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THE PANULCILLO AND TERESA DE COLMO COPPER DEPOSITS: TWO CONTRASTING EXAMPLES OF FE-OX CU-AU MINERALISATION FROM THE COASTAL CORDILLERA OF CHILE.

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Abstract – The Coastal Cordillera of Chile hosts several world-class FeOx CuAu deposits, including Candelaria, Mantos Blancos, Manto Verde, and El Soldado. Despite this comparatively little has been published on Chilean FeOx CuAu systems. This paper presents observations from two small Chilean FeOx CuAu deposits of Lower Cretaceous age; Panulcillo and Teresa de Colmo.

Panulcillo is a pseudo-stratiform FeOx CuAu / Skarn deposit located within the metamorphic aureole of a monzodioritic intrusive. Chalcopyrite, bornite, pyrite and pyrrhotite occur with calcic amphibole as disseminations and microveinlets in K-feldspar-albite-silica altered meta-andesites, magnetite-albite-scapolite rich meta-andesites and in overlying garnet skarn.

Teresa de Colmo is a multiphase hydrothermal – tectonic breccia deposit associated with the emplacement of a leucodioritic stock. Chalcopyrite and pyrite is associated with albite and chlorite alteration and has been incorporated in a specularite-matrix breccia that cuts andesitic volcanic and sedimentary country rocks.

Although both deposits show many similarities, such as the presence of abundant Fe-oxides, Cu sulphides, strong pervasive sodic alteration and a spatial relationship to differentiated intermediate intrusives, they also show many significant differences. While Panulcillo appears to have formed in a semi-ductile regime and has abundant potassic alteration, amphibole and magnetite, Teresa de Colmo seems to have formed in a brittle regime, lacks potassic alteration, and has chlorite and specularite.

We consider these variations to be inherent in the FeOx CuAu family of deposits, and suggest that they do not reflect different ore-forming processes but rather changes in oxygen and sulphur fugacities, chemical equilibria, temperature and tectonic regime due to differing host rocks and levels of emplacement.

Introduction

The Coastal Cordillera of Chile represents one of the world's best exposed FeOx CuAu provinces. Stretching 1500 km from Tocopilla in the north to Santiago in the south (see Figure 1), the province hosts several significant FeOx CuAu ore-deposits, including Candelaria (360Mt of 1.1% Cu & 0.3g/t Au), Mantos Blancos (400Mt of 1% Cu) Manto Verde (250Mt of 0.75% Cu as oxide) and El Soldado (200Mt of 1.5% Cu).

Despite the province's world-class credentials and excellent exposure, comparitively little deposit scale research or regional investigation has been conducted on Chilean FeOx CuAu systems to date. What little there is, is often in unpublished university theses, spanish language journals or conference proceedings, or as so often is the case, company reports. This paper presents previously unpublished observations from two small FeOx CuAu deposits of Lower Cretaceous age; Panulcillo and Teresa de Colmo.

The Panulcillo copper deposit is located in the Chilean Coastal Cordillera near the town of Ovalle, about 70 Km south of the city of La Serena, and 500 Km north of Santiago (Figure 1). The deposit was first exploited by the Central Chili Copper Mining Co. of France beginning around 1860, followed by the english Banco Anglo de Coquimbo between 1919 and 1925, when organised mining stopped due to depressed metals prices. Since then the dumps and pillars of the deposit have been worked on and off by a variety of small Chilean companies and informal "Pirquineros". The deposit is currently owned by the state mining company, Empresa Nacional de Mineria (ENAMI), and is at present being explored by Rio Tinto Mining and Exploration Limited. (Rio Tinto).

Total historic production at Panulcillo is estimated to have been about 3 million tonnes, with grades ranging from 10% Cu in the supergene enrichment zone, to 3.5% Cu in the hypogene sulphide zone (Carrascal 1989 and Narváez et al. 1998). Exploration drilling by ENAMI has since defined a new sulphide resource of approximately 10.4 million

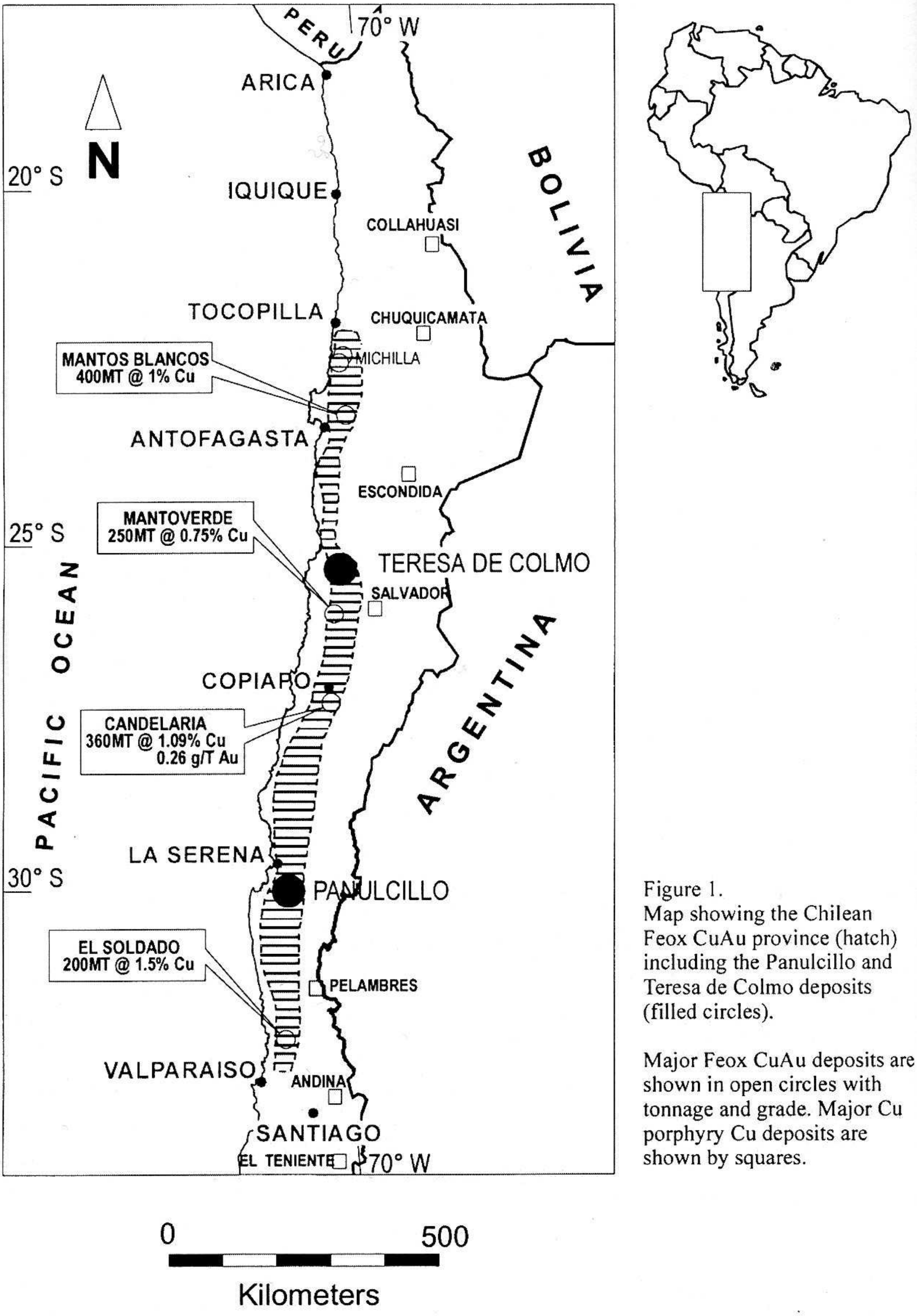

Figure 1.
Map showing the Chilean Feox CuAu province (hatch) including the Panulcillo and Teresa de Colmo deposits (filled circles).

Major Feox CuAu deposits are shown in open circles with tonnage and grade. Major Cu porphyry Cu deposits are shown by squares.

tonnes at 1.45% Cu. Although gold reaches up to 0.1 g/t in parts of the deposit it is erratic and has not been included in the resource.

The Teresa de Colmo deposit is located 75 Km southeast of the port of Taltal, in the Coastal Cordillera of Region II, northern Chile, at a mean elevation of 1,200 mts above sea level (Figure 1).The area is an old copper mining district that has been intermitently exploited since the 1950's. Historical extraction was centered on high-grade oxide and sulphide copper zones from underground workings. During 1994 and 1995 this deposit was explored by Rio Tinto, including aproximately 16,000 mts of reverse-circulation and diamond drilling.

The total geological resource estimated at the Teresa de Colmo deposit is 70 million metric tonnes of 0.8%, of which 20 million are oxides and 50 million are sulphides. Gold is typically below 20 ppb for the whole deposit, but in the high-grade mineralised zones, it grades from 100 to 250 ppb.

Both of these deposits can be considered members of the FeOx CuAu family of deposits, showing as they do many similarities with other deposits worldwide. However, despite being part of the same family of deposits , at first sight they bear little resemblance to one another. The deposits are described in the following sections, drawing upon previously unpublished work by Rio Tinto geologists, Enami and others.

Section I - The Panulcillo Deposit

Regional and Local Geology

The geology of the coastal belt in and around the Panulcillo copper deposit (Bohnhorst 1967) consists of a thick sequence of Lower Cretaceous, Neocomian rocks which dip and young to the east (Figure 2). In the west the basal part of the sequence is represented by the Estratos de Tamaya Formation, which is dominated by andesitic volcanics of supposed marine origin with minor intercalations of rhyolite. This unit is overlain by the Estratos del Reloj Formation, a transitional marine-continental sequence consisting mainly of porphyritic andesitic volcanics towards the base passing up into minor lenses of limestone and volcaniclastic sediments towards the top. These rocks are in turn overlain by the mainly continental volcano-sedimentary Arqueros Formation. These three units constitute the Ovalle Group, and are the stratigraphic equivalents of the Bandurrias Formation which hosts the Candelaria deposit 400 km to the North. This group is overlain by the continental sedimentary Quebrada Marquesa Formation, which can in turn be correlated with the Chañarcillo Formation to the North. This entire Cretaceous sequence has been intruded by coeval calc-alkaline plutons dominated by granodiorites to monzonites with smaller bodies ranging in composition from syenite through to gabbro.

The Panulcillo deposit is hosted entirely within the upper members of the Estratos del Reloj Formation, which strikes north-south and dips to the east at between 40 and 70 degrees, forming a rugged 600 mt high mountain range. In the immediate area of the deposit the Estratos del Reloj Fm. is dominated by andesitic rocks, with the lensoid "Morenita" Limestone in the middle (Figure 3). The rocks which underlie the Morenita Limestone and outcrop to the west are referred to in this paper as the Lower Andesitic Sequence (LAS) and the rocks which overlie the limestone, and outcrop to the east are referred to as the Upper Andesitic Sequence (UAS). The LAS has a greater proportion of massive andesitic porphyry than andesitic breccia, tuff or epiclastic, while the UAS in contrast has a greater proportion of breccia, tuff and epiclastic.

Two kilometres to the north of the deposit these rocks are in contact with a large circular monzonite to quartz-monzodiorite (Carrascal 1989), which forms rolling lowland areas. This intrusive body is surrounded by a district-scale metamorphic aureole 2 to 4 kilometres wide.

The Panulcillo deposit lies entirely within this metamorphic aureole. The andesitic rocks of LAS and UAS have been recrystallised to fine-grained meta-andesites, dominated by highly variable proportions of biotite, amphibole, pyroxene and magnetite, together with lesser calcic and sodic feldspars, and have been termed "mafic hornfelses".The limestones have been recyrstallised to grosular and andraditic garnets in the north nearer the contact with the intrusive, decreasing away to the south where they are dominated by marble.

In additon, bimetosomatic reactions between the andesitic rocks and limestones during metamorphism, have produced calc-silicate hornfelses and skarns. These reaction zones are dominated by variable amounts of pale grosular and andraditic garnet, diopside, wollastonite, pyroxene, and epidote. They are best developed along, and often obliterate, the hornfels-marble contacts, although they are sometimes discordant. These metamorphic and bimetasomatic rocks comprise the host rocks to the FeOx CuAu mineralisation at Panulcillo.

Deposit Geology

The Panulcillo deposit consists of several elongate lensoid bodies of copper mineralisation. These lenses, or "Mantos" as they are known in Spanish, strike north-south, dip to the east subparallel to the stratigraphy of the Estratos del Reloj Fm., and are stacked pancake-style one upon the other (Figure 4). The mantos are developed within the Morenita Limestone and in the footwall rocks of the Lower Andesitic Sequence, and they present different characteristics depending on the host rocks. Of the several mantos, two of them are of significant grade and tonnage; The Upper Manto, hosted within the Morenita Limestone; and the Lower Manto, hosted within the Lower Andesitic Sequence;

The Upper Manto

The Upper Manto outcrops and was the source of copper for the historical production at Panulcillo (3Mt). This came from the Caracoles, Mina Nueva and Rosario pits, and the San Gregorio adit, all within the recrystallised Morenita Limestone (Figure 3).

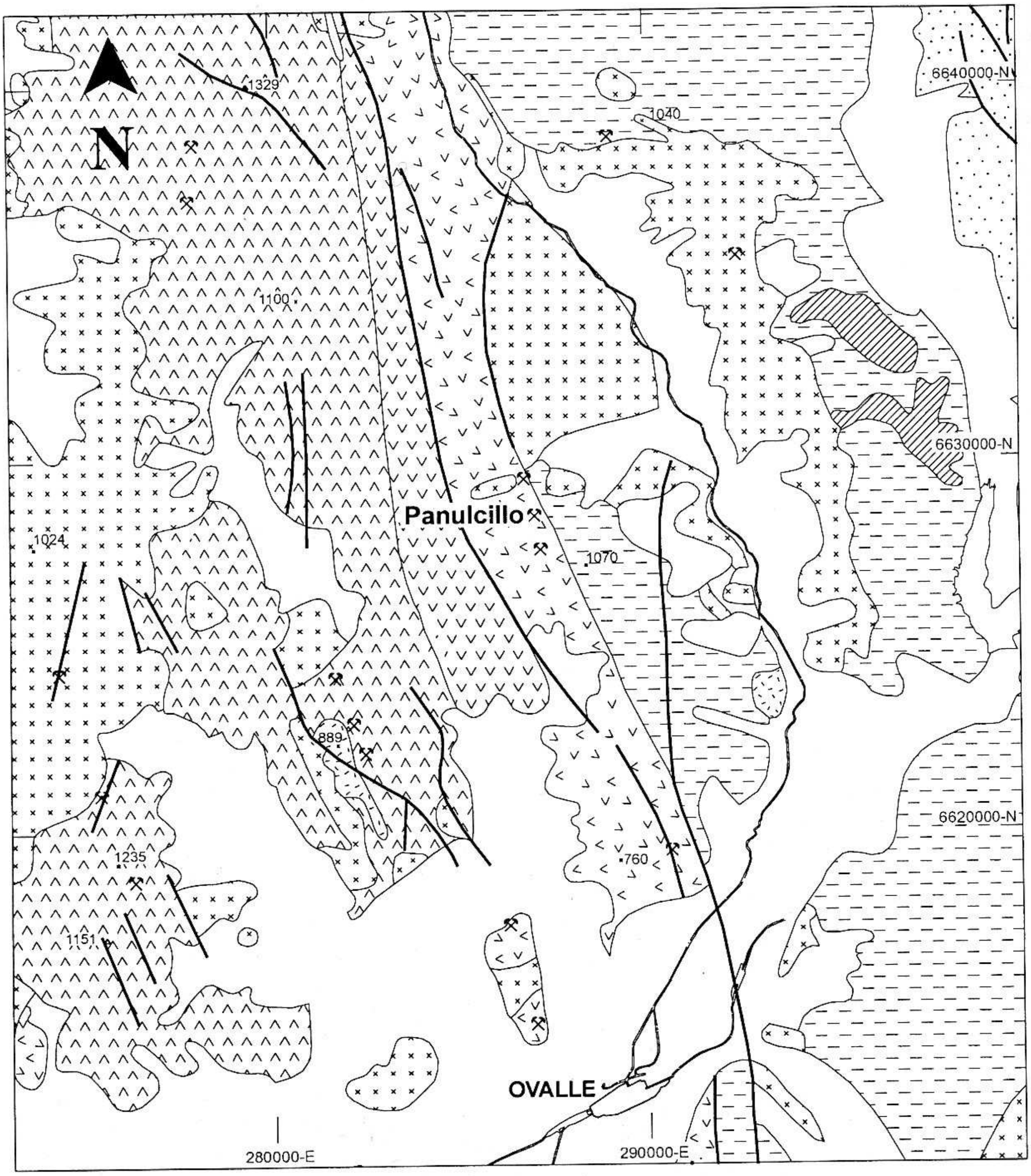

Figure 2. Regional geological plan of the Panulcillo deposit

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☐ Cover

▨ Hydrothermal alteration

Quebrada Marquesa Fm.

⁘ Clastic sedimentary rocks and andesitic volcanics with unconformity about 100-250 mts below manganese unit

Ovalle Group

Arqueros Fm.

☰ Andesitic volcanics with ocoites in upr part and marine sediments near base

Estratos del Reloj Fm.

< Andesitic volcanics, locally ocoitic with Lenses of marine sediments

v Marine sediments with andesitic volcanics

Estratos de Tamaya Fm.

^ Andesitic volcanics with intercalations of breccia, rhyolitic ignimbrites and red sandstones and conglomerates

× Intrusive rocks

Porphyry and intrusive andesite

0 KM 2.5

Mineralisation in the Upper Manto consists of chalcopyrite, pyrite, pyrrhotite and minor sphalerite and galena infilling veins, incipient breccias and intergranular spaces in garnet-dominant skarn, with grades generally highest near the marble-hornfels contact or in subvertical veins. Minor gold, averageing about 100 ppb, occurs in Upper Manto skarn, but does not occur in the Lower Manto.

Although not well documented, pyrite appears to increase at the expense of chalcopyrite with depth down-dip, and pyrrhotite appears to increase towards the north.

Related alteration and infill minerals (Hopper 1990) are dominated by garnets with lesser calcite, phlogopite and magnetite. Dark red-brown andraditic garnets occur as infill with, and as alteration around, chalcopyrite mineralisation, and cross-cuts earlier honey brown to pale green andraditic to grosular garnets .

This local pattern is superimposed on a larger zoning pattern of dark brown garnets near the intrusive contact passing into pale brown and greenish garnets (Ardilla 1993) along 1 km of strike. Calcite, phlogopite and magnetite occur as infill together with chalcopyrite.

Skarn-style sulphide mineralisation in the Upper Manto has been affected by supergene processes resulting in the following vertical mineral zoning (Carrascal 1989):

Oxidised Zone: 0-50 mts, limonites with Cu and Fe sulphates and carbonates.

Secondary Enrichment Zone: 50-120 mts, bornite, chalcocite and native Cu, with pyrite and chalcopyrite. Historical grades of 10-20% Cu .

Primary Zone: chalcopyrite, pyrite, pyrrhotite. Grades on the order of 0.5 to 3 % Cu.

The central portion of the Upper Manto, centred on the Caracoles Pit, had a strike length of 160 mts and a thickness of 45 to 50 mts at surface increasing to 70 mts at a depth of 150 mts below surface (Ardilla 1993). Although the lense pinches out and swells along its length, the total strike length of the carbonate-hosted skarn-style mineralisation is on the order of 1,500 mts.

In general the Upper Manto is subparallel to the stratigraphy and occurs close to and/or along the contact between the Morenita Limestone and the surrounding andesitic rocks. These mineralised areas grade quickly into skarnoid and then marble on the Morenita side. On the andesitic side the mineralisation grades out into a narrow (1-5m) zone of K-feldspar alteration and then into magnetite-rich hornfelses. The thickness of the skarn and the grade of related mineralisation decreases towards the south away from the intrusive; in the Caracoles pit skarn dominates over marble, in the Mina Nueva pit marble dominates over skarn . At the southern end of the Morenita skarn is almost absent.

The Lower Manto

The Lower Manto does not outcrop, and was discovered, with the help of serendipity, 30 to 50 metres beneath the Morenita Limestone during exploratory drilling by ENAMI in 1994. Subsequently it has been defined by 12,511 mts of infill diamond drilling by ENAMI, and 2,781 mts of exploratory reverse circulation drilling by Rio Tinto.

The main axis of the Lower Manto occurs at a depth of 250 to 300 mts below surface, measures approximately 800 mts along strike NS, and up to 250 mts EW. The thickness of mineralisation varies from about 20 to 150 mts, with an average thickness of about 30 mts. Preliminary reserve calculations for the Lower Manto indicate a demonstrated resource of approximately 10.4 million tonnes at 1.45% Cu with a 0.50% Cu cut-off (Narváez et al. 1998).

Mineralisation in the Lower Manto, and other andesite-hosted lenses, consists of chalcopyrite and bornite with lesser pyrite and pyrrhotite, as bleby disseminations and hairline crackle-veinlet infill within hornfelsed and hydrothermally altered rocks of the Lower Andesitic Sequence.

The Lower Manto is less regular in form than the Upper Manto and seems to be controlled by secondary permeability more than by lithological contacts. Alteration-mineralisation is more podiform and less stratiform than the Upper Manto. Nonetheless, the Morenita Limestone appears to have acted as a chemical or physical "cap rock" such that in general the Lower Manto forms a pseudo-stratiform lense, striking NS and dipping to the East, subparallel to the limestone and Upper Manto.

Alteration-mineralisation in the Lower Manto (Hopper 1990) appears to be zoned. Andesitic rocks in the axial portion of the lense are flooded by variable amounts of abundant, often texturally destructive, K-feldspar, silica and albite. Although only poorly documented, this axial "silica-feldspar" alteration appears to be K-feldspar dominated near the centre of the lense (pink), passing out into albite dominated towards the edges (grey). Rocks in this silica-feldspar alteration zone show signs of shear-induced lamination, folding and brecciation. In general laminar shearing appears to be best preserved towards the lense centre with breccia best developed towards the edges (Figure 4).

The axial silica-feldspar alteration passes out into magnetite-rich and biotite-rich andesitic rocks which albite and scapolite (Ardila 1993). Although magnetite and biotite are abundant in hornfelses throughout the district-wide metamorphic aureole, magnetite and biotite appear to be more strongly developed around the Lower Manto. The magnetite in particular is coarser grained and notably more abundant than in the district, and seems to form a halo or sheath around the silica-feldspar alteration.

Within the axial zone, chalcopyrite, bornite, pyrite and pyrrhotite occur mainly as disseminated vermicular blebs, hairline crackle-veinlets or breccia infill which cut the silica-feldspar alteration . In the outer magnetite halo sulphides occur as veins, veinlets and intergranular disseminations. These contrasting occurrence styles are thought to reflect the impermeable, brittle nature of the silica-feldspar flood, and the more competent but porous

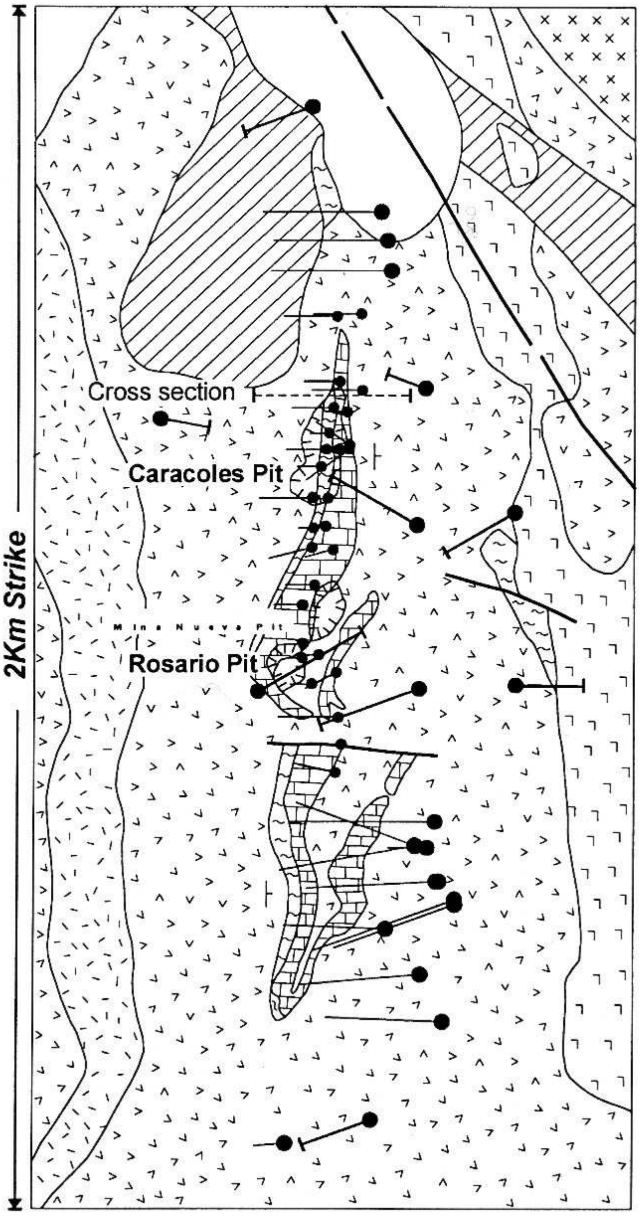

Figure 3. Geological plan of the Panulcillo deposit

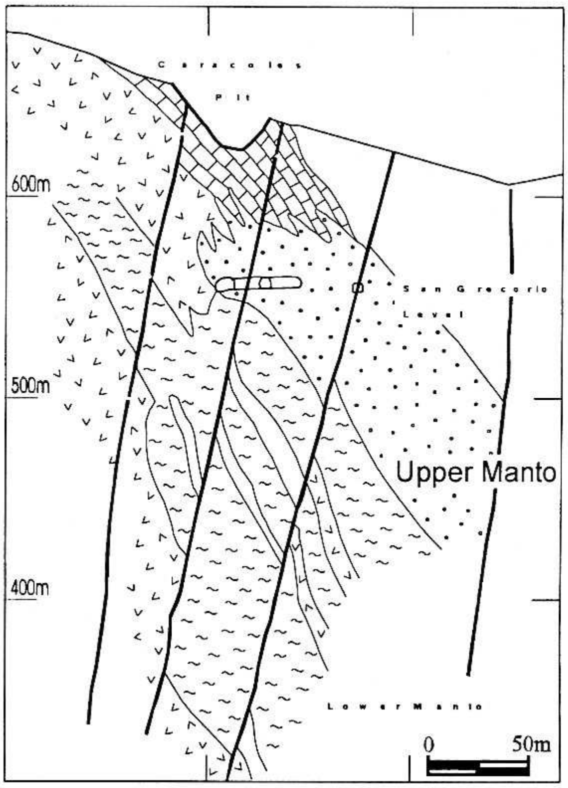

Figure 4. Geological section through the Panulcillo deposit showing Upper and Lower Mantos.

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▧	Morenita limestone - marble	▨	Biotite schist
⁘	Garnet skarn	⁞	Albite alteration
˅	Magnetite - rich hornfels	×	Monzodiorite
~	Silica - feldspar alteration	⬡	Abandoned Pit
˥	Kspar-epidote altered tuffs	—●	Drill holes

nature of the coarse magnetite rich halo.

Gangue minerals associated with the sulphides are dominated by pale green calcic amphibole, calcite, chlorite and magnetite with lesser feldspars, quartz, and biotite. These occur mainly as infill but sometimes form narrow alteration selvedges around channelways.

Drillholes through the centre of the Lower Manto, beneath the caracoles pit, show sulphide zoning across the lense;

Edge pyrite pyrite>chalcopyrite pyrite<chalcopyrite>bornite chalcopyrite<bornite bornite Centre

The same zoning is thought to occur along the lense also, with the difference that pyrrhotite appears and then increase towards the north (Narváez et al. 1998), apparently at the expense of Cu sulphides .

Paragenetic Sequence

As with most FeOx CuAu deposits, the alteration and mineralisation of the Panulcillo deposit reflects the complex overprinting and intermingling of several distinct paragenetic assemblages. Each assemblage is related to the other, and is part of a larger dynamically evolving system.

Preliminary paragenetic logging of diamond drill-core (Hopper 1999) suggests that there are about 5 different stages, numbered from 1 to 5. Stage one is the first to affect the rocks, and stage 5 is the last to affect the rocks. These stages are described below and summarised in the accompanying table.

Stage 1 is dominated by rocks enriched in Si, K, Fe and Na. Three different rock facies seem to have formed at roughly the same time: In the Lower Manto the pink to grey rocks of the silica-feldspar alteration zone, dominated by silica, Kspar and albite, and the enveloping halo of coarse intergrown magnetite, biotite, albite and/or scapolite overprint the metamorphic hornfelses of the Lower Andesitic Sequence. In the Upper Manto spotted to massive skarn of pale honey coloured garnet overprints the marbles of the Morenita Limestone.

These facies do not occur as infill in veins or breccias. They form pervasive alteration zones. They are thought to have originally co-existed because there is no clear evidence of one cutting the other. Rather they "intermingle" near contacts, with K-feldspar cutting magnetite say, and magnetite cutting K-feldspar.Alteration bodies are pseudostratiform suggesting lithological or bedding planar focussing.

Stage 2 seems to be an event of rock breakage and remobilisation. The brittle silica-feldspar altered rocks were brecciated, sheared and torn, and the more ductile magnetite hornfels remobilised to fill the spaces. Where the breakage was incipient the magnetite forms a fine crackle network. Where advanced it forms breccia matrix. Areas of alternating millimetric bands of laminated magnetite, silica and K-feldspar may be the result of bedding parallel laminar shearing.

Stage 3 is an infill event. It is typified by a mineral assemblage including, but not restricted to, amphibole in the Lower Manto or red-brown garnet in the Upper Manto. These occur with pyrite, chalcopyrite and bornite. In additon to these minerals infill magnetite, feldspar, quartz, calcite, and biotite/chlorite may or may not be present in variable proportions. In addition phlogopite and pyroxene (idocrase?) also occur in the skarn of the Upper Manto.

This "Main Stage" assemblage cuts across the silica-feldspar rocks, skarns and hornfelses of stages 1 and 2 and is clearly later. These channelways sometimes, but not always, have alteration haloes around them, which may be dominated by kspar, biotite, albite, amphiboles or brown garnets. Stage 3 mineralisation occurs in all of the "pre-main stage" units. In the silica-feldspar zone it occurs as veins, breccias and crackle networks due to the brittle nature of the rock. In the skarn it occurs as irregular triangular infill between the garnet grains. In the magnetite hornfelses it occurs as intergranular disseminations and grain chains, with veins becoming more common as the grain size decreases.

Stage 4 appears to be dominated by epidote and calcite with variable amounts of quartz, chlorite and albite. Pyrite and pyrrhotite occur locally in this assemblage. Stage 4 occurs as channelway infill, which cross-cuts the previous stages. Chloritic alteration of earlier biotites, amphiboles

Pre Main Stage		*Main Stage*	*Post Main Stage*	
STAGE 1	**STAGE 2**	**STAGE 3**	**STAGE 4**	**STAGE 5**
Pervasive silica-feldspar and honey coloured garnet "alteration". Enveloped by pervasive magnetite-biotite alteration.	Breakage and shearing of stage 1 rocks and partial remobilisation of magnetite into laminae, veinlets and breccia matrices.	Chalcopyrite-bornite-pyrite-pyrrhotite infill in veinlets, and intergranular spaces associated with amphibole / brown garnet infill and alteration	Calcite-epidote and possible pyrite / pyrrhotite infilling veinlets.	Weak sericite alteration along channelways.
		Chloritic alteration of earlier minerals?		

Summary Table of the Panulcillo Paragenetic Sequence.

and feldspars may correspond to this stage or Stage 3.

Stage 5 is represented by only rare sericite alteration which appears to be a late overprint.

Dating of coarse-grained infill phlogopite from the Upper Manto (Ardila 1993) gave an age of 115 ma ± 3ma for Main Stage alteration-mineralisation. This is within the range of most Chilean FeOx CuAu deposits between Copiapo and Ovalle.

Genetic Considerations

The Main Stage mineralisation and alteration observed at Panulcillo clearly cross-cuts, and post-dates the metamorphic hornfelses, marbles and bi-metasomatic skarns which occur in the district-wide aureole of the monzodiorite intrusive. Main Stage mineralisation-alteration at Panulcillo is therefore late metamorphic to post-metamorphic in timing.

Despite this the mineralisation-alteration at Panulcillo shows a clear spatial relationship to the metamorphic hornfelses, marbles and skarns; for example the lower manto pinches out where the marbles pinch out, despite the fact that it is hosted entirely in hornfels, and the nearest similar occurrence lies on the opposite side of the intrusive, where hornfels is in contact with carbonates. This spatial affinity for carbonate rocks is seen throughout much of the Chilean FeOx CuAu province and suggests that the presence of carbonate rocks may have played an important role in focussing mineralisation-alteration, be it directly or indirectly.

Because of the competency contrast, and stratigraphic discontinuity they represent in the otherwise monotonous andesitic sequence, the marbles may have helped focus district and local stresses, resulting in faulting, shearing and fracturing near the marble-hornfels contacts. Alternatively the marbles may have acted as a physical and/or chemical barrier to the mineralising fluids. The third alternative is that the bimetasomatic reaction between the limestones and andesites during metamorphism set up a geochemical gradient which drew in, trapped, and probably interacted with, any late to post-metamorphic hydrothermal fluids.

The presence of hornfels is critical in providing a host for the mineralisation. In the majority of Chilean carbonate-related FeOx CuAu deposits the mineralisation occurs as infill in fractured or brecciated hornfels, or as grains disseminated in porous andesitic rocks, be they recrystallised or not. This reflects the importance of secondary permeability in focussing the mineralisation. The presence of significant quantities of magnetite in the hornfelses has also been cited as an important precursor for the precipitation of the copper mineralisation, though this is probably of much lesser importance than the presence of carbonate. This is evidenced by the widespread presence of fractured magnetite hornfelses throughout the Chilean Coastal Cordillera which are totally barren of Cu mineralisation.

The volumes of Cu and Au seen in Panulcillo could perhaps have been derived from the immediate country rocks during metamorphism and bimetasomatism. Rock-chip sampling suggests that the rocks of the Lower Andesitic Sequence which underlie the Lower Manto are depleted in Cu with respect to normal Chilean andesites. The small volume of mineralisation at Panulcillo and the single stage of Cu mineralisation, could also be evidence that in the case of Panulcillo, the Cu and Au were drawn in from the surrounding rocks by the bimetasomatic gradient.

Although this bimetasomatic interchange between the carbonates and andesites could account for the Cu, Au, Ca, Mn, Si and other minor components seen in the Panulcillo system, it can only account for a small proportion of the massive volumes of Fe seen throughout the district-wide metamorphic aureole and the K and Na seen in the pre-main stage alteration flood. It is suggested that much of the Fe, K and Na was derived from the monzodiorite intrusive or one of its differentiates. The presence of K-feldspar pegmatites, and bodies of layered magnetite-ilmenite gabbro suggest that these components were being concentrated and could have formed late-magmatic Fe, K and Na rich hydrothermal fluids.

It is the combination of the bimetasomatic geochemical engine of the carbonates, and the ground preparation of the hornfelses, which "captured" these late-magmatic hydrothermal fluids and gave rise to a "coupled" metasomatic-hydrothermal system. Such "coupling" would account for the co-mingling of ore-forming processes which is so typical, and indeed problematic, in this family of deposits. The relative contribution of magmatic versus metasomatic components to the coupled system could be the critical difference between a standard FeOx CuAu deposit such as Panulcillo, and a "world-class" deposit such as Candelaria.

Section II – The Teresa de Colmo Deposit

Regional Geology

The regional geological setting (Figure 5) of the Teresa de Colmo area comprises a gently dipping sequence of porphyritic andesite flows and volcanic breccias with intercalated sandstone and conglomerate layers, which are assigned to the Lower Cretaceous Aeropuerto Formation (Ulricksen, 1979). These stratified units are intruded by medium-grained granodioritic intrusives dated at 112 Ma (Naranjo *et al*, 1984), that form part of the Coastal Batholith, and are discordantly underlain by intermediate to acid volcanic rocks of the Chile-Alemania Formation (Chong, 1973), of Tertiary age. All these units have been eroded and covered by unconsolidated oligocene gravel deposits.

In terms of tonnage Teresa de Colmo is the most significant of the copper deposits. In addition to these metallic mineralisation types, apatite cemented breccias are exploited 6 km to the north of the Teresa de Colmo deposit.

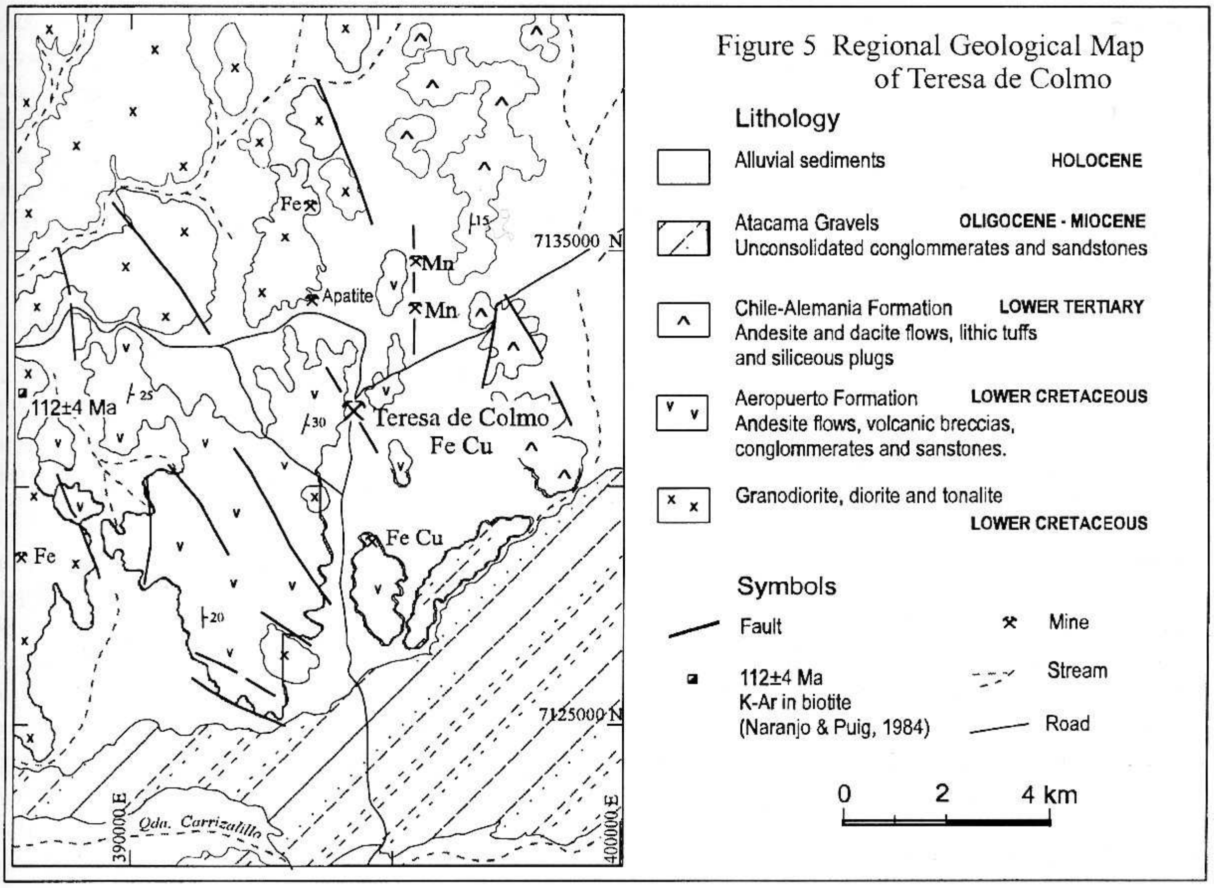


Figure 5 Regional Geological Map of Teresa de Colmo

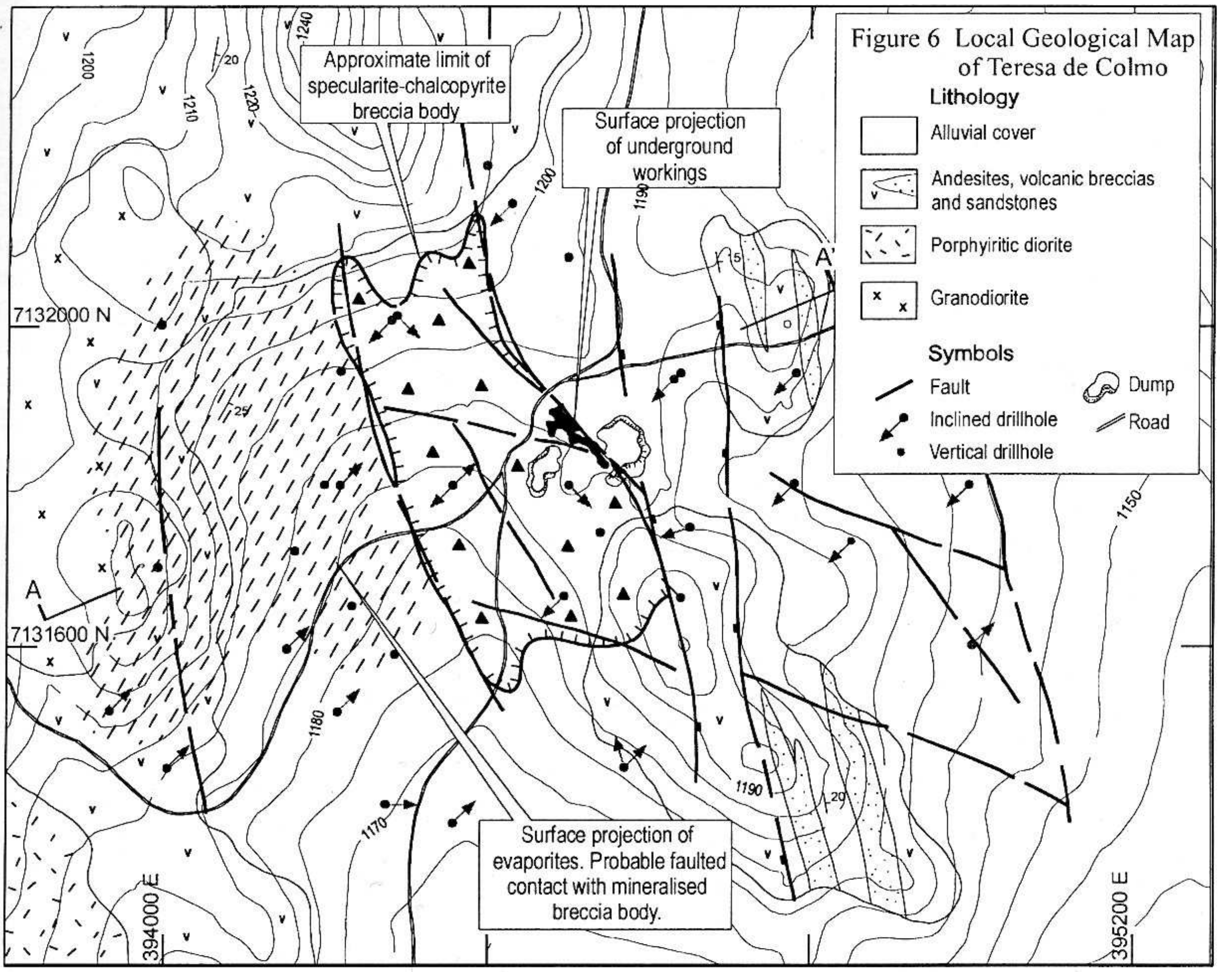


Figure 6 Local Geological Map of Teresa de Colmo

The main structures in the area are strike-slip faults, which exhibit a strong control on the morphology, formation and distribution of the deposits of the region. These structures are parallel to the Atacama Fault System, the most important structural feature in the Coastal belt of northern Chile and which has a long-lived deformation history, initiated during the Middle Jurassic (Scheuber *et al*, 1990).

Local Geology

The Teresa de Colmo deposit is hosted by andesitic volcanic and sedimentary rocks, cut by medium-grained Lower Cretaceous stocks. The deposit consists of a specularite-rich sub-vertical breccia body, developed in a dilational jog related to sinistral strike-slip faults.

The volcanic rocks are dominantly brown-green, porphyritic to aphanitic andesites, with intercalated layers of fine to medium grained sandstone and medium-grained conglomerate (Figure 6). An evaporite sequence was also recognized in diamond drillholes, which apparently concordantly underlies the volcano-sedimentary package. This evaporite unit is recognised to more than 200 mts depth and consists of well-laminated layers of gypsum, anhydrite and calcite, with some thin intercalations of chlorite, hematite, tourmaline, pyrite, and plagioclase (Correa, 1999).

A fine to medium-grained granodiorite and a porphyritic diorite outcrop to the west of the Teresa de Colmo deposit where they intrude the volcanics, sediments and, presumably, the evaporites. Figure 7 shows the interpreted contact relationship between all of these units. The intrusives do not show significant hydrothermal alteration, but they exhibit an anomalous content of specular hematite, as disseminations and in veinlets. In addition to these intrusive bodies, a leucodiorite stock was identified in drilling beneath 500 mts, with moderate albite alteration and weak disseminated chalcopyrite, pyrite and bornite mineralisation.

Two post-mineral dyke phases have also been recognised; One is related to the porphyritic diorite intrusive and the other is a microdiorite with a high content of disseminated magnetite. According to trench mapping, the microdiorite dyke cuts the porphyritic diorite dykes.

Structural control has played a very important role in the Teresa de Colmo deposit. Detailed trench and underground mapping has allowed the identification of important faults and their differentiation into mineralised (feeder) faults and non-mineralised faults (Pope, 1995). These structures show evidence of several phases and directions of syn and post-mineral faulting. Superposition of these deformations onto a breccia style of mineralisation has lead to a complex and irregular distribution of mineralisation, that has complicated the interpretation and evaluation of the deposit.

At surface, the breccia body appears to be located at the intersection between a group of NNW trending faults and a group of WNW trending faults (Figure 6). NNW trending fault surfaces usually have horizontal slickenslides displaying sinistral displacement, overprinted by steeply plunging slickenslides indicating a later extensional displacement (Pope, *op cit*). At the intersection of NNW trending faults with WNW trending faults brecciation is more intense and coincides with high-grade Cu mineralisation. The WNW trending faults exhibit steeply plunging grooves and slickenslides indicating extension. Post-mineral displacements are recorded by a later extensional movement that overprints the strike-slip faults. This resulted in the dislocation of the deposit by block faulting.

Mineralisation

The mineralised body at Teresa de Colmo is a subvertical hydrothermal-tectonic breccia system, that extendes for 600 mts in a NNW direction. The width varies between 180 and 300 mts and the depth is close to 450 mts from surface (Figures 6 and 7).

The breccia is usually matrix-supported and poorly sorted. It normally contains subangular to subrounded fragments of different types of andesites and sandstones, 1 to 60 cm in diameter, in a dark, dense, coarse-grained specularite matrix. The breccia which dominates the central part of the deposit contains subrounded polymictic clasts, and in many cases shows evidence for more than three stages of brecciation. This is indicated by the presence of coarse-grained specularite clasts with chalcopyrite, hosted within another clast supported by a fine-grained specularite matrix. These successive events of brittle deformation and brecciation reflect repeated displacements in the areas of fault intersection.

The copper mineralisation in the Teresa de Colmo deposit is found primarily in the breccia matrix, with lesser veinlet-hosted and disseminated mineralisation, in a ratio of 4:1:1. Examination of textural and paragenetic relationships indicates that the Teresa de Colmo pyrite – chalcopyrite–specularite hypogene mineralisation was deposited during at least two stages as described below.

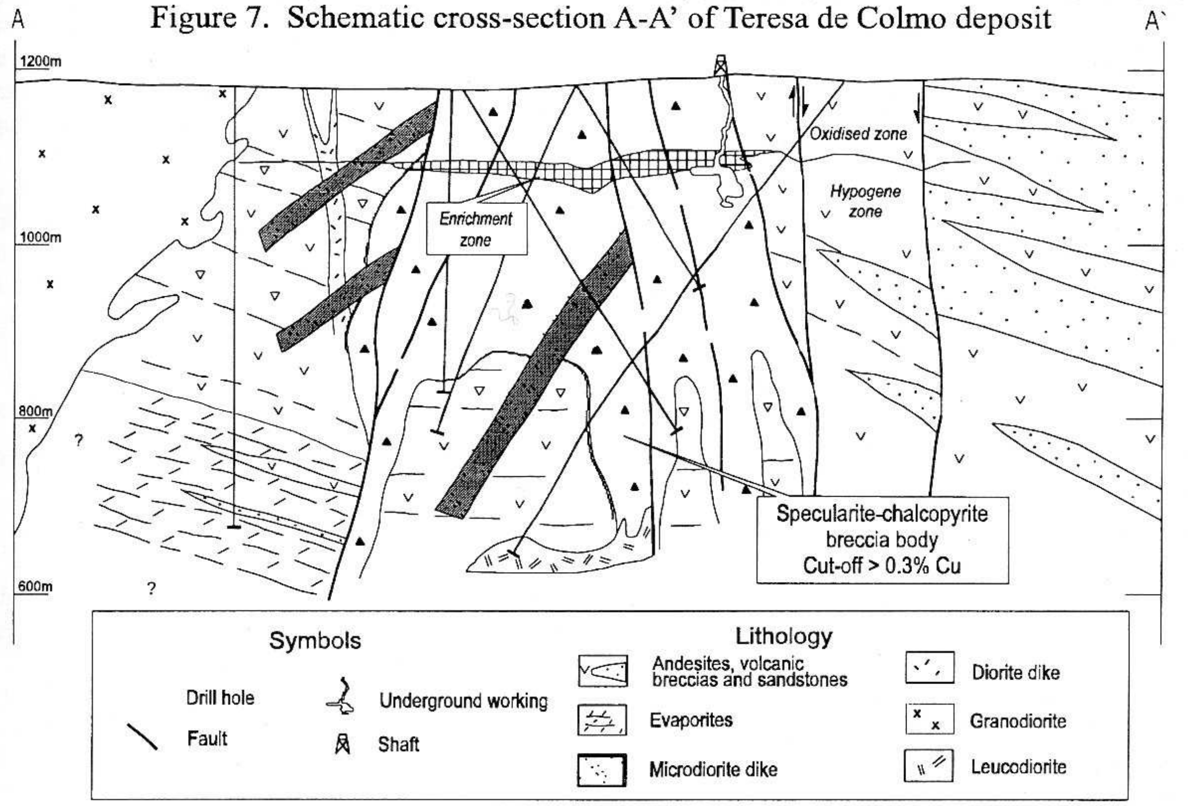
First stage

This stage is characterised by idiomorphic pyrite and subidiomorphic chalcopyrite, the latter frequently nucleating on the former, suggesting that the chalcopyrite is later than the pyrite. This replacement is more intense in the core of the deposit with a ratio of 5:1 chalcopyrite: pyrite, while towards the periphery this ratio is close to 1:1. The chalcopyrite mineralisation occurs in three main styles: a) coarse grained brecciated clumps within veins and the matrix of the more strongly brecciated zones; b) veins of pure chalcopyrite up to several centimetres in thickness; and c) disseminated in microveinlets within andesites, and in the matrix of coarse grained sandstones and conglomerates.

Second stage

This stage is characterised by specularite mineralisation, which generally uses the same fractures as the sulphide mineralisation. This mineralising phase is thought to be lower temperature and brittle, and is interpreted to represent

Figure 7. Schematic cross-section A-A' of Teresa de Colmo deposit



an explosive pressure release, resulting in the formation of collapse breccias, with well-developed space-infilling textures. The specularite normally consists of coarse-grained idiomorphic blades that line vein margins, or clasts within the breccia bodies. Coarse grained idiomorphic calcite commonly mantles the specularite and, along with minor gypsum, forms the last phase to crystallise within the open spaces.

The vertical zonation of the Cu mineralisation (Figure 7) begins with the oxidised zone, which extends from surface to 90 mts depth. Below this a thin, secondary enrichment zone of 10 to 20 mts thickness has been developed. Beneath this the hypogene zone extends from 110 mts to at least 500 mts depth.

The oxidised zone is characterised by brown - green Cu - Fe oxides that consists essentially of atacamite, malachite and *almagre*, with minor chrysocolla and cuprite. Atacamite and malachite usually are found on fracture surfaces, while the *almagre* (informal name gives to a reddish, dusty Cu-Fe oxide mineral similar to Cu-pitch) is found in-situ, replacing large chalcopyrite crystals. These oxidised Cu minerals apparently represent the in-situ oxidation of sulphides, without a substantial vertical movement of Cu.

The secondary enrichment zone consists of a restricted flat subhorizontal body and is comprised of secondary chalcocite and covellite. This enrichment zone is limited because chalcopyrite has largely replaced pyrite, so only a minor amount of leaching has been generated during weathering.

The primary hypogene zone consists of chalcopyrite and pyrite with minor bornite and chalcocite.

Hydrothermal Alteration

The host rocks to the mineralised breccia body at Teresa de Colmo show weak to moderate evidence of hydrothermal alteration, that normally extends up to 150 mts away from the Fe-Cu mineralised zone. The alteration mineral assemblages are interpreted to result from at least two independent stages, similar to the mineralisation itself:

First Stage

The earliest alteration assemblage comprises albite (sodic alteration) and chlorite with minor silicification and calcite. Albite partially replaces plagioclase phenocrysts and pervasively affects the groundmass of the volcanic rocks. Chlorite replaces hornblende phenocrysts and to a lesser extent plagioclase feldspars. Silica and calcite are scant and normally occur in thin veinlets and as microcrystalline aggregates in the groundmass of rocks. This alteration stage was clearly associated with the sulphide mineralisation. Chalcopyryte-pyrite veinlets usually have thin albite halos.

Second stage

This latter phase consists of specularite, coarse calcite and anhidrite/gypsum. The alteration is not pervasive, but is typically confined to veins, up 1 mt wide, and the brecciated zones, where specularite, calcite and lesser anhidrite/gypsum occur as space filling gangue minerals which crystallised from the vein or void margin to the center in the above order.

In adition to these alteration phases, a pervasive red hematite alteration overlies or mantles the entire mineralised area. This alteration could be interpreted as a distal part of the albite-chlorite assemblage, or a cooler temperature more distal equivalent of the specularite breccias (Pope, 1995).

Sulphur Isotopes

A sulphur isotope study was done by Ledlie (1998) on the sulphides and sulphates present in the Teresa de Colmo deposit, to determine the nature and source of the mineralising fluids. This study has special relevance considering that the mineralised body is spatially close to a major evaporite sequence, that has been postulated as a source of sulphur and metalliferous brines or hypersaline fluids (Barton *et al*, 1996).

The values obtained of $d^{34}S$ for chalcopyrite vary between -3,36 and 5,51‰ and for pyrite range from 0,15 to 5,15‰. Results of $d^{34}S$ presents in late anhidrite/gypsum veins have a mean of 3,31‰, while in the evaporites the $d^{34}S$ vary between 16,7 and 18,24‰.

These results suggest a magmatic hydrothermal source of $d^{34}S$ for sulphides and sulphates in the Teresa de Colmo deposit, contrasting with the values of the evaporites that would indicate a marine origin. The wider range of chalcopyrite isotope values in comparison with pyrite values might indicate more than one stage of copper mineralisation, as suspected from textural observations and paragenetic relationships.

The main conclusion is that the source of $d^{34}S$ for sulphide and sulphate within the Teresa de Colmo deposit is magmatic and not related to or influenced by the evaporites, despite their proximity.

Genetic Considerations

The Teresa de Colmo specularite – chalcopyrite deposit is thought to be a multiphase hydrothermal - tectonic breccia body associated with the structurally focussed emplacement of a discrete leucodioritic stock (Figure 7). This stock is thought to be a metal and volatile-rich late-stage differentiate of the Coastal Batholith, which was emplaced during a change from an extensional to a sinistral strike-slip regime related to the Atacama Fault Zone (Pope, 1995).

Discussion

Both Panulcillo and Teresa de Colmo can be considered members of the FeOx CuAu family of deposits. Both deposits are high Fe, low S systems in which Fe-oxides are a major constituent (Pollard & Taylor 1999). Cu-Au Mineralisation occurs with relatively little Fe-sulphide and overprints earlier pervasive sodic alteration. However, despite these important similarities, the two deposits also show major differences.

In addition to sodic alteration, Cu-Au mineralisation at Panulcillo occurs with pervasive potassic alteration represented by K-feldspar and biotite. A significant calcic component is also represented by amphiboles, epidote and calcite, while Chlorite, although present, is a relatively minor component. In contrast, Teresa de Colmo has no potassic alteration, and calcic alteration is limited to calcite.

The Panulcillo system therefore seems to have contained more K and Ca than Teresa de Colmo. The extra Ca can be accounted for by the interaction of the Morenita Limestone with the surrounding rocks and fluids, while the extra K on the other hand could have come from the monzodiorite intrusive, which by definition is more potassic than the leucodiorite observed at Teresa de Colmo.

The Panulcillo deposit lies entirely within a district-wide aureole of weak to moderate magnetite alteration, and is surrounded by an envelope of intense magnetite-albite-scapolite alteration. Magnetite also occurs as a minor component of the Main Stage mineralisation. At Teresa de Colmo on the other hand, the main stage mineralisation is hosted by a specularite-matrix breccia, surrounded by strong specularite alteration passing out into pervasive district-wide red-hematite dusting.

Ductile shear-induced deformation, lamination and brecciation is a common feature at Panulcillo, whereas brittle hydrothermal or explosive matrix-supported breccias have not been observed. Teresa de Colmo in contrast is a well developed matrix-supported breccia body. Ductile fabrics are absent.

Chalcopyrite at Panulcillo zones into bornite, and pyrite into pyrrhotite. At Teresa de Colmo however mineralisation is restricted to chalcopyrite and pyrite.

The contrasting Fe-oxide species imply that Panulcillo formed under reducing conditions whereas Teresa de Colmo formed under oxidising conditions. The presence of pyrrhotite and bornite in Panulcillo may also be taken as an indication of more reducing conditions.This suggests that Panulcillo formed at greater depths in the crust than Teresa de Colmo, as supported by the observation of ductile textures in the former, and the more brittle textures of the later.

The differences between the Panulcillo deposit and the Teresa de Colmo deposit can therefore be accounted for by local factors, such as the presence or absence of carbonate rocks, composition of related intrusives, and depths of emplacement, which in turn influence the tectonic regime and style of mineralisation. Not withstanding these locally induced variations, the dominant components of the two deposits, Fe, Cu, Au and Na, remain the same and reflect a common parentage.

In our opinion the Panulcillo and Teresa de Colmo deposits were formed by similar hydrothermal fluids rich in Fe, Cu, Au and Na which were derived from intermediate intrusive rocks, and which then interacted with the country rocks in varying degrees, under distinct conditions, and with different consequences. The relative contribution of the original parent fluids and the subsequently modified daughter fluids to the final mineralising system depends on a wide range of variables including temperature, depth, the nature of the country rocks, and the degree of coupling.

We consider the bewildering diversity of FeOx CuAu deposits to be an inherent characteristic of the family, reflecting as it does the variability of the host rocks with which the parent fluids have interacted. Nonetheless, however modified the daughter fluids become, the original magmatic-derived parent fluid remains, and gives rise to the common features which underpin the FeOx CuAu family of ore-deposits, both in Chile and worldwide.

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