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LA CANDELARIA AND THE PUNTA DEL COBRE DISTRICT, CHILE: EARLY CRETACEOUS IRON-OXIDE Cu-Au(-Zn-Ag) MINERALISATION

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Abstract - La Candelaria is the largest of the iron oxide Cu-Au(-Zn-Ag) deposits in the Punta del Cobre belt, which also hosts the Punta del Cobre district, sensu strictu. The Punta del Cobre belt lies within an Early Cretaceous continental volcanic arc/marine back-arc basin terrane. The volcanic arc and marine carbonate back-arc sequences are intruded by Early Cretaceous granitoid plutons that form part of the Chilean Coastal Batholith. The deposits of the Punta del Cobre belt occur along the eastern margin of the batholith within (e.g., La Candelaria) or just outside the contact metamorphic aureole (e.g., the Punta del Cobre district). Andesitic volcanic and volcaniclastic host rocks are intensely altered by biotite-quartz-magnetite. This style of alteration extends much further to the east of the intrusive contact than the metamorphic mineral associations in the overlying rocks that are clearly zoned outboard. Local areas of intense calcic amphibole veining that overprints all rock types occur within the contact metamorphic aureole. Chalcopyrite mineralisation is paragenetically late, because it crosscuts and thus post-dates all of the major metamorphic and metasomatic assemblages. Deposits lying close to the batholith contact and the deeper parts of the deposit in the Punta del Cobre district are characterised by abundant magnetite accompanied by biotite-quartz alteration, which is superposed by fracture-controlled calcic amphibole, and chalcopyrite-pyrite mineralisation. Potassium feldspar-chlorite and/or biotite ± quartz plus magnetite ± hematite occur in the intermediate parts of the hydrothermal system. These assemblages grade up-section and, in places, laterally into pervasive albite-chlorite-calcite-hematite that are spatially associated with Cu-Au mineralisation in the more distal portions of the system. Tectonic structures and the intersection of these structures with the contact of massive volcanic rocks and overlying volcaniclastic rocks control mineralisation. Previously published isotopic ages of alteration minerals associated with metallic mineralisation indicate that the bulk of the iron oxide mineralisation formed between 116 and 114 Ma, and the main copper-gold mineralisation between 112 and 110 Ma. These ages suggest that hydrothermal activity occurred coeval with the emplacement of the Copiapó Batholith and regional uplift. They also imply that burial at the time of mineralisation did not exceed 2 to 3 km. Preliminary stable isotope data are compatible with an important magmatic component in the ore-forming fluids and a cooling/mixing model is presently favoured to explain the genesis of La Candelaria and the deposits in the Punta del Cobre district.

Introduction

The Candelaria deposit is located about 20 km south of Copiapó, Chile. It is the largest of the iron oxide Cu-Au deposits that constitute the Punta del Cobre belt. La Candelaria has mineable reserves of 470 Mt @ 0.95 % Cu, 0.22 g/t Au, and 3.1 g/t Ag. The deposit was discovered in 1987 by the exploration branch of Compañía Minera Ojos del Salado, a fully owned subsidiary of Phelps Dodge Corporation, which operated the Santos mine in the Punta del Cobre district, *sensu strictu* (Ryan *et al.*, 1995; Fig. 1). The Punta del Cobre district is located about 3 km northeast of La Candelaria. It hosts several medium and small underground mines (e.g., Carola, Socavón Rampa, Resguardo, and Trinidad) that mine high grade ore zones (1.2-2.0 % Cu, 0.2-0.6 g/t Au, 2-8 g/t Ag). Ore production is up to about 1.5 Mt/yr. for the larger mines of the district (e.g., Socavón Rampa). In this contribution we give a description of the iron oxide-rich Cu-Au(-Zn-Ag) mineralisation and alteration of the Candelaria deposit and the Punta del Cobre district. We summarise relevant previously published data, and results of our ongoing investigations. Finally, we discuss the ore genesis and its geologic context.

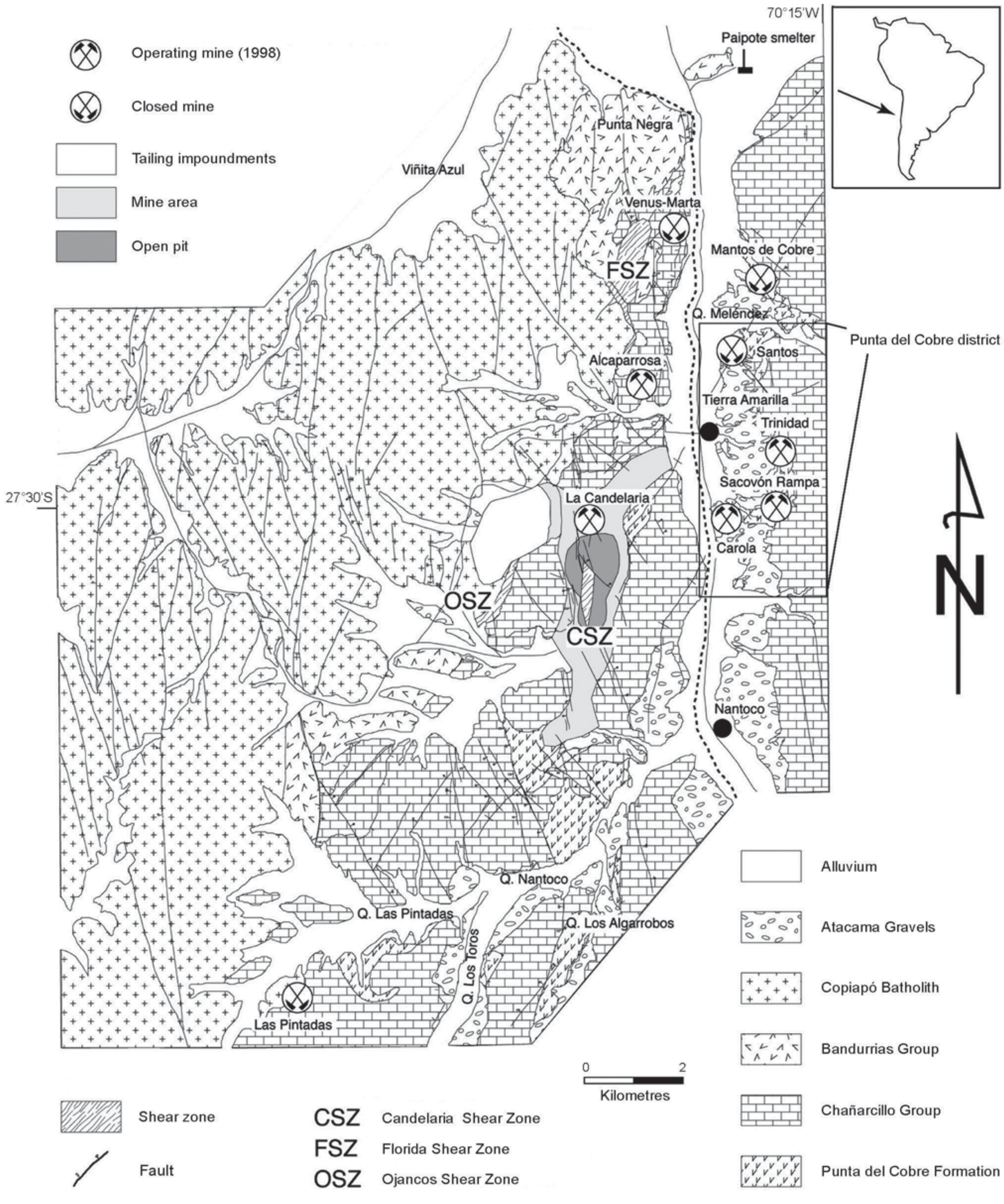


Figure 1: Geological map of the area south of Copiapó (modified from Tilling, 1976, and Arévalo, 1994, 1995).

Geological Context

The iron oxide Cu-Au(-Zn-Ag) deposits of the Punta del Cobre belt are hosted mainly by volcanic and volcaniclastic rocks that are part of an Early Cretaceous continental volcanic arc and marine back-arc basin terrane. Back-arc basin formation commenced in Berriasian times and until the late Aptian up to 2000 m of carbonate rocks of the Chañarcillo Group accumulated in this basin (Corvalán, 1974; Pérez *et al.*, 1990). In late Aptian-Albian times, the area was uplifted above sea level. Conglomerates, andesitic lavas, and pyroclastic rocks of the Cerrillos Formation (up to 4500 m) were unconformably deposited on the partly eroded rocks of the Chañarcillo Group (e.g., Segerstrom and Parker, 1959; Zentilli 1974; Jurgan, 1977). Granitoid plutons of the Copiapó Batholith (K-Ar and $^{40}Ar/^{39}Ar$ ages range from 119 to 97 Ma; e.g., Arévalo, 1994, 1995, 1999) intrude the back-arc sequence in the western part of the area (Fig. 1). The batholith caused a contact metamorphic aureole in the bedded rocks averaging 2.5 km in width (Tilling, 1962).

District Stratigraphy

The pre-late Valanginian Punta del Cobre Formation hosts the Candelaria deposit and the deposits of the Punta del Cobre district. The Punta del Cobre Formation is divided into two members, the Geraldo-Negro Member and the overlying Algarrobos Member (Marschik and Fontboté, 2001a; Fig. 2). The Geraldo-Negro Member is composed mainly of massive andesitic volcanic rocks of the "Lower Andesites" (>300 m) and altered originally dacite domes and flows of the "Meléndez Dacites" (up to 200 m) that locally overlie the latter, e.g., in the Punta del Cobre district. The Algarrobos Member (up to >800 m) comprises mainly volcaniclastic breccias, conglomerates and tuffaceous rocks with lenses of massive andesitic volcanic rocks. Ammonites indicate a Berriasian age for the upper part of the Algarrobos Member (Tilling, 1962). The Algarrobos Member passes vertically and laterally into the overlying Chañarcillo Group. The lower part of the Chañarcillo Group is commonly represented by alternating carbonate and volcaniclastic beds of the Abundancia Formation or their metamorphosed equivalents. The Abundancia Formation grades vertically and laterally into limestones of the Nantoco Formation, in places however, the Abundancia Formation is absent and the Punta del Cobre Formation is directly overlain by the Nantoco Formation, e.g., at Quebrada Los Algarrobos and Quebrada Los Toros (Figs. 1 and 2).

Three horizons within the lithological complex Algarrobos Member serve as local marker horizons in the Punta del Cobre district. These marker horizons are the "Basal Breccia" (up to 25 m), the "Trinidad Siltstone" (up to 60 m), and the "Upper Lavas" (up to 45 m). The "Basal Breccia" is a red continental polymictic volcaniclastic breccia that, in places, is conglomeratic. Locally, it contains lenses of and laterally passes into sandstone. The "Basal Breccia" overlies the "Meléndez Dacites" or the "Lower Andesites" where the "Meléndez Dacites" are absent. It has been correlated with a similar horizon on top of the "Lower Andesites" penetrated by exploration drilling conducted by E.M. Mantos Blancos at Quebrada Los Algarrobos, south of La Candelaria. The "Trinidad Siltstone" overlies the "Basal Breccia" in the Punta del Cobre district and in turn is overlain by the "Upper Lavas". It correlates with the tuffaceous rocks ("Tuffs or Volcaniclastic Sediments" of Ryan *et al.*, 1995) that underlie rocks equivalent to the "Upper Lavas" at the Candelaria deposit (Fig. 2). The "Trinidad Siltstone" comprises siltstones and cherts that locally contain large clasts (up to about 1 m) of a whitish weathered, dark colored brecciated limestone. The "Upper Lavas" are a discontinuous horizon defined by lenses of altered basalt to basalt andesitic volcanic flows that laterally and vertically grade into volcanic breccias, tuffs and reworked tuffs, siltstones, cherts, and carbonate rocks.

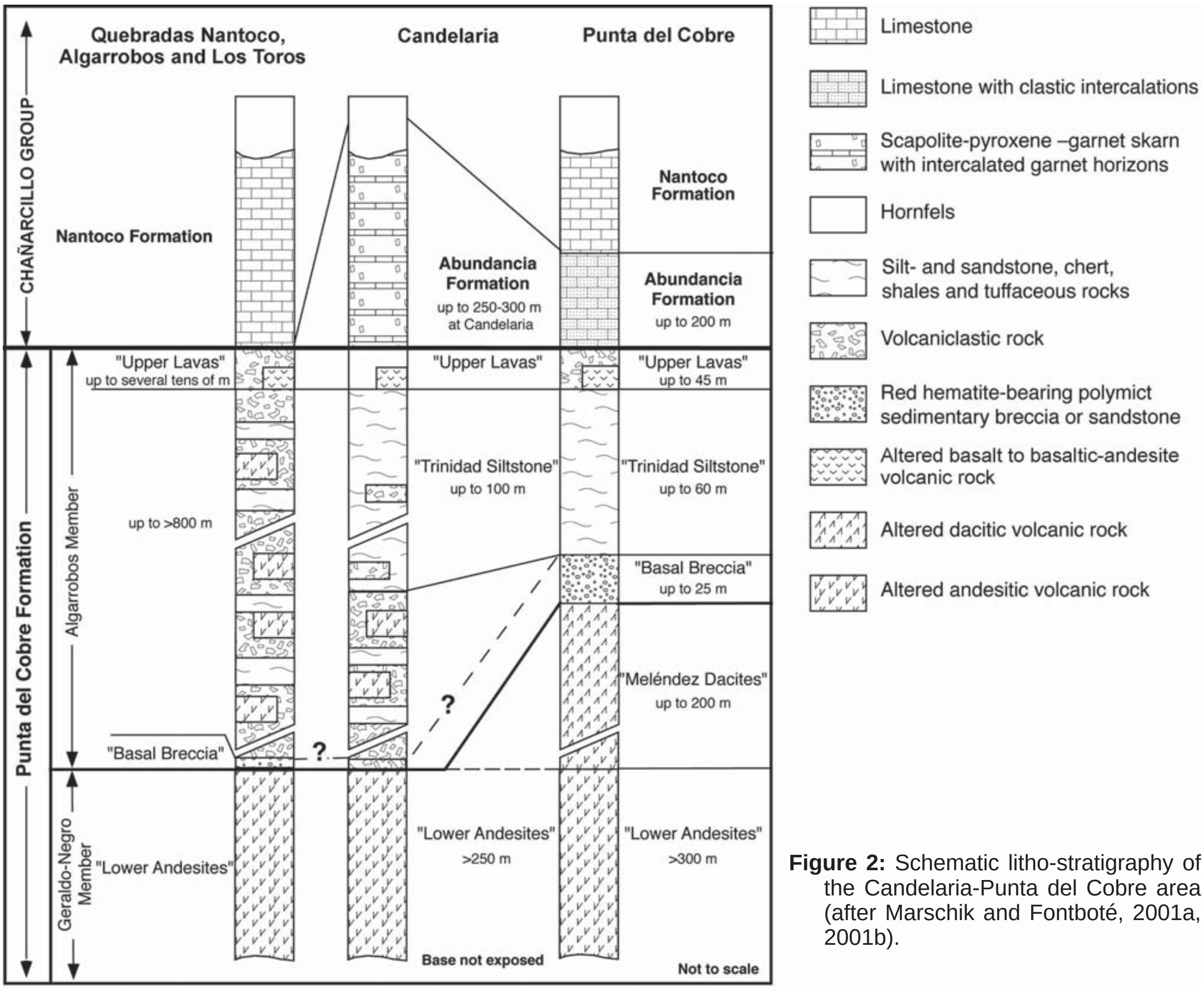


Figure 2: Schematic litho-stratigraphy of the Candelaria-Punta del Cobre area (after Marschik and Fontboté, 2001a, 2001b).

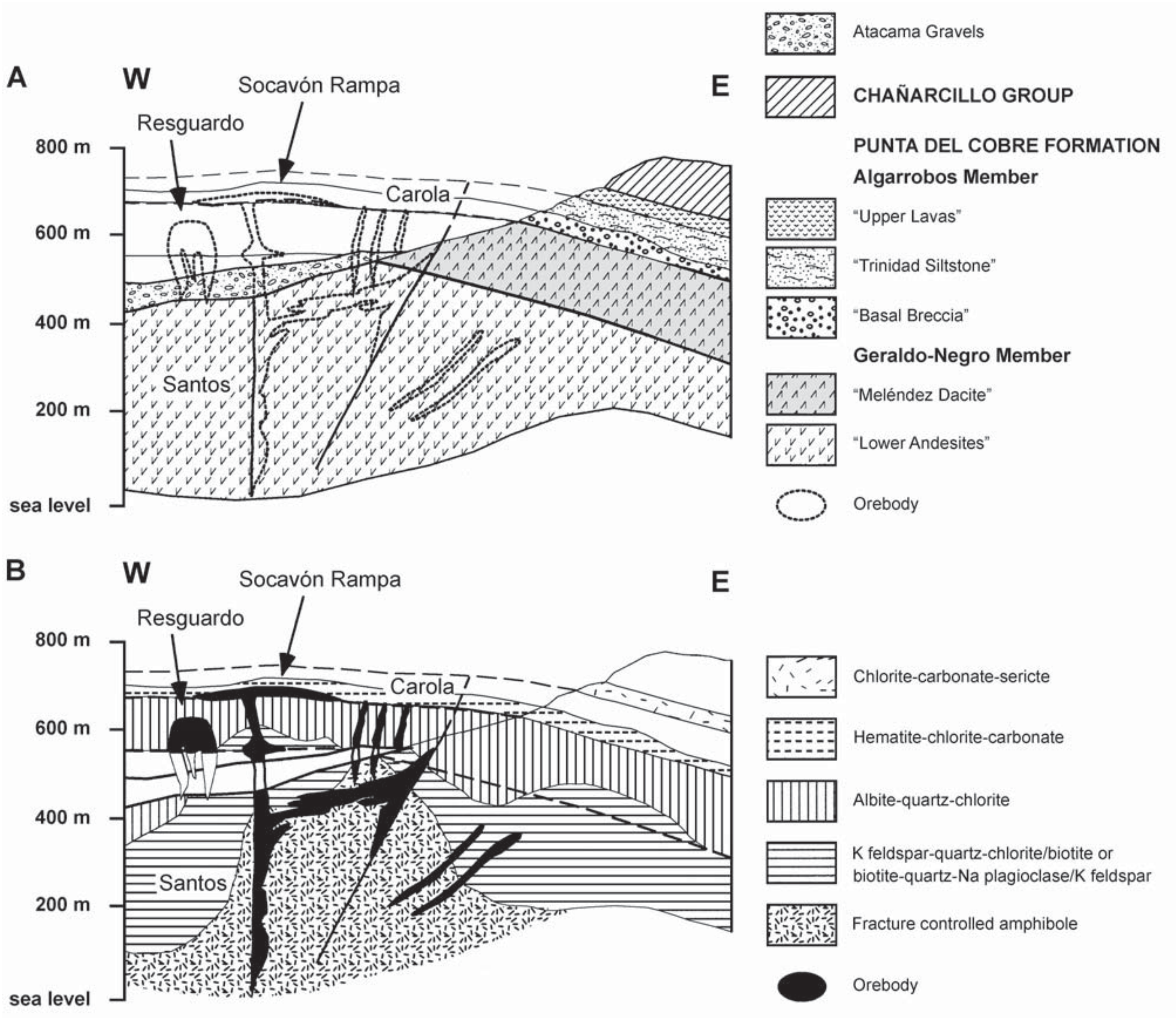


Figure 3: Cross-section through the Santos mine in the northern part Punta del Cobre district (after Flores, 1997): **A)** stratigraphy, **B)** distribution of the main alteration types. The relative stratigraphic position and idealised shape of orebodies from deposits in the southern Punta del Cobre district are indicated.

Tectonic Structure

The main structural elements in the Candelaria-Punta del Cobre area are a large northeast-trending antiform, known as the Tierra Amarilla Anticlinorium, the southeast-verging El Bronce fold-thrust system (Arévalo and Grocott, 1997), a dense set of north-northwest to northwest-trending high-angle sinistral transcurrent faults, broadly northeast-trending high-angle and moderately (30 to 50˚) west dipping faults, and sinistral east-northeast-trending high-angle faults.

The Punta del Cobre district sits at the eastern limb of the Tierra Amarilla Anticlinorium. In contrast, the Candelaria orebody is located near the centre of the anticline on an elevated block, which is bounded by the north-northwest-trending Bronce and Farellón faults to the west and east, respectively. The north-northwest-trending sinistral sub-vertical Lar fault cuts the Candelaria orebody and laterally displaces it by about 300 m and vertically by about 100 m in an east-block-down sense. North-northwest to northwest-trending sinistral faults, in places, control parts of the mineralisation (e.g., Camus, 1980; Marschik and Fontboté, 1996). They experienced post-ore reactivation (Ryan *et al.*, 1995). North-northeast-trending, 30 to 70° west dipping discontinuous zones of intense foliated biotitised rocks occur in the Candelaria pit (Candelaria Shear Zone) and west of Alcaparrosa mine (Florida Shear Zone). These zones of foliation probably represent segments of a large shear zone that is cut and displaced by the sinistral north-northwest to northwest-trending, and east-northeast-trending high-angle brittle faults, and the broadly northeast moderately west dipping faults. Taking the Lower Cretaceous age of the sheared rocks and other geologic evidence into account, burial could not have exceeded more than 2 to 3 km, which means that ductile deformation occurred far above the structural level of the ductile-brittle transition. Therefore, the Candelaria and Florida shear zones are interpreted to represent heat-induced ductile deformation related to batholith emplacement as suggested for other ductile shear zones associated with high level intrusions now exposed in the Early Cretaceous magmatic arc of northern Chile (e.g., Grocott *et al.*, 1993).

Contact Metamorphism

Contact metamorphism mainly caused mineralogical changes in affected country rocks. Contact metamorphic assemblages appear to be largely stratigraphically controlled and are zoned from west to east, i.e., outboard of the batholith contact. Within the contact aureole, limestones of the Chañarcillo Group are converted into proximal andraditic garnet ± sodic scapolite skarns that zone outward into marble. Tuffaceous and shaly beds intercalated with limestones near the base of the Chañarcillo Group, and volcaniclastic rocks in the upper part of the underlying Punta del Cobre Formation were transformed into proximal diopsidic-hedenbergitic pyroxene-sodic scapolite ± andraditic garnet skarns or biotite, quartz, or pyroxene ± epidote ± K-feldspar hornfelses. Further outboard from the contact, these same units are characterised by chlorite-carbonate ± epidote assemblages. In massive volcanic rocks, thermal contact metamorphism produced two parallel north-northeast-trending largely overlapping zones of a calcic amphibole ± biotite ± epidote ± chlorite ± sericite assemblage near the batholith contact grading into epidote-chlorite ± quartz ± calcite assemblage to the east (Marschik and Fontboté, 1996). Locally, these zones in turn grade into alkali metasomatised rocks that in places host the ore deposits. The Punta del Cobre district lies just outside the contact metamorphic aureole, whereas the Candelaria deposit is located within the contact aureole, with the result that its host rocks have been subjected to more intense thermal metamorphism and deformation.

Hydrothermal Alteration

Hydrothermal alteration in the Candelaria-Punta del Cobre area, in general, is metasomatic resulting in marked changes in the geochemical compositions of the affected massive igneous rocks (Marschik and Fontboté, 1996). In contrast to contact metamorphic assemblages, hydrothermal assemblages commonly transgress stratigraphy.

In the Punta del Cobre district, pervasive albite-chlorite-calcite-hematite alteration occurs in the dacitic volcanic rocks in the upper levels of the mines (Fig. 3). It grades down-section (and locally laterally) into pervasive K-feldspar-chlorite and/or biotite ± quartz ± calcite plus magnetite ± hematite alteration. The deeper parts of the mines are characterised by fracture-controlled calcic amphibole ± epidote alteration on the previously pervasive biotite-quartz-magnetite altered andesitic wall rocks. Copper-gold mineralisation is associated with all these hydrothermal alteration mineral assemblages.

Alteration spatially associated with, however commonly pre-dating copper mineralisation at La Candelaria include pervasive biotite-quartz-magnetite, and magnetite-amphibole assemblages in the upper part of the "Lower Andesites" and in the lower part of the Algarrobos Member, and biotite-almandine-rich garnet ± magnetite ± grunerite-cummingtonite ± cordierite ± trace tourmaline alteration in the tuffaceous rocks that correlate with the "Trinidad Siltstone" (Figs. 4 and 5). Veinlets with

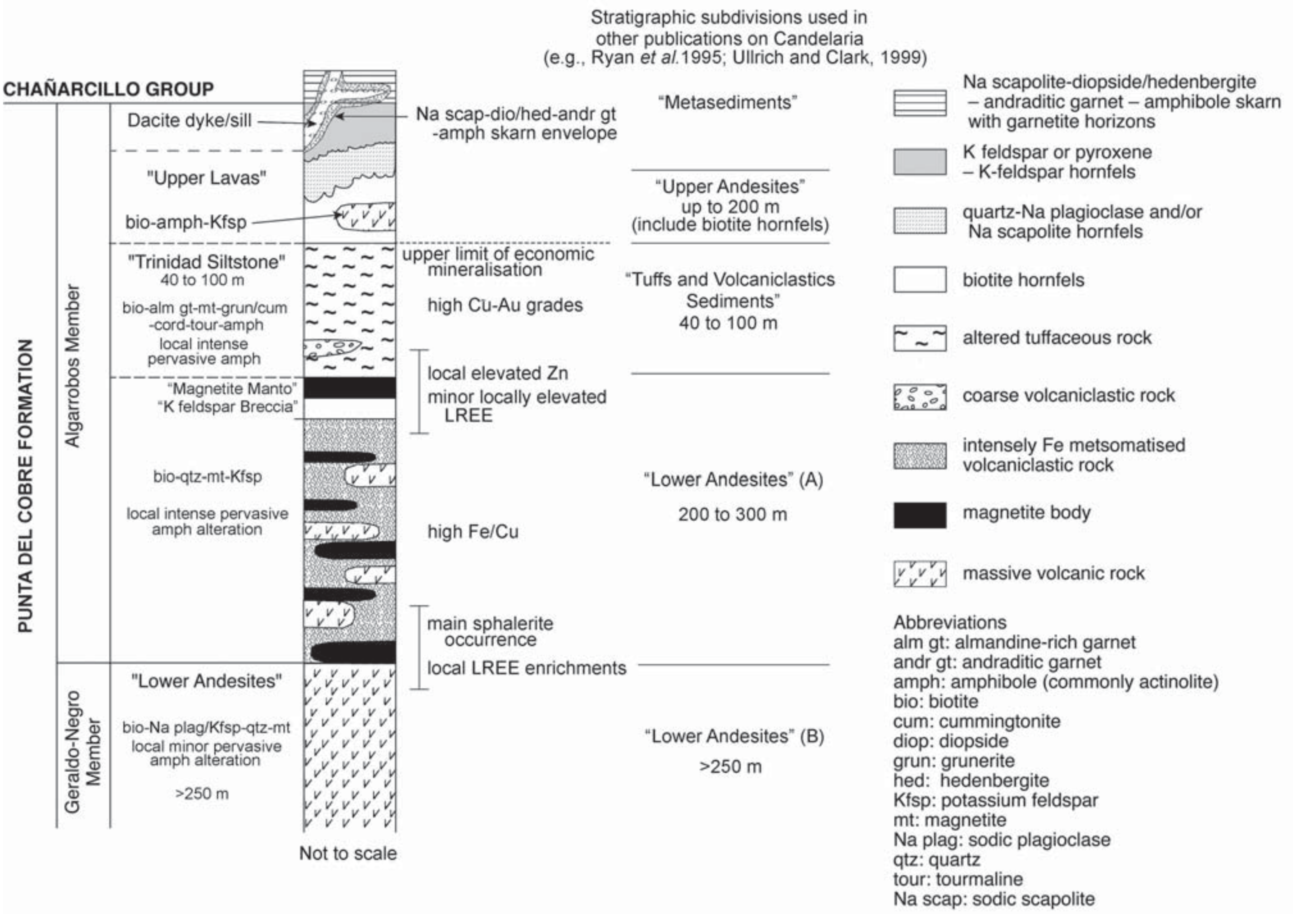


Figure 4: Schematic stratigraphic column of the Candelaria deposit. Main pervasive alteration types are indicated.

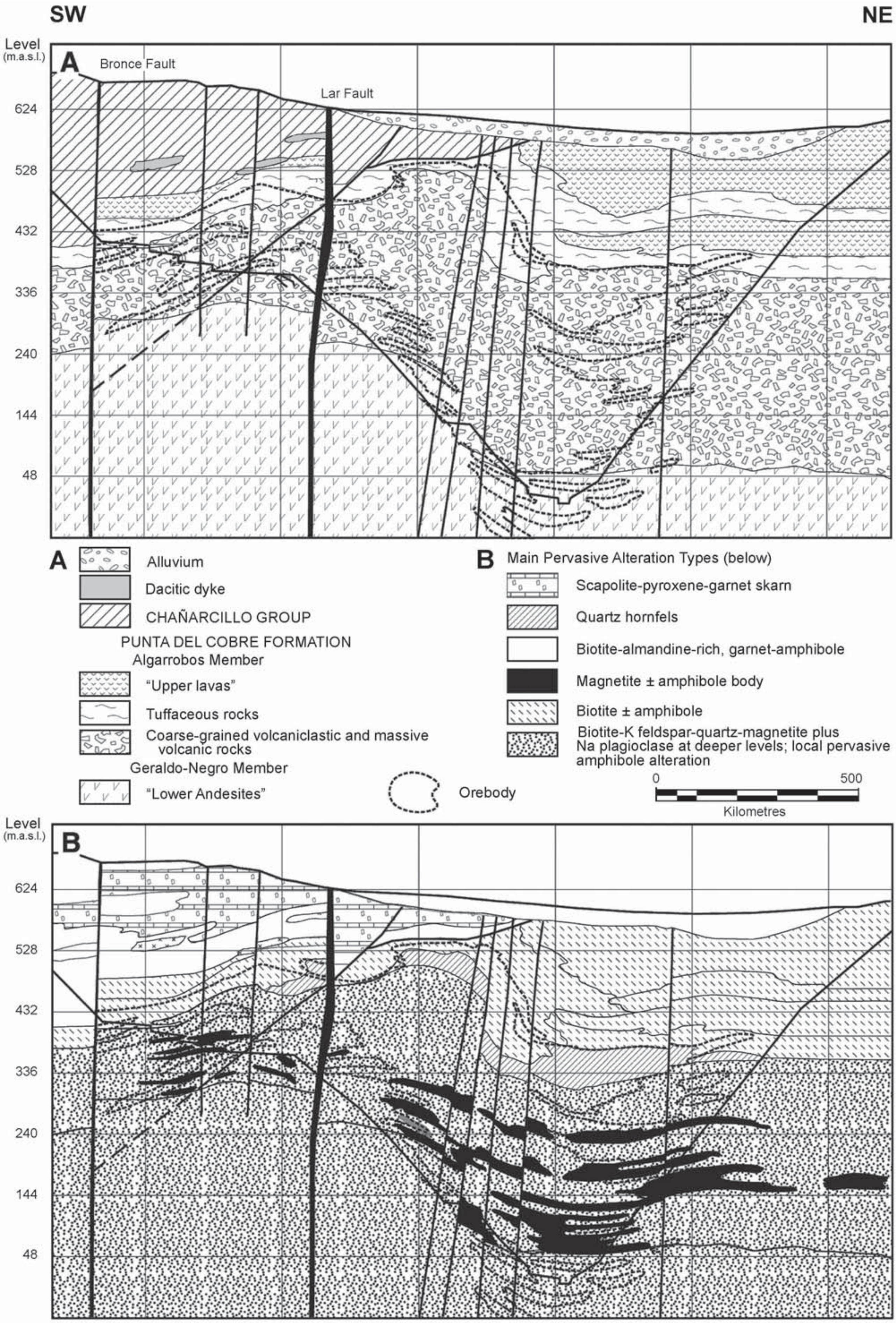


Figure 5: Cross-section through the Candelaria deposit: **A)** stratigraphy, **B)** distribution of the main pervasive alteration types, and on facing page, **C)** orebody at a 0.4 % Cu cut off grade.

variable proportions of albite, calcic amphibole (mainly actinolite, ferro-actinolite, or actinolitic hornblende), quartz, K-feldspar, and biotite among others, with or without chalcopyrite-pyrite ± magnetite mineralisation, in places, cut the pervasive biotite-rich assemblages. Textural evidence and cross-cutting relationships indicate that the vein mineral assemblages are a result of superposition of several discrete alteration events, which largely pre-date main stage copper mineralisation (see paragenetic sequence below).

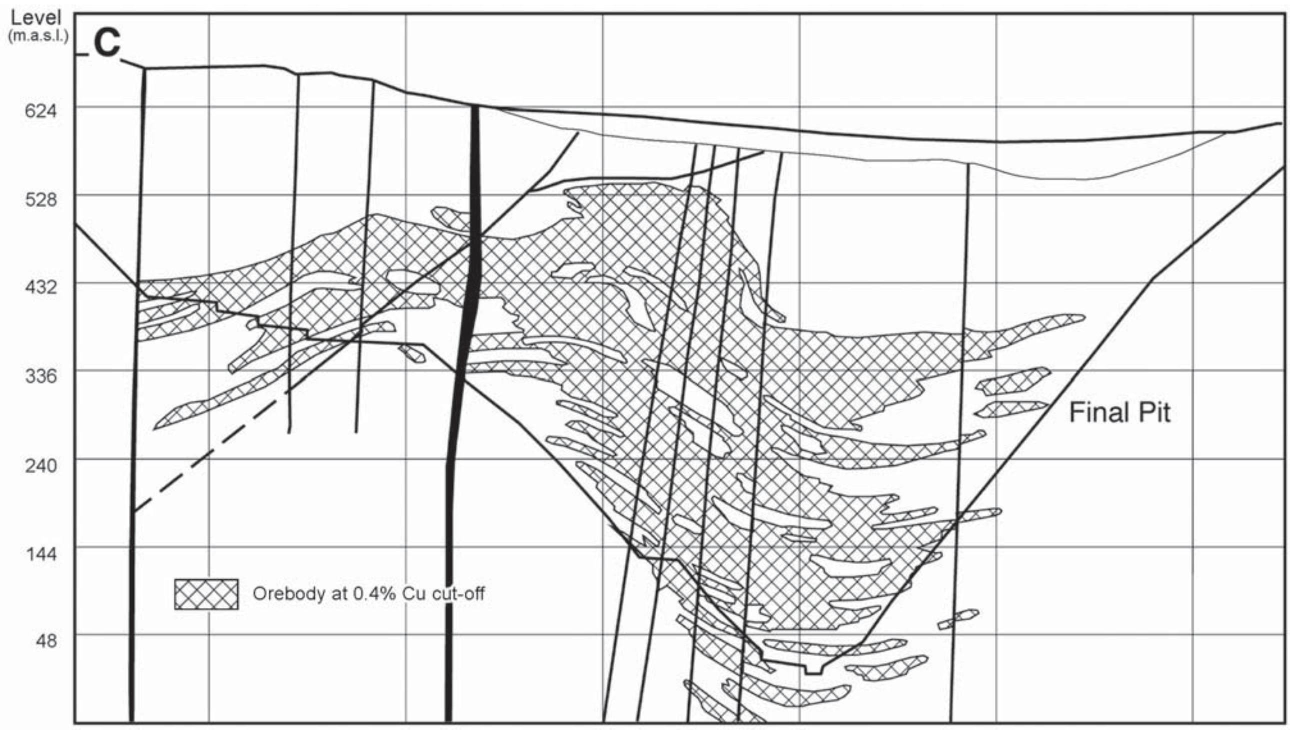
Ore Mineralogy

Hypogene ore mineralogy consists mainly of magnetite and/or hematite, chalcopyrite, pyrite. Pyrrhotite is common in the upper central part of the Candelaria orebody and it is reported from Carola mine (Hopf, 1990; Ryan *et al.*, 1995). In both of these mines, sphalerite is present and zinc concentrations locally exceed 1.0 wt.%. Gold occurs as micron-sized grains commonly associated with chalcopyrite, as inclusions in pyrite, and as a ternary Hg-Au-Ag alloy (Hopf, 1990; Ryan *et al.*, 1995). Molybdenite and arsenopyrite are observed in trace quantities at La Candelaria. Elevated concentrations of light rare-earth elements are present locally (e.g., in La Candelaria, Carola, and Socavón Rampa mines; Marschik and Fontboté, 2001b).

Copper-Gold Mineralisation

Copper-gold mineralisation occurs as massive veins, discontinuous veinlets and stringers cutting the altered host rocks or magnetite replacement bodies, as breccia fillings, and concordant lens-like replacement and pore-infill bodies (mantos). Most of the important orebodies in the district are controlled by the intersection of north-northwest to northwest-trending faults with the contact of the Algarrobos Member and the underlying Geraldo Negro Member (Figs. 3 and 5). Mantos of banded chalcopyrite-pyrite commonly with hematite are centreed on these intersections in the Punta del Cobre district, where mineralisation extends downward from this level for about 150 to 200 m. In this interval, mineralisation takes the form of elongated or, in places, curious "molar" shaped breccia bodies hosted in the "Meléndez Dacites" and in the "Lower Andesites". The breccia bodies taper downwards into vein-like roots. At the Carola mine, chalcopyrite veins and veinlets cutting through the manto in the "Basal Breccia" into the overlying "Trinidad Siltstone" can be seen. However, commonly the upper contact of the "Basal Breccia" marks the upper limit of mineralisation in the Punta del Cobre district.

The Candelaria deposit comprises zones of widely spaced network of discontinuous veins that are commonly up to 20 cm wide, stringers, disseminations, breccia in-fill and mantos. Large veins (up to 1 to 1.5 m wide) are emplaced into the north-northwest to northwest-trending structures and high-grade ore zones follow these trends. The Candelaria orebody is located at the intersection of the Candelaria Shear Zone with the north-northwest to northwest-trending brittle faults at the contact of the Geraldo-Negro and Algarrobos members. Most of the ore is hosted in the upper part of the "Lower Andesites" and the overlying coarse volcaniclastic rocks of the Algarrobos Member, whereas highest ore grades occur in the tuffaceous rocks ("Trinidad Siltstone") in the upper part of the deposit (Ryan *et al.*, 1995; Fig 4). The upper limit of the economic mineralisation at Candelaria is marked by the lower contact of the "Upper Lavas". However, veins and veinlets with iron-copper mineralisation that are geochemically similar to mineralisation in the Candelaria orebody, are fairly common cutting all the way through the section into the metamorphosed limestones of the Chañarcillo Group as well. Chalcopyrite-pyrite-magnetite replacement bodies (mantos) and veins and roughly bedding-parallel lenses of massive magnetite are found in scapolite-pyroxene



± garnet skarns near La Candelaria (e.g., Bronce deposit; Díaz, 1990). Similar mineralisation occurs in several places near the batholith contact mainly in volcaniclastic rocks that are intercalated in the metamorphosed limestones of the Chañarcillo Group (e.g., Las Pintadas, Venus-Marta).

Iron Oxide Occurrence

Iron metasomatism, in places, formed magnetite and/or hematite veins and veinlets, irregularly and lens-shaped massive magnetite replacement bodies, and breccias with a magnetite-rich matrix. Magnetite is the predominant iron oxide species at La Candelaria and in the mines in the Punta del Cobre district. However, pseudomorphous replacements of specularite by magnetite that are common in veinlets and veins in most of the deposits of the Punta del Cobre belt including La Candelaria (Hopf, 1990; Marschik and Fontboté, 2001b) indicate that iron oxide mineralisation in these veins commenced with specularite formation and that the latter was widespread. This early specularite is locally preserved in the upper portions of the deposits, e.g., in the Socavón Rampa and Carola mines. A late phase of hematite formation that post-dates main copper mineralisation is correlated with barren specularite veining recognised throughout the Candelaria-Punta del Cobre area. Hematite is ubiquitous in the "Basal Breccia" in the Punta del Cobre district and discontinuous layers of massive magnetite usually several centimetres to 2 to 3 decimetres thick occur in places within red cherts higher in the sedimentary sequence. Massive irregularly shaped massive magnetite bodies and veins are commonly restricted to the deeper levels of the deposits in the Punta del Cobre district. Barren hydrothermal breccias with albitised volcanic rock fragments in a matrix of magnetite are observed in the upper part of the volcanic rocks in surface outcrops north of Quebrada Meléndez (Mantos de Cobre mine area; Fig. 1).

At Candelaria, there are several phases of magnetite formation, which have still to be classified. Small boudinaged magnetite lenses (commonly 3 to 5 cm) occur in foliated rocks of the Candelaria Shear Zone, indicating minor movements of the latter probably during the initial stages of magnetite formation, since the bulk of the iron oxide mineralisation is unaffected by shear deformation. Magnetite is common near the upper contact of the Geraldo-Negro Member and in the lower part of the Algarrobos Member. At this level, large barren and mineralised magnetite bodies occur in the Candelaria deposit (Figs. 4 and 5). Lenses of banded magnetite are locally found in the Algarrobos Member above the Candelaria orebody and magnetite mantos occur in the lower part of the Chañarcillo Group (Díaz, 1990).

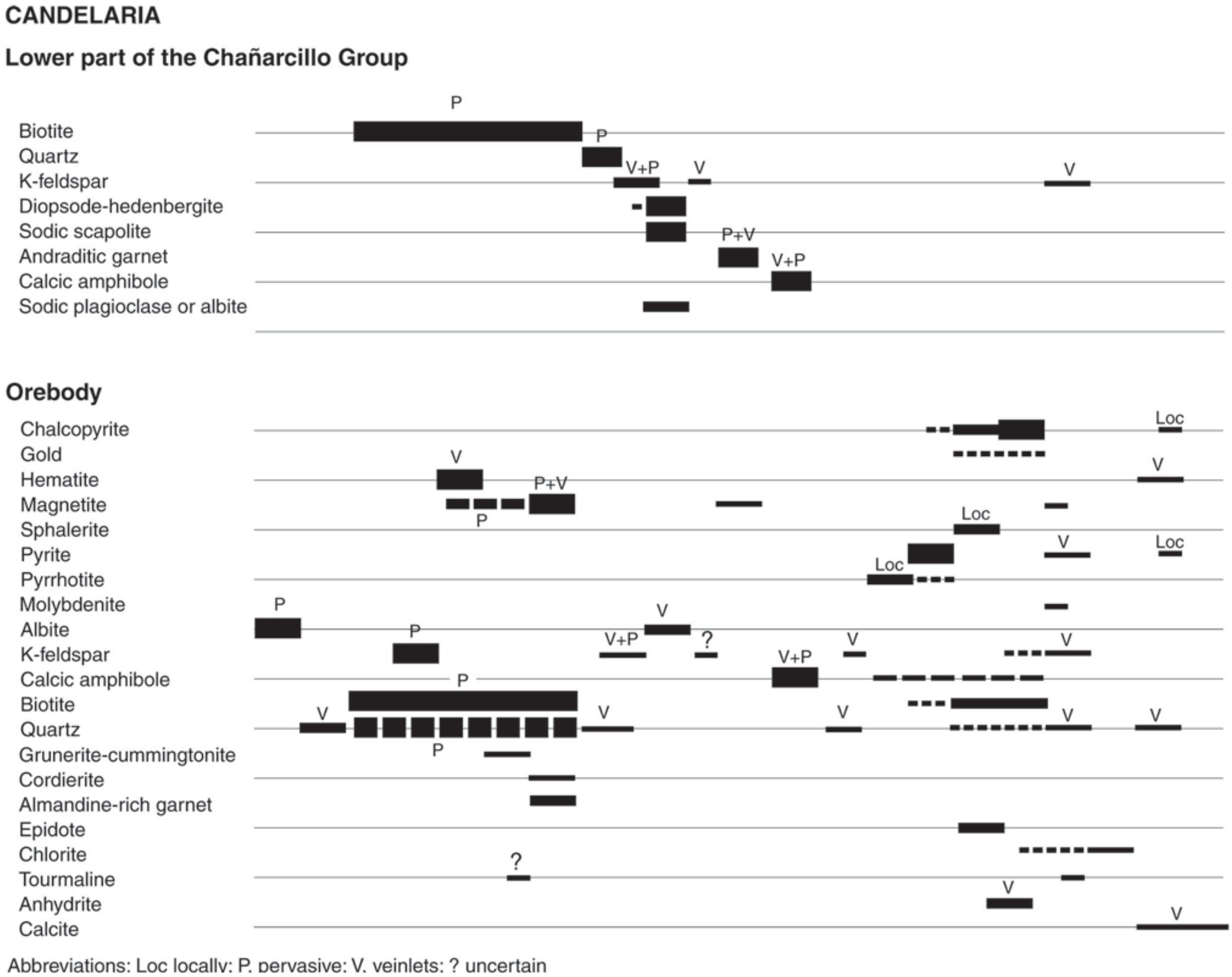


Figure 6: Paragenetic sequence of the main ore and alteration minerals in the Candelaria deposit. The thin continuous lines are for readability of the diagram and have no paragenetic implications.

Paragenetic Sequence

The paragenetic sequence of the Candelaria deposit is shown in Fig. 6. Hydrothermal activity initially caused widespread pervasive albitisation in igneous rocks, which, at La Candelaria and in the Punta del Cobre district, is commonly overprinted by pervasive potassic alteration (Marschik and Fontboté, 1996). At Candelaria, biotite alteration and silicification that accompanied intense iron metasomatism in the volcanic and volcaniclastic rocks and biotite-almandine-rich garnet assemblages in the overlying tuffaceous rocks are followed by several veining events, each event using permeability provided by the preceding event(s). This multiple use of fractures caused a variety of complex vein mineral assemblages that are only apparently paragenetic. The most relevant veining events in the orebody post-dating the early biotitisation and main iron oxide mineralisation are: quartz ± K-feldspar; albite (locally plus probably contemporaneous minor sodic scapolite); calcic amphibole; quartz; and K-feldspar. Chalcopyrite-pyrite is among the latest veining events. Chalcopyrite ± pyrite invades all previously formed veinlets mentioned above; cuts through the early pervasive biotite-quartz-magnetite alteration, and occurs in fractures of almandine-rich garnet. It follows and crosscuts foliation planes of the Candelaria Shear Zone. Chalcopyrite-pyrite commonly is fills open-spaces in actinolite veins. However, actinolite veinlets cutting pyrite veinlets are occasionally observed. The close spatial association of actinolite and chalcopyrite-pyrite suggest that both are formed broadly contemporaneous. Amphibole-biotite plus quartz with interstitial chalcopyrite-pyrite mineralisation are observed locally at Candelaria and the association of amphibole-K-feldspar is common. Potassium feldspar veining events pre- and post-date chalcopyrite-pyrite mineralisation. These relationships indicate that potassic alteration (K-feldspar and biotite) rather than the earlier albite veining (i.e., sodic alteration) is accompanying the main copper mineralisation. Anhydrite cuts, is intergrown with, and is cut by chalcopyrite-pyrite suggesting that anhydrite also was coeval with the main copper mineralisation. Calcite occurs late in the paragenetic sequence commonly post-dating chalcopyrite-pyrite mineralisation.

Above the Candelaria orebody, alteration mineralogy is quite different from that in the ore zone partly due to differences in the original types of lithologies present (Fig. 4). Biotite hornfelses developed probably coeval with the biotite-quartz-magnetite alteration in the orebody. These biotite hornfelses, and biotite-actinolite-K-feldspar bearing volcanic rocks of the "Upper Lavas" that occur locally at La Candelaria are cut by scapolite veinlets. The biotite hornfelses grade up-section into overprinting quartz plus sodic plagioclase and/or scapolite hornfelses, which in turn are locally overprinted by K-feldspar or pyroxene-epidote ± K-feldspar alteration preserving a hornfels-like appearance. Hornfelses grade into sodic scapolite - diopsidic-hedenbergitic pyroxene ± andraditic garnet skarns with garnetite horizons, which represent the lower part of the Chañarcillo Group.

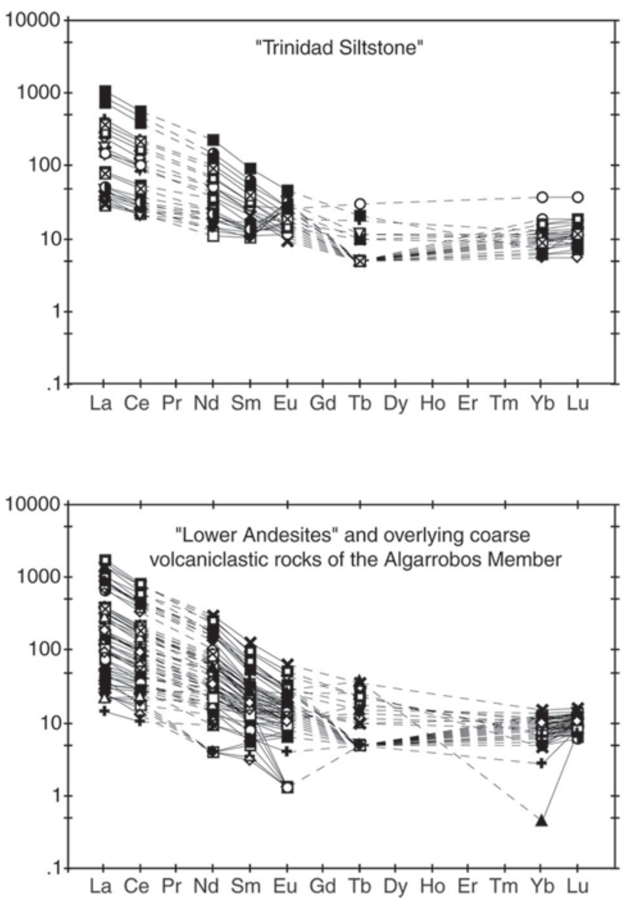


Figure 7: Chondrite-normalized rare-earth element pattern of rocks of the Candelaria deposit (reference chondrite of Nakamura, 1974). Elevated light rare-earth element concentrations occur locally in the ore zone. The concentrations of Pr, Gd, Dy, Ho, Er, and Tm were not measured.

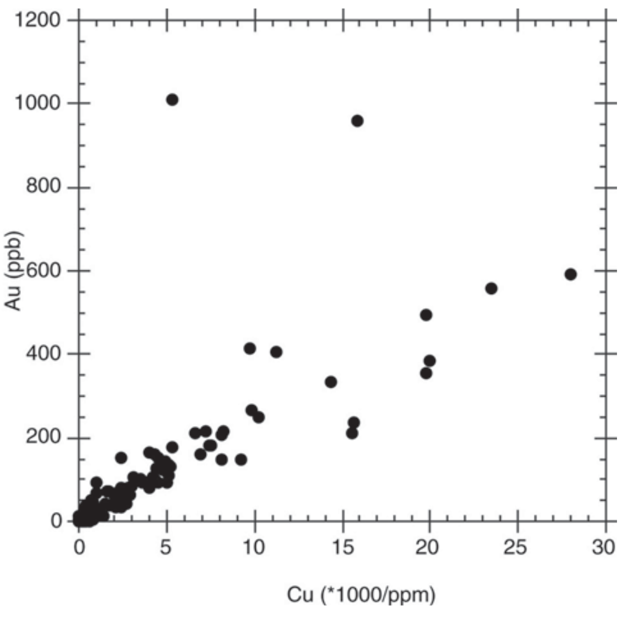


Figure 8: Variation diagram for copper and gold concentrations in eight-metre composite samples of the Candelaria ore zone.

Whole-Rock Geochemistry

Average and maximum element concentrations of 91 samples from eight-metre composites of the La Candelaria orebody are given in Table 1. Rare-earth element patterns of the analyzed rocks are shown in Fig. 7. The mineralisation at La Candelaria is anomalous in light rare-earth elements, Zn, Mo, and Ag. Elevated rare-earth element and Zn concentrations occur mainly near the contact of the Geraldo-Negro Member with the Algarrobos Member (Fig. 4), and also near the lower contact of the tuffaceous rocks that correlate with the "Trinidad Siltstone" indicating a stratigraphic control on the deposition of their host minerals. The Candelaria deposit is poor in U compared with other iron oxide-rich Cu-Au deposits as e.g., Salobo, Brazil (e.g., Requia and Fontboté, 1999), and Olympic Dam, Australia (e.g., Oreskes and Einaudi, 1990), respectively. Due to the multiple metasomatic events, correlations between element pairs are generally poor. One exception is Cu and Au, which shows a good positive correlation (Fig. 8).

Table 1: Average and maximum concentrations of selected elements in 91 x eight-metre composite samples from rocks that host the Candelaria orebody.

Element	Unit	Average	Maximum
TiO_2	wt. %	0.52	1.22
Al_2O_3	wt. %	11.20	15.93
FeO	wt. %	20.31	41.68
MgO	wt. %	3.96	8.21
MnO	wt. %	0.21	1.60
CaO	wt. %	3.54	8.59
Na_2O	wt. %	1.24	4.85
K_2O	wt. %	3.51	8.52
P_2O_5	wt. %	0.19	0.66
Au	ppb	136.0	1010
Ag	ppm	1.6	11.9
As	ppm	36.5	1400
Ba	ppm	845.2	7400
Br	ppm	2.4	75
Cd	ppm	1.0	28.9
Co	ppm	50.1	320
Cr	ppm	60.8	350
Cs	ppm	4.3	19
Cu	ppm	4831.5	27950
Hf	ppm	3.5	6
Mo	ppm	8.4	78
Ni	ppm	45.5	148
Pb	ppm	16.0	219
Rb	ppm	114.3	250
Sb	ppm	1.6	5.4
Sc	ppm	12.9	24
Sr	ppm	112.5	345
Th	ppm	3.4	6.2
U	ppm	2.1	7.7
V	ppm	134.1	360
Y	ppm	19.9	41
Zn	ppm	347.4	7453
La	ppm	99.7	510
Ce	ppm	140.2	720
Nd	ppm	40.0	190
Sm	ppm	5.3	26
Eu	ppm	1.3	5
Tb	ppm	0.4	1.9
Yb	ppm	2.0	8.2
Lu	ppm	0.4	1.23

Stable Isotope Geochemistry and Microthermometry

Sulphur isotope ratios of sulphides from the Candelaria deposit fall into a range of $\delta^{34}S_{CDT}$ values between 0.3 and +3.1 ‰ (Marschik *et al.*, 1997b; Marschik and Fontboté, 2001b). These values overlap with those obtained from sulphides of the Punta del Cobre district, which range from -0.7 to 1.1 ‰ $\delta^{34}S_{CDT}$. These sulphur isotopic signatures are compatible with a magmatic sulphur source. Sulphur was either directly provided by magmatic fluids or, alternatively, by non-magmatic fluids that have leached sulphur from volcanic rocks. A general decrease in $\delta^{34}S_{CDT}$ values in chalcopyrite and pyrite from the mines Santos and Socavón Rampa (Punta del Cobre district) is observed up-stratigraphy, which is interpreted to reflect oxidation of the ore fluid as it approaches the volcanic rock/sediment contact (Marschik *et al.*, 1997b).

Homogenisation temperatures of hypersaline fluid inclusions in post-magnetite quartz with interstitial chalcopyrite from La Candelaria range from 370 to >440°C. Two phase (vapor-liquid) inclusions in anhydrite homogenise between 340 and 470°C, and two phase (vapor-liquid) inclusions in paragenetically late calcite at ≤180°C. These preliminary results are consistent with homogenisation temperatures of ≥328°C for hypersaline CO_2-rich fluid inclusions in quartz from La Candelaria reported by Ullrich and Clark (1999) and similar to homogenisation temperatures of saline fluid inclusions (29 to 34% $NaCl_{equiv.}$) in calcite from the Punta del Cobre district that are between 125 and 175°C (Marschik *et. al.*, 1997a).

Oxygen isotope ratios of quartz associated with chalcopyrite from La Candelaria are between 11.2 to 12.6 ‰ $\delta^{18}O_{SMOW}$. Calculated isotopic composition of a fluid in equilibrium with this quartz is between +5.9 and +8.9 ‰ $\delta^{18}O_{SMOW}$ for a temperature range of 370° to 440°C (using isotope fractionation factors of Friedman and O'Neil, 1977). These results are compatible with a fluid of magmatic origin or a non-magmatic fluid equilibrated with silicates at high temperatures. Preliminary oxygen isotope compositions of calcite from the Santos and Socavón Rampa mines (Punta del Cobre district) range from +14.3 to +15.3 ‰ $\delta^{18}O_{SMOW}$ and those of calcite from the Candelaria deposit are between 11.7 and 11.9 ‰ $\delta^{18}O_{SMOW}$. A fluid in equilibrium with the calcite from the Punta del Cobre district has $\delta^{18}O_{SMOW}$ values approximately between -2.8 and +4.7 ‰ and with the calcite from La Candelaria between -5.4 and +1.3‰ at temperatures of 100 to 180°C. These results indicate that non-magmatic fluids have played an important role in the later stages of hydrothermal activity.

Age of Hydrothermal Alteration

Incremental heating experiments on biotite from the biotite-quartz-magnetite alteration in the "Lower Andesites" of Santos mine (Punta del Cobre district) gave an $^{40}Ar/^{39}Ar$ inverse isochron age of 114.9±1.0 Ma (all errors reported at ±2σ). This age is in agreement with a Rb-Sr isochron of 116.8±2.7 Ma calculated from seven whole rock analyses (Marschik *et al.*, 1997a). The same study gave an $^{40}Ar/^{39}Ar$ total fusion age of 114.6±1.6 Ma and a $^{40}Ar/^{39}Ar$ total fusion weighted mean age of 111.6±1.4 Ma (2 analyses) for ore-related biotite from the Resguardo mine (Punta del Cobre district). $^{40}Ar/^{39}Ar$ plateau ages for hydrothermal biotite from the biotite-quartz-magnetite alteration in the "Lower Andesites" at La Candelaria and amphibole associated with chalcopyrite are 114.1±0.7 and 111.7 ±0.8 Ma, respectively (Ullrich and Clark, 1999). Two $^{40}Ar/^{39}Ar$ correlation ages of 111.0 ±1.4 and 110.7 ±1.6 Ma for biotite from mineralised host rocks at La Candelaria (Arévalo *et al.* 2000) are consistent with the younger biotite age obtained from biotite of the Resguardo mine reported above.

Discussion

The isotopic ages combined with paragenetic relationships allow to distinguish two superposed hydrothermal stages: an early iron oxide stage and a superposed copper sulphide stage (e.g., Marschik and Leveille, 1998; Ullrich and Clark, 1998, 1999; Marschik and Fontboté, 2001b). The older biotite ages suggest that early biotitisation that accompanied the bulk of the iron oxide mineralisation occurred at about 116 to 114 Ma, whereas the superposed sulphide mineralisation took place at about 112 to 110 Ma. The time of the copper mineralisation is best represented by the amphibole age of 111.7±0.8 Ma (Ullrich and Clark, 1999) because amphibole probably is largely coeval with the main chalcopyrite mineralisation. The $^{40}Ar/^{39}Ar$ total fusion weighted mean age of 111.6 ±1.4 Ma of hydrothermal biotite from Resguardo mine (Marschik *et al.*, 1997a) and the two $^{40}Ar/^{39}Ar$ correlation ages of 111.0±1.4 Ma and 110.7 ±1.6 Ma of biotite from La Candelaria (Arévalo *et al.* 2000) are also consistent with this second major hydrothermal stage. These younger biotite ages could represent the age of the biotitisation that accompanied main copper mineralisation. Alternatively, some of the older biotite (e.g. those close to main fluid conduits) may have experienced argon loss due to re-heating above their closure temperature for argon retention (~300 to 350ºC) during the main copper mineralisation.

The isotopic ages obtained by various methods show that the mineralisation at La Candelaria and in the Punta del Cobre district are the same age, within analytical error. These ages and other geologic arguments suggest that mineralisation at La Candelaria and in the Punta del Cobre district are genetically related. The age data indicate that the duration of hydrothermal activity was >2 Ma and that mineralisation at Candelaria-Punta del Cobre was broadly coeval with the emplacement of the Copiapó Batholith and with late Aptian-Albian regional uplift. They imply that burial at the time of mineralisation did not exceed 2 to 3 km, i.e., the thickness of the Chañarcillo Group (Marschik *et al.*, 1997a).

The main iron oxide mineralisation took place probably at temperatures of about 500°-600°C. These temperature estimates are based on formation temperatures for early (pre-chalcopyrite) alteration in the tuffaceous rocks of the Algarrobos Member at La Candelaria determined by Ullrich and Clark (1997) using biotite-garnet Fe-Mg exchange geothermometry. The available preliminary homogenisation temperatures of fluid inclusions in quartz and anhydrite suggest temperatures in the order of 340 to >470°C for the main copper mineralisation. Subsequent cooling of the hydrothermal system is indicated by the homogenisation temperatures of ≤180°C of fluid inclusions in late-stage calcite. The presently favoured model for the ore formation at La Candelaria and in the Punta del Cobre district is summarised in Fig. 9. The data shown are compatible with a magmatic sulphur source and predominantly magmatic fluids that cooled and possibly mixed with external non-magmatic fluids thereby precipitating the ore minerals (Marschik and Fontboté, 2001b). The nature of the non-magmatic fluids remain to be determined. Other possible ore-forming processes

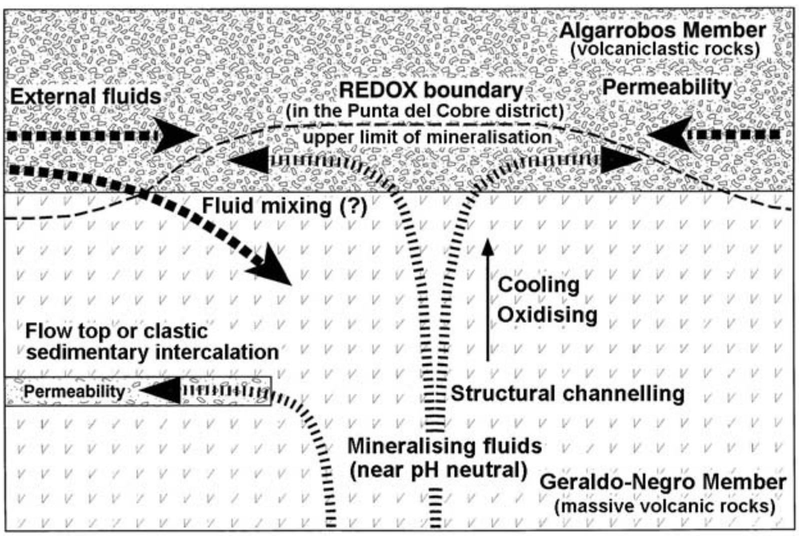


Figure 9: Presently favoured model for the ore formation at Candelaria and in the Punta del Cobre district. The ascending near pH neutral and relatively oxidized mineralizing fluids were channeled in tectonic structures. Cooling of these fluids and possibly mixing with external fluids in the upper part of the fractured volcanic rocks and the permeable volcaniclastic sediments may have caused the ore minerals to precipitate. In the Punta del Cobre district, the upper limit of mineralization appears to be controlled by a redox boundary. A trend towards lighter sulphur isotopic compositions up-stratigraphy is interpreted to reflect oxidation of the ore fluid as it approaches the volcanic rock/ sediment contact (Marschik et al., 1997b). Generalized oxidizing conditions at this level are consistent the abundance of the hematite in the volcanic rocks and in the overlying "Basal Breccia".

particularly those involving non-magmatic evaporite-derived brines circulating around the cooling batholith and contributing to alteration and mineralisation (e.g., Barton and Johnson 1996; Barton *et al.*, 1998; Ullrich and Clark, 1999) cannot be dismissed at present.

Conclusions

Hydrothermal iron oxide copper-gold mineralisation at La Candelaria and in the Punta del Cobre district is epigenetic, significantly post-dating the deposition of the Lower Cretaceous host rocks. The isotopic ages derived from various analytical methods show that the mineralisation at La Candelaria and in the Punta del Cobre district are the same age supporting geologic arguments, which suggest that they are genetically related. These ages indicate that the duration of hydrothermal activity in the area was >2 Ma. They imply that metallic mineralisation at Candelaria-Punta del Cobre occurred at a palaeodepth of not more than 2 to 3 km broadly coeval with the emplacement of the Copiapó Batholith and with regional uplift. The summarised data is consistent with ore fluids of predominantly magmatic origin. However, it cannot be excluded that non-magmatic fluids (e.g., meteoric waters, basinal or evaporitic brines etc.) circulating around the cooling batholith were also involved in the alteration and ore-forming processes. There is a marked zonation in the district regarding metallic mineralisation and alteration mineral assemblages. Contact metamorphic assemblages appear to be stratigraphically controlled, whereas hydrothermal alteration in general is discordant. However, particular alteration mineral assemblages (e.g., biotite-quartz-magnetite or albite-chlorite-carbonate) at a more local scale are largely confined to particular litho-stratigraphic units. Copper mineralisation is controlled by the intersections of generally north-northwest to northwest structures with the favorable contact between the upper volcaniclastic unit of the Punta del Cobre Formation and the underlying massive volcanic rocks of the same formation. Copper orebodies are found both inside and outside of the contact metamorphic aureole, and while also showing strong stratigraphic control, they also transgress stratigraphy and earlier metamorphic/alteration assemblages.

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