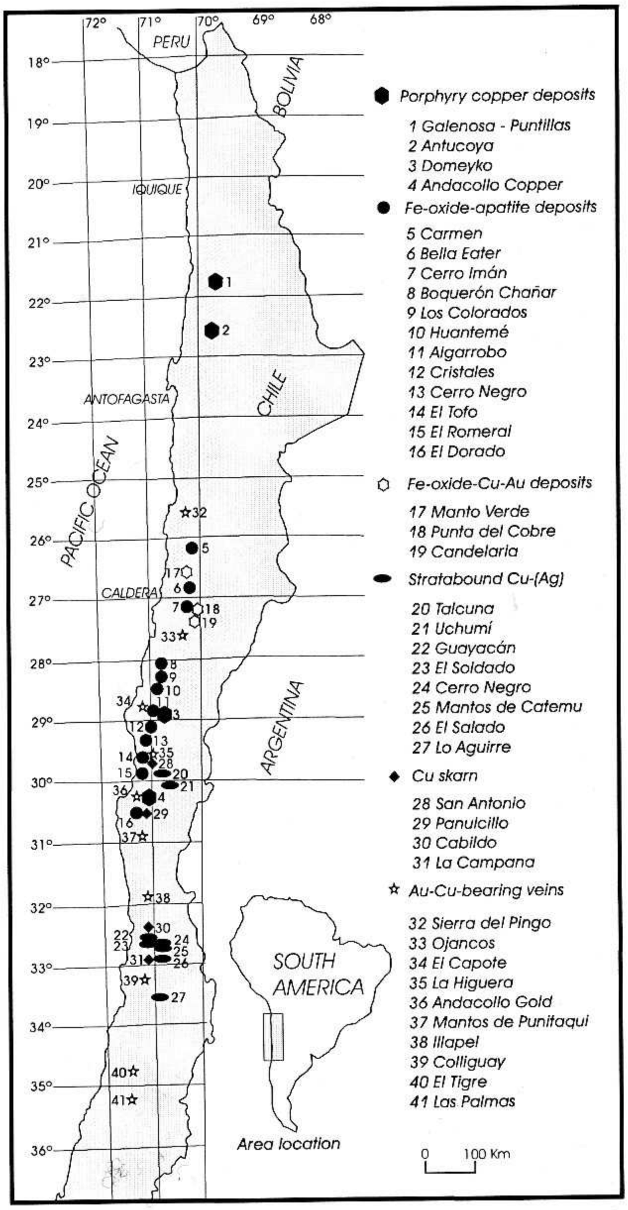


Figure 4: Lower Cretaceous metallogenic belt in central-northern Chile showing the variety of deposit types that occur along this belt besides the Cu- (Ag) strata-bound deposit.

volcano-sedimentary strata formed in intermontane basins with red-beds and carbonaceous mudstones (eg. Cerro Negro, Talcuna, Uchumi) (Figs. 4-5). Furthermore, the belt of Lower Cretaceous volcano-sedimentary rocks and plutonic complexes hosts a diverse suite of copper, iron and gold deposits including: Fe-oxide Cu-Au deposits (Candelaria, Manto Verde, Manto Ruso, Farola, Generosa), porphyry copper deposits and prospects (Andacollo, Antucoya, Puntilla, Domeyko), Cu skarns (Panulcillo, Cabildo and La Campana districts), magnetite-apatite deposits of the "Chilean Iron Belt" (eg. Los Colorados, El Algarrobo, and Romeral, Espinoza, 1990) (Fig. 3), and mesothermal Au-Cu-bearing veins (Andacollo Gold, Capote, Mantos de Punitaqui, and Colliguay districts) (Fig. 4). The most significant deposits of the Lower Cretaceous belt are: strata-bound Cu-(Ag), Fe-oxide Cu-Au, magnetite-apatite, porphyry copper, and Cu skarn deposits. According to available geochronological data all these deposits were formed in the uppermost Early Cretaceous.

The largest deposit of this group of strata-bound Cu-(Ag) deposits is El Soldado, that is located about 120 km north

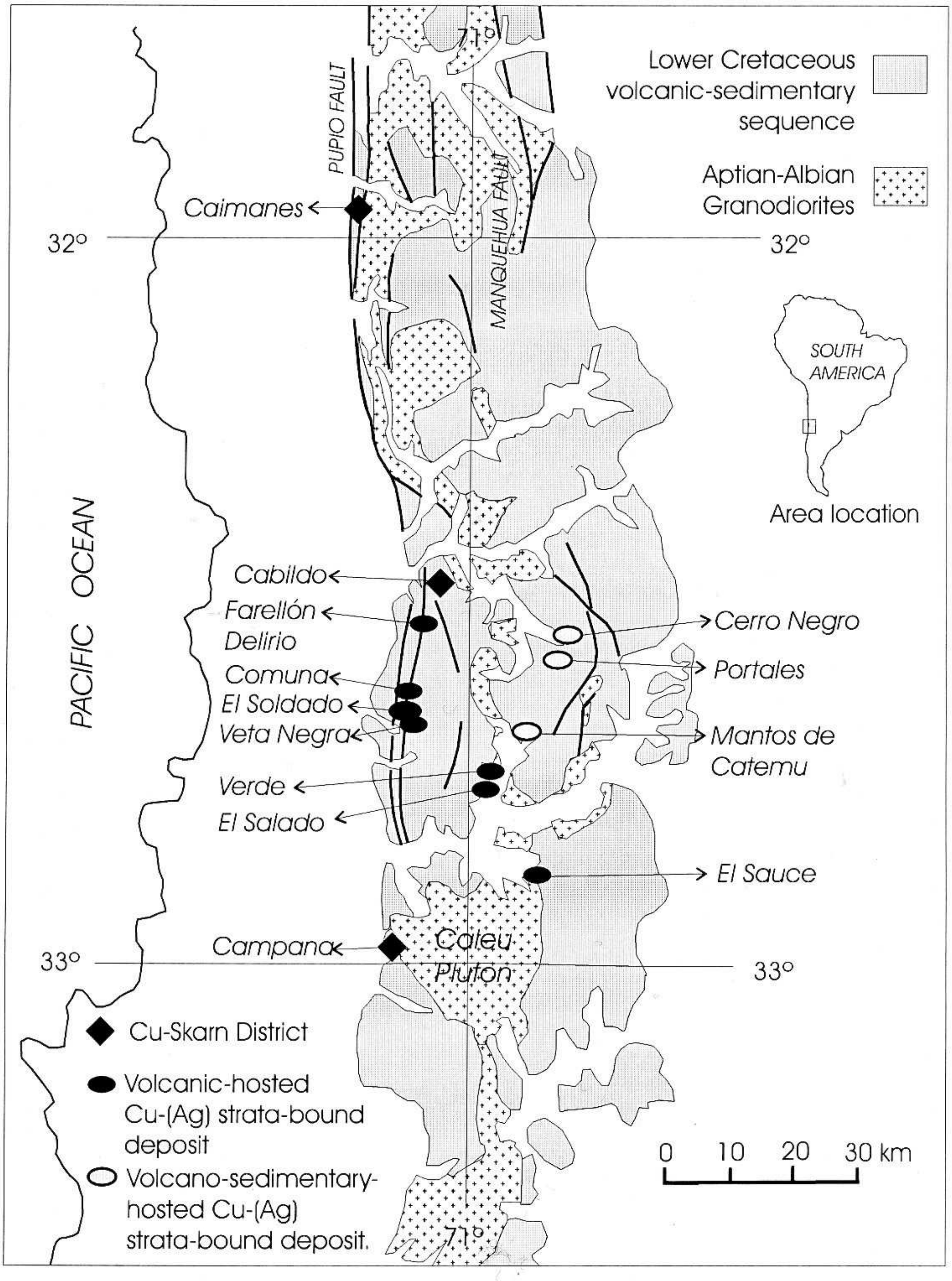


Figure 5: Volcanic-hosted and volcano-sedimentary-hosted Cu- (Ag) strata-bound deposits in the Coastal Cordillera of central Chile between 32° and 33°S. The belt of Lower Cretaceous volcanic sequence with sedimentary intercalations and Aptian - Albian granodioritic plutons emplaced within this unit are shown. Geology simplified after Rivano et al., 1993 and Rivano and Sepulveda, 1991.

of Santiago, in the Coastal Cordillera of central Chile (Fig. 5). The deposit is hosted by a sequence of felsic and basaltic units (Boric, et al., this volume) dipping ~30° to the east, that constitutes the Upper Member of the Lower Cretaceous Lo Prado Formation (Rivano et al., 1993). El Soldado consists of numerous isolated orebodies with intervening barren zones, distributed in about a dozen individual orebody clusters or blocks. These blocks are spatially distributed within a volume of about 2 km in length by 1 km wide and 600 m in vertical extent (Wilson and Zentilli, 1999). Within the blocks, individual subvertical orebodies are extremely variable in size, from very small to 450 m long, 150 m wide, and 450 m in vertical extent (Boric, 1997). Although described as strata-bound at a regional scale, in detail the El Soldado orebodies are distinctly discordant, displaying a strong structural control (Ruge, 1985). The orebodies are preferentially developed within a generally N-S to NNW regional fracture system, especially where N-S, E-W, and NW faults intersect. The overall fault pattern at El Soldado is consistent with transtensional zones along a longitudinal sinistral fault system. Away from these zones of structural permeability, orebodies can be best described as veins (Boric, 1997). Lithologic control is exerted by the relatively more brittle felsic flows (trachyte-rhyolite) and their feeders, which are more richly mineralised in comparison of more mafic (andesite-basalt) flows and tuffs (Martin, 1981, Ruge, 1985). Late andesitic-basaltic dykes are generally barren (Boric, 1997). Hypogene ore minerals are chalcopyrite, bornite, and chalcocite that occur as dissemination and veinlets, largely filling primary and secondary porosity of the volcanic host rocks. According to Boric (1997) many individual orebodies in a block show a mineralogical zoning: a core of chalcocite-hematite or chalcocite-bornite-hematite is followed outward by approximately concentric zones of bornite-chalcopyrite, chalcopyrite, and pyrite in the most external zone. The deeper roots of the orebodies contain relatively more pyrite than their upward terminations. Although oxidised copper zones exist near the surface and mixed ores were exploited, supergene enrichment is not significant. Common waste or gangue minerals are pyrite, hematite, magnetite, calcite, chlorite, albite, microcline, bitumen, and minor amounts of sphalerite, galena, and arsenopyrite. The copper grade is extremely variable (Klohn et al., 1990). Lateral limits of the orebodies are characterised by abrupt changes of Cu grade from a nucleus at about 2% Cu to marginal zones at 1.2-0.5% Cu within a few metres (Ruge, 1985, Klohn et al., 1990). The wall rock between the orebodies is generally barren (<0.15% Cu, Klohn et al., 1990). Hydrothermal alteration consists of abundant calcite, chlorite, albite, microcline, epidote, opaline silica, titanite, and rutile-anatase, and some sericite and clay minerals, with primary rock textures largely being preserved (Holgrem, 1987, Boric, 1997).

Highly saline (ca. 30-40 wt.% NaCl equivalent) three-phase fluid inclusions in quartz related to sulphide mineralisation at El Soldado yielded minimum homogenisation temperatures ranging between 200°-257°C (without pressure correction), with no evidences of boiling being observed (Holgrem, 1987). The same study found that fluid inclusions within late barren calcite at El Soldado are also highly saline but with lower homogenisation temperatures from 82° to 104°C. On the other hand, three-phase fluid inclusions in quartz from quartz-bornite amygdules at El Salado yielded homogenisation temperatures from 250° to 430°C, whereas the occurrence of some vapour-rich inclusions suggests boiling (Nisterenko et al., 1973). El Salado is a minor volcanic-hosted stratiform Cu-(Ag) deposit located 18 km SE from El Soldado (Fig. 5), and close to the western border of a granodioritic intrusion with a biotite K-Ar ages of 118 ± 3 Ma (Rivano et al., 1993).

Many radiometric dates (K-Ar, $^{40}Ar/^{39}Ar$, Rb/Sr) reported from El Soldado range from 131 to 99 Ma supporting the Early Cretaceous age for this copper deposit (Munizaga et al., 1988, Boric and Munizaga, 1994, Boric, 1997). The oldest radiometric ages at El Soldado are from 131 to 118 Ma and are in agreement with the stratigraphic Neocomian (lower Early Cretaceous) age of the host volcanics. A group of younger ages from 113 to 96 Ma are considered to represent the alteration/mineralisation event; this group of radiometric ages includes dates of veinlets of K-feldspar and albite associated with copper sulphides that are mostly concentrated between 105 and 101 Ma (Boric, 1997). According to this radiometric data mineralisation at El Soldado temporally coincides with the K-Ar age range of Cretaceous batholiths that are emplaced within the Lower Cretaceous volcano-sedimentary sequence and outcrop some 12.5 km NE and 18 km SE of El Soldado (118-96 Ma; Rivano et al., 1993). This is also true for the 117-94 Ma ^{40}Ar-^{39}Ar age range of the Caleu Pluton that crosscuts the Lower Cretaceous sequence some 25 km south of El Soldado (Parada and Larrondo, 1999, Parada et al., 2001) (Fig. 5). Cu-bearing skarn deposits occur in metamorphosed limestone intercalations of the Lower Cretaceous sequence within the contact aureole of Aptian-Albian (upper Early Cretaceous) intrusions, whereas volcanic-hosted Cu-(Ag) strata-bound deposits are present farther from the same plutons (eg. the Cabildo and La Campana districts; Carter, 1961, Tidy, 1970, Moya, 1980). Therefore, Cu-(Ag) mineralisation at El Soldado coincides temporally with an Aptian-Albian regional plutonic event characterised by the emplacement of large batholithic masses within the previously deposited Lower Cretaceous volcanic-sedimentary sequence, but was also coeval with Cu skarn mineralisation associated with the contact zones of the Aptian - Albian plutons.

Recently, Wilson et al. (submitted) have dated 10 samples of K-feldspar (adularia) from El Soldado by the stepwise-heating ^{40}Ar-^{39}Ar method. For hydrothermally precipitated K-feldspar in close association with copper sulphides, the ages range from 100.5±1.5 Ma to 106±1.1 Ma, with a mean of 103±1.3 Ma, which these authors interpret to be the main age of copper mineralisation at El Soldado. K-feldspar unrelated (or with dubious relationship) to ore, yields ages between 109.4±1.1 Ma and 112±2 Ma (mean = 110±1.4 Ma). They interpret these older ages to represent redistribution of alkalis in response to low-grade metamorphism of the host sequence. The ca. 110 Ma welldefined argon release spectra are variably reset by the ca. 100 Ma hydrothermal mineralisation episode. High levels of atmospheric Ar were detected in all K-feldspar samples. They are tentatively attributed to connate basinal and metamorphic fluids that were heavily contaminated by meteoric waters. Fission track dating of apatite in the host rocks yields an age of ca. 90 Ma, indicating fast cooling of the system post-mineralisation; time-temperature modelling of fission track-length data are compatible with initial fast exhumation, followed by slow exhumation and cooling to surface temperatures (Wilson et al, submitted).

The timing of the copper mineralisation of El Soldado coincides with the 100-96 Ma ^{40}Ar-^{39}Ar age range of secondary K-feldspar and sericite from volcanic rocks of the Lower Cretaceous sequence some 10 km south of El Soldado (Fuentes et al., 2001, Morata et al., 2001). The occurrence of secondary albite, K-feldspar, prehnite-pumpellyite, laumontite, epidote, calcite and minor sericite is widespread within the Lower Cretaceous sequence in central Chile, with the primary textures of the rocks being preserved (eg. Levi et al., 1989). These secondary minerals are traditionally interpreted as products of a low-grade regional metamorphism of the Mesozoic sequence (Levi et al. *op. cit.*, Fuentes et al., 2001, Morata et al., 2001). The geochronological data now available show that this regional metamorphic event may in part coincide temporally with the emplacement of large batholithic masses within the Lower Cretaceous volcano-sedimentary pile and also with the Cu-(Ag) mineralisation at El Soldado and Cu-bearing skarns, although adularia may have also crystallised earlier during the burial history of the basin according to the data of Wilson et al. (submitted).

At the Lo Aguirre deposit, on the western outskirts of Santiago city, Cu-bearing ores occur within andesitic-basaltic lavas and breccias of the Barremian-Aptian Veta Negra Formation forming a main irregular orebody 600 m long, 200 m wide, and 150 m in vertical extent. Lo Aguirre and two minor satellite orebodies (San Antonio and Carreton) are peripheral to a barren dioritic stock. Hypogene mineralisation comprises disseminated chalcocite and bornite with successive outer zones of bornite-chalcopyrite, chalcopyrite-pyrite and pyrite. The copper sulphides concentrate within the more porous levels of the host volcanic rocks and were partly oxidised by supergene activity. Hydrothermal alteration minerals are calcite, quartz, hematite, chlorite, epidote, and clay minerals. At Lo Aguirre a whole rock K-Ar age of 110±4 Ma was obtained for an andesite sample and a Rb-Sr isochron of 113±3 Ma, which were interpreted to represent the probable age of hydrothermal alteration related to mineralisation in this deposit (Munizaga et al., 1988). However, a later ^{40}Ar-^{39}Ar dating of albite from mineralised rocks yielded a date of 102±5 Ma that places the mineralisation at Lo Aguirre as temporally concurrent with that at El Soldado (Munizaga, verbal communication).

Another group of relatively small strata-bound Cu-(Ag) deposits in central Chile is hosted by Lower Cretaceous sedimentary or volcano-clastic rocks (Cerro Negro, Uchumi, Talcuna, Camus, 1990). These are roughly tabular conformable orebodies ("mantos") restricted to a specific stratum, being interconnected by poorly mineralised sections. Copper mineralisation is concentrated in the upper few metres of a specific sedimentary or pyroclastic level that normally underlies either a massive volcanic or mudstone impervious stratum. Typical examples occur at Talcuna (Boric, 1985), and Cerro Negro (Elgueta et al., 1990). At Talcuna, stratiform Cu-(Ag) mineralisation mostly occurs along a 10 to 15 m thick bituminous lapilli tuff band, with economic-grade ore-shoots extending for only some tenths of metres from the intersection between the lapilli tuff level and subvertical NNW-trending veins. These veins have open-space filling textures, evidence of hydraulic fracturing and have been interpreted as feeders of hydrothermal fluids that mineralised the bituminous lapilli tuff band beneath an impervious manganese-rich level of tuffaceous sandstones and mudstones (Boric, 1985, Moreno, 2001). Present exploitation within the Talcuna district concentrates on NW-elongate ore shoots that developed along the intersection of the above mentioned lapilli tuff level with veins; rich pockets coincide with the occurrence of abundant bitumen (Moreno, 2001). Coexisting liquid-rich and vapour-rich fluid inclusions in calcite (suggesting trapping of a boiling hydrothermal fluid) associated with copper sulphides at the Talcuna orebodies yielded homogenisation temperatures from 70° to 170°C and salinities from 5 to 27 wt.% NaCl equivalent (Oyarzun et al., 1998). These authors interpreted the wide range of salinity variation as the result of complex interaction between boiling of the hydrothermal fluid and mixing with non saline waters during mineralisation at Talcuna. In addition, fluid inclusions in calcite from cavity filling in andesites in the area of the deposits yielded homogenisation temperatures in the range of 120° - 205°C and salinities from 11 to 19 wt.% NaCl equivalent. These were taken to represent an earlier stage of mineralisation at Talcuna (Oyarzun et al., 1998).

The strata-bound deposits of this group have been formed within the Lower Cretaceous sequences deposited in shallow marine to intermontane lacustrine sedimentary basins with coeval volcanic deposits (Camus, 1990). Hypogene minerals are bornite, chalcopyrite, chalcocite, pyrite and minor sphalerite and galena. Gangue minerals are calcite, chlorite, hematite, epidote, zeolites, and local magnetite. In addition, Zentilli et al. (1997) and Wilson and Zentilli (1999) documented that bitumen commonly occurs within these strata-bound Cu- (Ag) deposits hosted by Lower Cretaceous volcano-sedimentary strata (Uchumi, Talcuna, Cerro Negro) suggesting that copper mineralisation in these deposits was deposited within degraded petroleum reservoirs.

Isotopic Constraints

The volcanic-hosted strata-bound copper deposits (Upper Jurassic and Lower Cretaceous) are characterised by δ^{34}S values ranging from -10 to +10‰ suggesting magmatic derivation of sulphur, whereas the Lower Cretaceous strata-bound deposits within sedimentary-volcanic strata contain isotopically lighter sulphur(δ^{34}S -10 to -40‰) suggestive of reduction by organic matter or biogenic fractionation (Munizaga et al., 1994, 1995). However, barite present in the upper levels of the mineralised bodies at Cerro Negro with $\delta^{34}S$ +10 suggests an ultimate magmatic source for the sulphur of these sulphates (Munizaga, et al., 1994). Isotopic data for gangue calcite ($\delta^{13}C$ = -10 to 13‰; $\delta^{18}O$ = +12 to +18‰; initial $^{87}Sr/^{86}Sr$ = 0.7040 to 0.7056) preclude a major involvement of seawater in most Cu-(Ag) strata-bound deposits as suggested by Chavez (1985). At Mantos Blancos the initial $^{87}Sr/^{86}Sr$ ratio of 0.7056 from ore-bearing calcite and from altered rocks contrasts with the lower initial $^{87}Sr/^{86}Sr$ ratios (0.7031-0.7041) of the Jurassic volcanics and plutonic rocks. According to Tassinari et al. (1993) these data imply that the hydrothermal fluids that formed Mantos Blancos were not entirely magmatic in nature, nor seawater, but probably they were a mixture of fluids from different origin or fluids that partially equilibrated isotopically with the host rocks. At the El Soldado and Lo Aguirre deposits initial $^{87}Sr/^{86}Sr$ ratios of 0.7047 and 0.7048 have been obtained respectively, which are higher than the average value of 0.7040 obtained for Lower Cretaceous un-mineralised volcanic rocks (Munizaga et al., 1988). These ratio values are compatible with a predominant magmatic derivation of the hydrothermal fluids at this deposits with minor crustal contribution of Sr, which are not compatible with marine or metamorphic waters that would have had higher initial $^{87}Sr/^{86}Sr$ ratios (Munizaga et al., 1988).

Initial $^{187}Os/^{188}Os$ ratios from sulphides of Mantos Blancos, El Soldado, Cerro Negro and Talcuna range from 0.5 to 4. These values are more radiogenic relative to the range of 0.2 to 0.5 obtained for major porphyry copper deposits (Chuquicamata, El Teniente) suggesting the involvement of crustal Os in the strata-bound deposits (Munizaga et al., 2000). Pb isotopic data for the Lower Cretaceous volcanic and sedimentary-hosted strata-bound Cu-(Ag) deposits of central Chile ($^{206}Pb/^{204}Pb$ = 18.316-18.574, $^{207}Pb/^{204}Pb$ = 15.557-15.605, $^{208}Pb/^{204}Pb$ = 38.115-38.456; Tosdal and Munizaga, 1996, and in press) form a field that extends along the average crustal growth curve of Stacey and Kramers (1975) on the $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram, although data for sedimentary-hosted deposits plot slightly beneath the curve on the less radiogenic side (Fig. 6a). On the $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram the strata-bound, Pb isotopic compositions for strata-bound Cu-(Ag) deposits lie below the average crustal growth curve (Fig. 6b). The Pb isotopic compositions for strata-bound deposits overlap the limited Pb isotopic data available for Cretaceous sedimentary and igneous rocks (Fig. 6) consistent with Pb derivation from the Lower Cretaceous volcanic and sedimentary rocks that host the strata-bound Cu-(Ag) mineralisation. This suggests that the lead at these deposits was derived from the host crustal rocks.

Discussion

The origin of the strata-bound Cu-(Ag) deposits hosted by the Jurassic volcanics of Northern Chile has long been a matter of controversy. Stratiform orebodies were first regarded as syngenetic volcanic exhalative (Ruiz et al., 1965, 1971, Stoll, 1965). However, their epigenetic origin is now widely demonstrated, by the subsequent discovery of unconformable orebodies, the spatial relationship of copper mineralisation around Upper Jurassic intrusive stocks and sills, and significant hydrothermal alteration (albite, chlorite, quartz, sericite, calcite, sphene, scapolite, anatase) associated with copper-rich sulphide disseminations (chalcocite, bornite) within the volcanic host rocks (Palacios and Definis, 1981, 1981b, Dreyer and Soto, 1985, Orquera, 1987, Espinoza et al., 1996). The hydrothermal derivation of these volcanic-hosted copper deposits, related to subvolcanic intrusive bodies is the most accepted hypothesis (Espinoza, 1981, 1982, Chavez, 1985, Palacios, 1990, Espinoza et al., 1996), although hydrothermal derivation from batholiths has also been proposed by Vivallo and Henriquez (1998), while some authors have alternatively suggested a diagenetic-metamorphic origin (Sato, 1984, Sillitoe, 1990).

Although the overall geochronological data for the Jurassic strata-bound Cu-(Ag) deposits is rather poor, it indicates that hydrothermal copper and subordinate silver mineralisation was introduced within the volcanic sequence after its accumulation and at a time coincident with a regional plutonic event characterised by the emplacement of large batholithic masses within the previously deposited Jurassic volcanic pile. The spatial and possibly temporal relationship of the strata-bound deposits with stocks and dykes appears to be suggestive of a direct genetic connection of the Cu-(Ag) mineralisation with subvolcanic intrusive bodies and this view has been widely postulated by different authors (Espinoza, 1981, 1982, Chavez, 1985, Palacios, 1990, Wolf et al., 1990, Espinoza et al., 1996). However, most of the subvolcanic intrusions are barren or poorly mineralised, a fact that could be taken to indicate that the mentioned relationship is accidental rather than genetic. In fact, both the subvolcanic intrusive bodies and hydrothermal fluid flow that deposited copper sulphides may have followed similar paths along zones of structural weakness within the volcanic pile. Structural control is apparent for some strata-bound deposits, but also for adjacent minor intrusions (eg. the Buena Vista and Nucleo X deposits of the Michilla district, Trista, 2001).

The origin of the Lower Cretaceous strata-bound Cu-(Ag) deposits has also long been a matter of controversy. Models range from volcanogenic syngenetic (Ruiz and Peebles, 1988, Camus, 1980), through hypotheses that call for fluids liberated during crustal thinning and low-grade metamorphism of the volcanic and volcano-sedimentary piles (Sato, 1984, Westra, 1988, Sillitoe, 1990), or fluids derived from granitoid plutons (Holgrem, 1987). An epigenetic hydrothermal origin is substantiated by new data of the largest deposit of this type (Holgrem, 1987, Boric, 1997, Wilson and Zentilli, 1999). In addition, Wilson and Zentilli (1999) suggested that organic matter was an essential component in the formation of El Soldado and other Lower Cretaceous strata-bound deposit. They recognise two main stages in the evolution of the El Soldado copper deposit. The first occurred at low temperatures (<100°C) when petroleum was introduced into the Lower

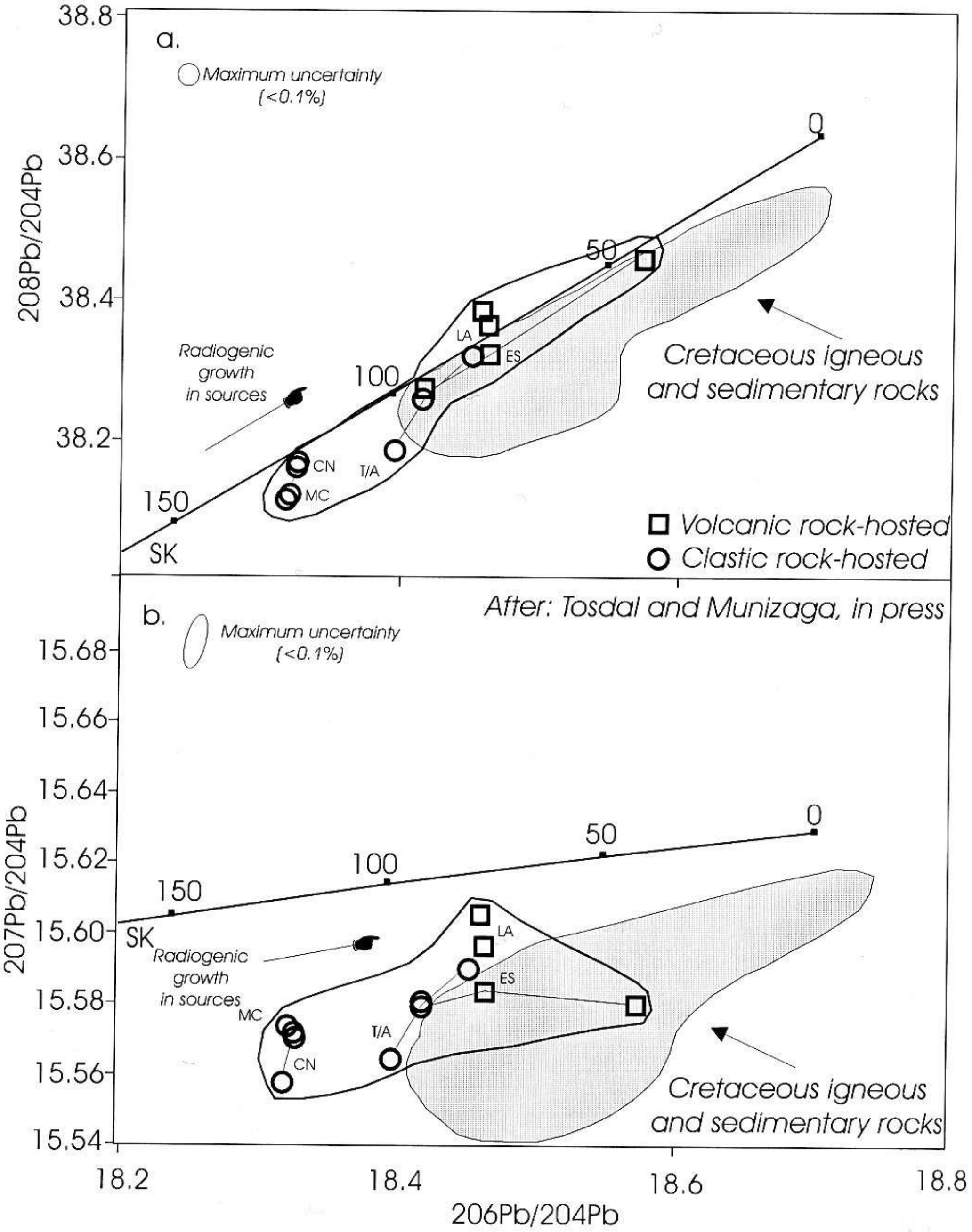


Figure 6: Lead isotopic evolution diagrams (extracted from Tosdal & Munizaga, 1996, in press)

(a) $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ and (b) $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ comparing sulphide Pb isotopic compositions of strata-bound Cu- (Ag) deposits with the field of major Cretaceous volcanic and plutonic rocks units and sandstone from the Talcuna-Corral Quemado basin. Tie lines link Pb isotopic composition for sulphide minerals from the same deposit. Time-integrated growth of Pb isotopic compositions of potential sources are, at the scale of the diagrams, subparallel to the average crustal growth curve, as indicated by the arrow. SK, average crustal growth curve of Stacey and Kramers (1975). Volcano-hosted Cu-(Ag) strata-bound deposit: ES, El Soldado; LA, Lo Aguirre. Volcano-sedimentary-hosted Cu- (Ag) strata-bound deposit: CN, Cerro Negro; MC, Mantos de Catemu; T/A, Talcuna and Arqueros.

Cretaceous rocks of the upper Lo Prado Formation and diagenetic (framboidal) pyrite formed during degradation of the petroleum, which later solidified as bitumen. The second stage was hydrothermal, with temperatures of 200° to >300°C when copper sulphides precipitated due to reduction of mineralising fluids by the organic matter in the host rocks and replacement of the pre-existing pyrite by copper sulphides; bitumen also acted as activated carbon, destabilising chloride complexes responsible for copper transport (Wilson and Zentilli, 1999). According to these authors the presence of bitumen within other strata-bound Cu-(Ag) deposits hosted by Lower Cretaceous strata (eg. Uchumi, Talcuna, Cerro Negro) suggests that degraded petroleum reservoirs were suitable sites for mineralisation by Cu-bearing solutions of different origins in north-central Chile. In fact the location of mineralised intervals within permeable clastic units that underlie impervious strata suggests that the sediment-hosted strata-bound deposits were formed by the invasion of hydrothermal fluids into older oil traps within particular stratigraphic levels (eg. Zentilli et al., 1994; 1997). These levels probably represented zones of fluid over-pressure (above hydrostatic) within the Lower Cretaceous sequence. Furthermore, the regional occurrence of bitumen within Chilean Lower Cretaceous volcanic rocks associated with minor copper deposits has also been described in the Copiapó Region of northern Chile (Cisternas et al., 1999; Hermosilla et al., 2001).

The radiometric data and metallogenic setting of El Soldado strongly suggest that this deposit is a distal copper mineralisation genetically related to hydrothermal fluid flow triggered by batholith emplacement and is concurrent in age with Cu skarn formation within contact aureoles of the same intrusions. Mineralising fluids could have been a mixture of magmatic, connate, and meteoric waters thermally mobilised by the large Aptian - Albian igneous masses that were emplaced within the Lower Cretaceous sequence along sinistral transtensional faults.

The early occurrence of bitumen at El Soldado and other Lower Cretaceous strata-bound deposits, combined with the radiometric data available, imply that diagenetic processes released hydrocarbons from the intercalated Jurassic-Lower Cretaceous marine sediments. Petroleum was accumulated within lithologic-structural reservoirs within the stratigraphic sequence and transformed into bitumen due to the relatively high geothermal gradient within the extensional and subsiding arc developed over attenuated crust. Later hydrothermal fluids, probably mobilised by Aptian - Albian plutons emplaced within the Lower Cretaceous volcanic-sedimentary sequence, appear to have utilised similar flow paths to those followed by the early hydrocarbons, so that Cu-(Ag) were deposited by reduction reactions with the organic matter and/or replacement of pre-existing diagenetic pyrite. Although the occurrence of organic matter has not been described within the Jurassic volcanic-hosted strata-bound Cu-(Ag) deposits of northern Chile, they also appear to be distal copper precipitation genetically related to igneous masses that were emplaced within the thick volcanic pile during the Late Jurassic. Their origin was probably similar, but cooling or dilution of the hydrothermal solutions could have controlled metal precipitation.

If subduction was essentially continuous since the beginning of the Jurassic, why were the major strata-bound Cu-(Ag) deposits restricted to relatively brief periods of geologic history? Many of the largest deposits show structural control, and in most cases the structural permeability seems to have facilitated access to primary permeability within the host formations. One common denominator to several of these Cu-(Ag) deposits is the presence within the metallogenic provinces of large scale, orogen-parallel strike-slip faults (eg. Fig. 2). These faults accommodated a sinistral shear component produced by oblique subduction between the Aluk (Phoenix) and South American plates during the Early Cretaceous (Naranjo et al., 1984; Herve, 1987; Brown et al., 1993; Reijs and McClay, 1998), although ^{40}Ar/^{39}Ar and Rb-Sr data from ductile shear zones indicate that the strike-slip fault system had been active since the Jurassic (Scheuber at al., 1995). Transtensional and tensional regimes within these fault systems have controlled both basin development, and access to magmas for volcanism and plutons as postulated by Dallmeyer et al. (1996). In addition, they led to large-scale tilting and inversion of basins, and probably modified basinal hydraulic systems.

In a structural analysis of the El Soldado deposit, Chavez (1988) concluded that the mineralised system developed simultaneously with, and represents the effects of, a short-lived sinistral brittle shear system; a similar structural control is apparent in the richest ore shoots of the Cu-skarn deposits in the Cabildo district some 20 km farther north (personal observation). Considering that the K-feldspar present in veins at El Soldado is ca. 103 Ma (Wilson et al., submitted), it can be suggested that a sudden influx of hydrothermal fluids coincided with regional sinistral shear congruent with the Atacama Fault Zone further north (eg. Maksaev 1990). Mesozoic plate configuration reconstructions are hampered by to the lack of any oceanic crust older than around 50 Ma off-shore from South America (Müller et al, 1997). Therefore the only reconstructions of Mesozoic plate configurations in the Pacific realm are based on investigations of remnants of Jurassic and Cretaceous oceanic crust in the western Pacific (Larson and Pitman, 1972, Zonenshayn et al., 1984). These reconstructions indicate that a spreading centre existed off South America and during this time the Aluk (Phoenix) plate converged with the South American Plate at a very oblique angle. In contrast, during the Late Cretaceous, the convergence approached orthogonal. This change correlated with the rapid separation of Africa and South America, with the latter overriding the oceanic plate to the west (Ramos and Aleman, 2000). We contend that it is at this time that inversion of the Cretaceous Basin occurred. This interpretation is compatible with apatite fission track dates of ca. 90 Ma at El Soldado, and 82-95 Ma at the Caleu Pluton revealing rapid denudation during the Late Cretaceous (Parada and Larrondo, 1999, Gana and Zentilli, 2000).

Pop et al. (2000) concluded that in the Punta del Cobre-Candelaria district in the Copiapo region, Fe-oxide-Cu mineralisation occurred during a brief interval between 111 and 103 Ma. Structurally, this region represents a brittle sinistral shear system where the large Fe-oxide-Cu-Au Candelaria and other lesser deposits of this type occur. At Candelaria mineralisation and shearing deformation took place at ca. 111 Ma according to ^{40}Ar-^{39}Ar data (Ullrich and Clark, 1999; Arevalo et al., 2000). In addition, a sinistral transtensional fault subsidiary of the Atacama Fault Zone hosts the breccias with Fe-oxide-Cu-Au matrix at the Manto Verde deposit. Its mineralisation is thought to be genetically related to intrusives that have been dated by K-Ar at 117±3 and 121±3 Ma (Vila et al., 1996).

The Jurassic Cu-(Ag) stratabound deposits likewise appear to be formed within an overall sinistral transtensional regime, although Scheuber and Gonzalez (1999) established a distinct stage of strong arc-normal extension between 160-

150 Ma revealed by brittle low-angle normal faults, tilting of the Jurassic volcanics, some ductile normal faults and the intrusion of N-S elongated batholiths in the Coastal Cordillera of northern Chile. According to these authors NE-SW trending dykes intruded within the period between ~155-147 Ma indicate subsequent oblique dilation and a reversal in shear sense. At Mantos Blancos a 150 Ma Rb-Sr errorchron in altered rocks has been taken to represent the mineralisation age (Tassinari et al., 1993), whereas andesitic dykes of NE-SW orientation crosscut mineralised bodies and were dated by K-Ar at 147-149±13 Ma (Chavez, 1985). Albeit imprecise, these age data for the largest Jurassic Cu-(Ag) strata-bound deposit suggest that mineralisation took place during late stages of pluton emplacement preceding a possible short-lived shear sense reversal.

Other authors have alternatively proposed that the emplacement of Fe-P magmas (Kiruna-type) originated Lower Cretaceous magnetite-apatite bodies along the Coastal Cordillera of northern Chile, whereas Fe-oxide-Cu-Au and volcanic-hosted strata-bound Cu-(Ag) deposits were generated by different levels of emplacement and release of hydrothermal fluids from these primogenitor Fe-P magma intrusions (Vivallo and Henriquez, 1997, Gelcich, 1999). However, there is an inconclusive and classic debate over the origin of the Chilean magnetite-apatite deposits. Some authors (eg. Nyström and Henriquez, 1994, 1995) contend that many such deposits are derived by melt crystallisation, whereas others suggest that they are hydrothermal replacements (eg. Hitzman et al., 1992; Bookstrom, 1995) and possibly formed from fluids that had little or no interaction with magmas (Barton and Johnson, 1996, Rhodes and Oreskes, 1999). In fact, the balance of evidence seems to favour a metasomatic origin for most magnetite-apatite deposits, related to the contact zones of Lower Cretaceous diorite bodies (Menard, 1995, Bookstroom, 1977, 1995). On the other hand, while the association with intrusions is controversial, a metasomatic origin is also obvious for the Fe-oxide-Cu-Au deposits of the Coastal Cordillera of northern Chile, although these iron-rich deposits have undergone paragenetically late additions of copper sulphide and Au (eg. Sillitoe, 1996). The Lower Cretaceous volcanic-hosted strata-bound Cu-(Ag) deposits have an uncertain association with intrusions, but their distribution peripheral to granodioritic batholiths has been long known (eg. Carter, 1961).

The available geochronological data indicate that strata-bound Cu-(Ag) deposits, Cu-bearing skarns, magnetite-apatite bodies, and Fe-oxide-Cu-Au deposits were formed along the present Coastal Cordillera of northern Chile during the same metallogenic episode in the uppermost Early Cretaceous. This metallogenic epoch was concurrent with fault-controlled emplacement of large batholithic masses within the Lower Cretaceous volcano-sedimentary sequence. Therefore the volcanic-hosted strata-bound deposits are regarded here as distal Cu-(Ag) mineralisation formed by hydrothermal fluids mobilised during batholith emplacement at shallow crustal levels and cooling. The actual fluids could have been derived from magmatic, connate, and meteoric sources that may have contributed in different proportions, whereas copper precipitation may have taken place either by interaction with organic matter or early pyrite as documented for the Lower Cretaceous deposits or mainly by fluid cooling or mixing/dilution in the case of Upper Jurassic deposits. Despite the controversial origin of the Lower Cretaceous magnetite-apatite bodies, and Fe-oxide-Cu-Au deposits of the Chilean Coastal Cordillera these deposits are certainly proximal to coeval batholitic masses, whereas the volcanic or sedimentary-hosted, iron-poor Cu-(Ag) strata-bound deposits occur distal from coeval batholiths. The actual metal association in the different Lower Cretaceous deposits could not only be conditioned by the distance from plutons, but also may reflect the composition of the magmas involved and different degrees of hydrothermal fluid mixing.

Conclusions

Volcanic-hosted strata-bound deposits, known as "Chilean manto-type", are characteristic of a first period of Andean evolution during which subduction-related arc magmatism took place under an overall extensional tectonic setting. However, there were two distinct periods of strata-bound Cu-(Ag) mineralisation, in the Upper Jurassic and uppermost Early Cretaceous respectively, both of which were coincident with batholith emplacement within the Mesozoic volcanic pile, probably controlled by transtensional sinistral regional faults. The strata-bound Cu-(Ag) deposits are always peripheral to, but distal from, coeval batholiths.

The prevalent view that these Cu-(Ag) deposits have an inherent genetic relationship with hydrothermal fluid derivation from subvolcanic stocks and dykes is contended here as these minor intrusions are largely barren and this hypothesis does not fit well with Sr, Os, and Pb isotopic data that call for contribution of these elements from the country rocks. Instead the strata-bound Cu-(Ag) mineralisation is regarded here as the product of hydrothermal fluids of mixed origin that were mobilised during the emplacement and cooling of batholiths within the Mesozoic sequence and deposited copper either where they reacted with organic matter, pyrite, or cooled/mixed with meteoric fluids away from their heat sources. The spatial relationship with minor intrusions, dykes and sills could be accidental and related to the structural control of both subvolcanic intrusions and hydrothermal fluid circulation.

Although strata-bound Cu-(Ag) mineralisation took place during the same metallogenic event that formed the magnetite-apatite bodies, and Fe-oxide-Cu-Au deposits along the present Coastal Cordillera, the possible relationships with these other types of deposits are hampered by the inconclusive debate of the magma injection versus hydrothermal replacement models. However, the balance of evidence seems to favour a metasomatic origin of the iron-rich deposits and they are certainly more proximal to batholiths than the iron-poor Cu-(Ag) strata-bound deposits.

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