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Rieger, A.A., Marschik, R. and Díaz, M., 2010 - The Mantoverde District, Northern Chile: an Example of Distal Portions of Zoned IOCG Systems; *in* Porter, T.M., (ed.), Hydrothermal Iron Oxide Copper-Gold and Related Deposits: A Global Perspective, v. 3 - Advances in the Understanding of IOCG Deposits; *PGC Publishing, Adelaide*, pp. 273-284.

THE MANTOVERDE DISTRICT, NORTHERN CHILE: AN EXAMPLE OF DISTAL PORTIONS OF ZONED IOCG SYSTEMS

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Abstract - The Mantoverde IOCG district is located in the Chilean Coastal Cordillera about 100 km north of the city of Copiapó. With an annual SX-EW production of 60 000 tonnes of fine copper, Anglo American's Mantoverde mine is one of the most important operations in the world exploiting this class of deposit. The hypogene ores, which have recently been evaluated, are mainly Cu-Au-bearing specularite and/or magnetite-rich breccias and stockworks. The orebodies are hosted in a tectonic block of Jurassic andesitic rocks between two branches of the north-south trending Atacama Fault Zone. The Mantoverde Fault (MVF), a major brittle, northnorthwest-trending, 40 to 50°E dipping structure, divides this block into an upper southwestern and a tectonically downthrown northeastern part. Four main ore zones, Kuroki, Mantoverde Norte, Mantoverde Sur, and Franko, occur along the MVF. Other major orebodies, Manto Ruso and Celso, are located in structures subparallel to, and at some distance from the MVF. Chalcopyrite is the main hypogene Cu mineral. The mineralisation can be subdivided into three hydrothermal stages: (1) an early high-temperature Iron Oxide Stage comprising the bulk of specularite-magnetite present in the district; (2) a Sulphide Stage responsible for the main Cu-Au mineralisation; and (3) a Late Stage, represented mainly by calcite ± specularite veining, specularite veining, and pervasive carbonatisation. The host rocks at Mantoverde suffered variable degrees of K-feldspar, chlorite, sericite, quartz and carbonate alteration, characteristic of the distal facies of zoned IOCG-systems.

The distribution of iron oxide phases within the district reveals an upward and outward zonation from magnetite-rich ores, representing the more proximal zones, to specularite-dominated ores in the distal portions of the hydrothermal system. A zonation is also recognised in the sulphur isotope signatures of chalcopyrite as a function of its spatial distribution. $\delta^{34}S_{VCDT}$ values centred around 0 ‰, suggesting a magmatic-derived sulphur component, are characteristic for chalcopyrite in orebodies with a close spatial relationship with the MVF in the southern and deeper central part of the Mantoverde district, representing the more internal parts of this IOCG hydrothermal system. Higher $\delta^{34}S_{VCDT}$ values, roughly around +6 ‰, are typical for northern part of the district or shallower levels of the hydrothermal system, and are suggestive of sulphur input from a non-magmatic source. The new data is consistent with previously suggested genetic models in which a metal- and sulphur-bearing magmatic-hydrothermal brine ascends, cools and mixes with a non-magmatic, more dilute surficial fluid, which also contributes sulphur (and metals?).

Introduction

The Mantoverde IOCG district is located in the Chilean Coastal Cordillera, approximately 50 km to the southeast of Chañaral harbour and 100 km north of the city of Copiapó (Fig. 1). The first documented work at Mantoverde dates back to the 18th century. Later, various companies explored in the area without substantial success. At the end of 1988, the property was optioned by Empresa Minera Mantos Blancos S.A., a subsidiary of Anglo American Plc. The company commenced exploration in 1989 and subsequently discovered a large orebody in the central part of the district, now known as Mantoverde Norte.

Mining activity started in 1996, with production focused on leachable copper oxides ores. The original resource was 120 Mt of copper oxides with an average grade of 0.72% Cu, at a 0.2% Cu cut-off, including a mineable reserve of 85 Mt at 0.82% Cu (Vila *et al.*, 1996). Complementary discoveries made up until 2007 include the Mantoverde Sur, Manto Ruso, Celso, Kuroki and Franko orebodies, which increased the total mineable reserve to 242.2 Mt of copper oxides averaging 0.64% Cu at a 0.15% Cu cut-off (Fig. 2). Based on the current three pit operation (Mantoverde Norte, Mantoverde Sur and Manto Ruso), the expected mine life has been extended until 2014. With an annual rock movement of 30 Mt and a fine copper production of 60 000 tonnes that comes from an on-site SX-EW operation, Mantoverde is one of the most important mining operations based on an IOCG deposit in the world. Recent drill testing has outlined an additional resource of 440 Mt of hypogene ore grading 0.56 % Cu and 0.12 g/t Au at a 0.20 % Cu cut-off.

In this contribution we summarise the main characteristics of the Mantoverde district, highlighting the new developments at Mantoverde Norte, Mantoverde Sur and Manto Ruso. We present a new paragenetic scheme, discuss new and previously published analytical data, and aspects of IOCG deposit formation in general.

Geologic Context

The basement rocks exposed along the coast in the Chañaral and Copiapó region are metasediments of Devonian to Carboniferous age (Mercado, 1978; Lara and Godoy, 1998) and Permo-Triassic plutons (Berg and Baumann, 1985; Brown, 1991). A magmatic arc/back-arc pair formed in Jurassic to Early Cretaceous times. It is characterised by an extensional regime in the back-arc and subduction-related calc-alkaline magmatism (Coira *et al.*, 1982; Mpodozis and Ramos, 1990). The latter caused deposition of the volcanic rocks of the Jurassic La

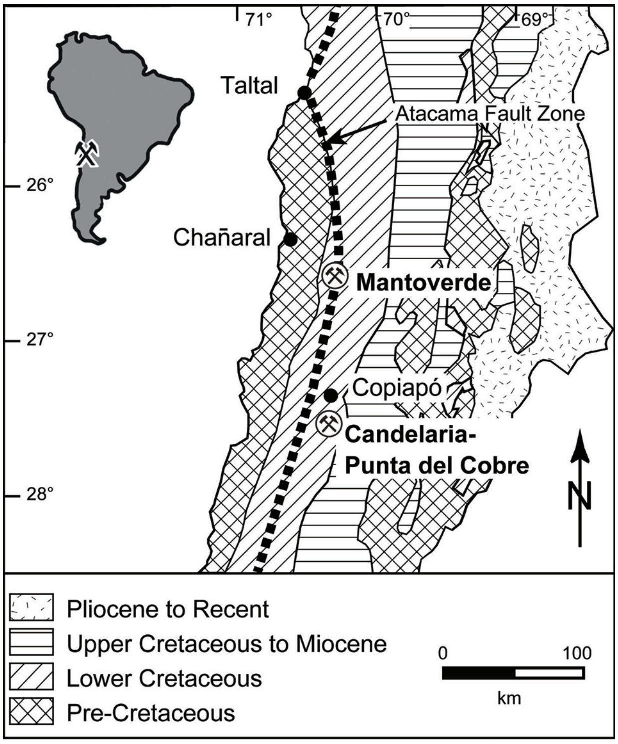

Figure 1: Regional geological and location map showing the position of the Mantoverde and Candelaria-Punta del Cobre IOCG districts.

Negra Formation (García, 1967; Lara and Godoy, 1998; Gelcich *et al.*, 2004) and the Lower Cretaceous Bandurrias Group (e.g. Moscoso *et al.*, 1982) in the Coastal Range and Precordillera. The volcanic rocks are intruded by Jurassic and Early Cretaceous granitoids (Berg and Breitkreuz, 1983; Berg and Baumann, 1985; Dallmeyer *et al.*, 1996; Lara and Godoy, 1998; Gelcich, 2005; Marschik and Söllner, 2006). Petrogenetic studies suggest that these plutons are derived from partial melts of the mantle under hydrous conditions without substantial crustal contamination ($^{87}\text{Sr}/^{86}\text{Sr} = 0.703$ to 0.706 and $\varepsilon\text{Nd} = +5.1$ to +6.4; Berg and Baumann, 1985; Hodkinson *et al.*, 1995; Marschik *et al.*, 2003). The Palaeozoic and Mesozoic units are partially covered by semi-consolidate Pliocene to Holocene colluvial gravels and unconsolidated Quaternary alluvial sediments.

The dominant structural feature in the region is the north-south trending Atacama Fault Zone (AFZ), which cuts the Jurassic and Cretaceous rocks (Naranjo, 1987), and allowed the emplacement of mantle-derived magmas into shallow crustal levels (Dallmeyer *et al.*, 1996; Grocott and Taylor, 2002; Fig. 1). The AFZ is a major arc-parallel structure, concave to the west, which extends at least 1000 km through the Chilean Coastal Cordillera from Iquique to La Serena and which has been active at least since Jurassic times (e.g., Scheuber and Andriessen, 1990; Taylor *et al.*, 1998 and references therein). During the Early Cretaceous the AFZ evolved as a ductile to brittle, trench-linked, sinistral, strike-slip duplex system (Brown *et al.*, 1993; Taylor *et al.*, 1998).

District Geology

The Mantoverde district represents a structural block of mainly volcanic rocks, limited by the central and eastern (or oriental) branches of the AFZ (Fig. 2). Both branches are connected by a 12 km long, 160 to 165° trending and 40 to 50°E dipping brittle structure, the Mantoverde Fault (MVF). The MVF and several minor northwest faults were initially sinistral strike-slip structures, which resulted from the duplex evolution of the AFZ (Brown *et al.*, 1993; Sanhueza and Robles, 1999). A later extensional event produced the reactivation of the MVF as a normal dip-slip scissors fault, together with the development of similar curved northnorthwest to north-south normal faults (Sanhueza and Robles, 1999; Fig. 3). This produced tilting of the northeastern part of the district with a northeastern-down sense (Orrego and Zamora, 1991; Sanhueza and Robles, 1999). The outcropping andesite flows, breccias and volcanoclastic rocks have been correlated with the Jurassic La Negra Formation (Lara and Godoy, 1998). These rocks have been interpreted as roof pendants (Mercado, 1978) and are surrounded by three Early Cretaceous plutonic complexes: the quartz monzodiorites and granodiorites of the Cerro Morado complex (130 to 135 Ma; Lara and Godoy, 1998), biotite-hornblende granodiorites of the Las Tazas complex (~130 Ma; Berg and Breitkreuz, 1983; Lara and Godoy, 1998), and hornblende-biotite granodiorites, quartz-diorites and tonalites of the Sierra Dieciocho complex (~120 to 127 Ma; Zentilli, 1974; Dallmeyer *et al.*, 1996; Lara and Godoy, 1998). Apophyses of these complexes occur at depth in the mineralised zones. Granitic dykes crop out subparallel to the MVF or to the eastern branch of the AFZ (Astudillo, 2001). Late porphyritic to microphaneritic dioritic dykes cut all of the volcanic and intrusive rocks in the district.

Mineralisation Styles

The major Mantoverde Norte and Mantoverde Sur ore zones, and the smaller Kuroki, Laura and Franko deposits show a close spatial relationship with the MVF (Fig. 2). In contrast, other deposits located in the northeastern (Manto Ruso and Celso) and southwestern (San Juan, not shown in Fig. 2) parts of the district are unrelated to the AFZ, although there is a relationship with subparallel northnorthwest to northwest structures. IOCG deposits commonly display a vertical zonation with respect to the iron oxide species, with specularite at shallow levels and magnetite at depth (e.g. Marschik and Fontboté, 2001). Such a vertical zonation is also present in the IOCG deposits in the Mantoverde district. Furthermore, a general district zonation with specularite-rich bodies in the northern and central part (Celso, Manto Ruso, Kuroki and Mantoverde Norte) to magnetite-dominated ore zones in the southern part (Mantoverde Sur and Franko) is recognised and interpreted as a result faulting and tilting, and partial erosion of the host rock sequence (Zamora and Castillo, 2001; Fig. 3).

Five main units relevant to mining have been defined in the Mantoverde Norte area: the Manto Atacama, the Transition Zone, the Mantoverde Breccia, the Magnetite Zone and the Breccia Verde (Fig. 4a). Similar, corresponding rock-types have been encountered in all of the ore zones in the district (Fig. 4b and c). The Manto Atacama is a specularite-cemented hydrothermal breccia, with a nearly tabular shape (0 to 200 m thickness), situated in the immediate hanging wall of the MVF at Mantoverde Norte (Fig. 4a). The Cu minerals (sulphides or supergene Cu oxides) occur interstitially to the specularite. The Manto Atacama grades into a Cu-bearing specularite stockwork, which is referred to as the Transition Zone. The Transition Zone was developed in andesite or diorite in the hanging wall of the MVF (Fig. 4a and b). Both, the Manto Atacama and the Transition Zone diminish in thickness towards the south i.e. towards the northern part of Mantoverde Sur,

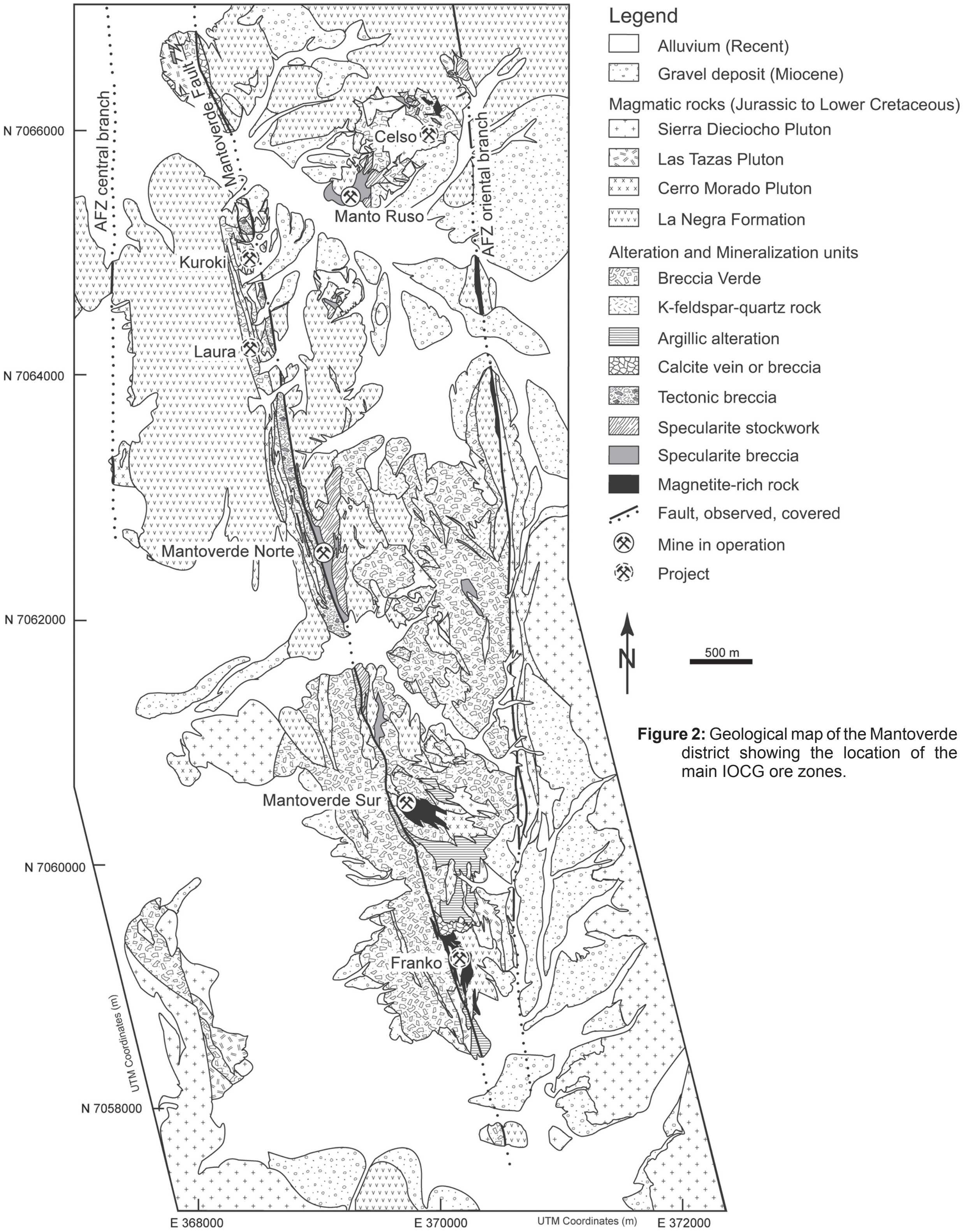

Figure 2: Geological map of the Mantoverde district showing the location of the main IOCG ore zones.

where they finally disappear. In the footwall of, and parallel to the MVF, lies the Mantoverde Breccia, which is a 20 to 40 m thick mineralised cataclasite rock of tectonic origin. The Magnetite Zone consists of Cu-Au-bearing massive magnetite bodies and magnetite-cemented breccias, or magnetite stockworks and disseminations. It is the predominant ore-type in the southern part of the district, where it is present both at depth and near surface. Core drilling confirms the continuity of the Magnetite Zone at depth between the presently operated Mantoverde Norte and Mantoverde Sur pits, and suggests that the bulk of the hypogene Cu-Au in the district is associated with it. The Breccia Verde shows close spatial relationships with iron oxide-rich Cu-Au bearing units (Fig. 4). It consists of silicified volcanic and dioritic fragments in a chlorite-quartz-rich matrix. The Breccia Verde is largely barren but may locally contain significant Cu-Au grades, which are mostly linked to zones with iron oxide veinlets.

At some distance from the MVF, in the northeast of the district, the main orebody of the Manto Ruso deposit comprises the Manto Ruso Breccia (Orrego and Zamora, 1991; Fig. 2 and 4c). Mineralisation appears to be not

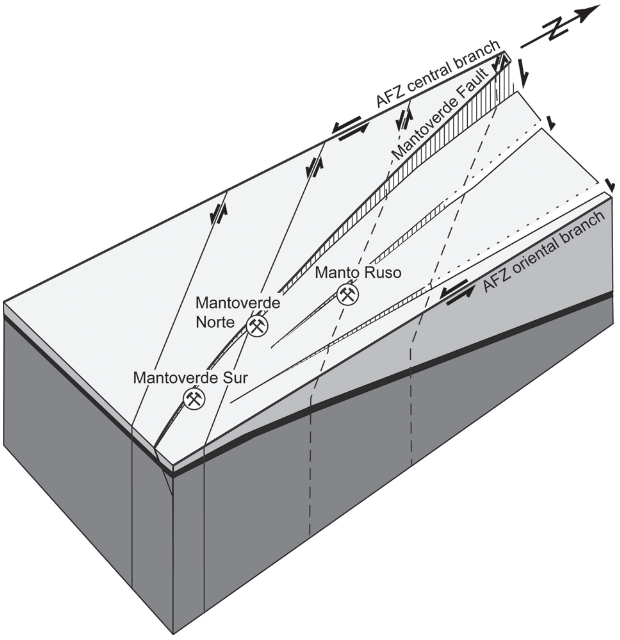

Figure 3: Structural model of the Mantoverde district (not to scale; after Orrego and Zamora, 1991, and Sanhueza and Robles, 1999). An imaginary reference horizon is shown in black to indicate the displacement of the northeastern part of the district.

only controlled by northnorthwest structures, but also by favourable subhorizontal volcanoclastic units. The Manto Ruso Breccia is a Cu-Au-bearing specularite-cemented breccia, with andesitic and dioritic fragments, that resembles the Manto Atacama at Mantoverde Norte, and grades into a dense specularite stockwork similar to the Transition Zone. A breccia similar to the Breccia Verde (Breccia Temprana of Orrego and Zamora, 1991) envelopes the two latter rock-types (Fig. 4c).

Hydrothermal Alteration

Chlorite-quartz alteration is widespread in the Mantoverde district. It grades from a slightly chloritised country rock, to chlorite-quartz veinlets, into chlorite-quartz-cemented hydrothermal breccias with mostly silicified and occasionally K-altered fragments (Breccia Verde, Breccia Temprana). The ore-related hydrothermal alteration in the district is characterised by variably intense K-alteration, silicification, chloritisation, sericitisation, carbonatisation, and/or argillic alteration. Additionally, the rocks can contain minor tourmaline, scapolite, titanite, allanite, zeolite and scarce relicts of hydrothermal biotite, which survived chloritisation. Later alteration phases re-use the conduits of earlier phases, which cause variably complex alteration mineral associations in rocks and veinlets. Intense potassium metasomatism is reflected by abundant K-feldspar (e.g. Vila *et al.*, 1996). The degree of alteration varies from selective replacement of the primary feldspar in the volcanic and intrusive host rocks, which allowed the preservation of the original textures, to texture destructive, pervasive K-alteration or K-feldspar floodings, which affected parts of the igneous host rocks. This latter type of alteration commonly envelopes specularite veinlets or is manifested as rims along the margin of breccia clasts which may be replaced more or less completely. An increase in sericite towards the mineralised bodies is recognised, supposedly formed at the expense of K-feldspar (Vila *et al.*, 1996). In the Transition Zone of Mantoverde Norte, cross-cutting relationships of veinlets suggest that pervasive K-metasomatism occurred prior to the chlorite-quartz±sericite alteration (Vila *et al.*, 1996). Similar relationships have been observed at several places in the district. Carbonatisation is mostly fracture-controlled and expressed as abundant calcite veins and veinlets, while minor siderite is present in places (Astudillo, 2001). Calcite veins are commonly barren in the hypogene Cu zone and cut the orebodies, although chalcopyrite fragments are observed locally in calcite veins where these veins cut through previously mineralised rocks. Minor quantities of chalcopyrite intergrowths or chalcopyrite veinlets cutting calcite have been occasionally observed (see 'Paragenetic Sequence' below). Carbonate veinlets may also contain Cu oxides near surface within the district (Orrego and Zamora, 1991; Zamora and Castillo, 2001). Argillic alteration, with kaolinite±chlorite±sericite, occurs in the proximities of the Magnetite Zone in the southern part of the district (Fig. 2).

Ore Mineralogy

The current production in the Mantoverde district comes from near surface leachable copper oxide ore. The thickness of the oxide zone at Mantoverde Norte and Mantoverde Sur varies from 150 to 250 m (Fig. 4). The Cu oxide minerals, which are spatially associated with specularite in the Manto Atacama and Transition Zone, are chrysocolla, malachite or brochantite, and minor atacamite, antlerite, cuprite or almagre (iron oxides with traces of copper termed 'sangre de toro' in Central and South America). These minerals are found mainly as part of the matrix, as filling of cavities or fractures, and as patina on, or as patches or disseminations in the rock fragments (pers. com. C. Astudillo, 2007). In the Mantoverde Breccia, the most important ore minerals occurring as filling of cavities and fractures are malachite, chrysocolla, almagre, atacamite and brochantite. In the Magnetite Zone of Mantoverde Sur, chrysocolla, brochantite and minor almagre are present as disseminations and/or as filling of veinlets or cavities. At Manto Ruso, the thickness of the oxidation zone varies roughly between 40 and 100 m (Fig. 4c). The supergene ore mineralogy comprises chrysocolla, brochantite, atacamite and almagre (Orrego and Zamora, 1991), which are disseminated in the matrix, as filling of veinlets, or as patina on, or patches within, the rock fragments of the Manto Ruso Breccia.

Beneath the oxidation zones, and in part coexisting with the Cu oxides, an up to 5 m thick, subhorizontal horizon of supergene enrichment is found (Vila *et al.*, 1996). This horizon is characterised mainly by chalcocite, covellite and minor native copper, cuprite, digenite and bornite. The hypogene sulphides are chalcopyrite and pyrite, which have been recognised underneath both the oxidation and supergene enrichment zones of Mantoverde Norte (Vila *et al.*, 1996), Mantoverde Sur (Zamora and Castillo, 2001) and Manto Ruso (Orrego and Zamora, 1991). Native gold or electrum have not been observed yet in samples from the Mantoverde district. However, there is a good positive correlation between gold concentration and Cu content, and gold has been detected in both, chalcopyrite and pyrite. Elevated concentration of light rare earth elements occur locally. Allanite is relatively common and is a potential host to these REE, whereas apatite is present in relatively small quantities in the deposits and probably plays only a minor role for the REE grade in the ore deposits. A systematic study of the REE mineralisation and distribution is still pending.

Paragenetic Sequence and Age of Mineralisation

The paragenetic sequence of the hypogene mineralisation in the Mantoverde district is illustrated in Fig. 5. In analogy with the Candelaria-Punta del Cobre IOCG system near Copiapó (Marschik and Fontboté, 2001), three main hydrothermal stages are distinguished: an early Iron Oxide Stage, a Sulphide Stage, and a Late Hydrothermal Stage.

The Iron Oxide Stage is characterised by intense iron metasomatism, pervasive K-feldspar alteration, silicification and hydrolitic alteration. Early specular hematite (hm-I), was followed by magnetite (mt-I), and the formation of mushketovite, the pseudomorphic replacement of specularite by magnetite. Minor tourmalinisation, and weakly developed Na(-Ca) alteration (scapolite) occurred after mt-I. Variably intense silicification, pervasive sericitisation and minor pyrite (py-I) formation culminated in a second phase of magnetite (mt-II) mineralisation, and chloritisation. Allanite occurs together with mt-II and chlorite. Locally, specularite may have developed instead of (or in addition to?) mt-II.

The main copper-gold mineralisation took place during the Sulphide Stage. Quartz, K feldspar-quartz and sericite ± quartz veining occurred before the sulphide mineralisation, while the main pyrite (py-II) crystallisation took place prior to chalcopyrite. The Late Hydrothermal Stage is characterised by pervasive carbonatisation, calcite veining, and another generation of specularite (hm-II). Thin quartz or sericite veinlets and minor pyrite ± chalcopyrite associated with calcite developed locally during this stage.

An Early Cretaceous age of the mineralisation is constrained by K-Ar-dating of two samples of hydrothermal sericite from Mantoverde Norte (Vila *et al.*, 1996). The minimum ages obtained were 117±3 Ma from an andesite of the Transition Zone and 121±3 Ma from a granite dyke (Vila *et al.*, 1996). An age estimate of 116 Ma for the magnetite formation, based on a two-point isochron from Re-Os analysis on magnetite, is consistent with the alteration ages (Mathur *et al.*, 2002).

Geochemistry

We analysed variably altered rocks from Mantoverde Norte, Mantoverde Sur and Manto Ruso, to determine major, trace and rare earth elements (REE) concentrations and investigate characteristics of the alteration. The analytical data was normalised against a reference andesite (reference data from the GERM Reservoir Database; Weaver and Tarney, 1984 and Ewart, 1982), to illustrate changes to the inferred original geochemical composition of the host rocks (Fig. 6). Sample MV 96-1 stems from the tectonic breccia (Mantoverde Breccia), whereas MV 96-4 and MV 07524 have been collected from the Transition Zone of Mantoverde Norte. These three samples have been taken from surface outcrops or near surface core sections. The sample MV 96-5 represents the upper part of the specularite breccia of the Manto Atacama at Mantoverde

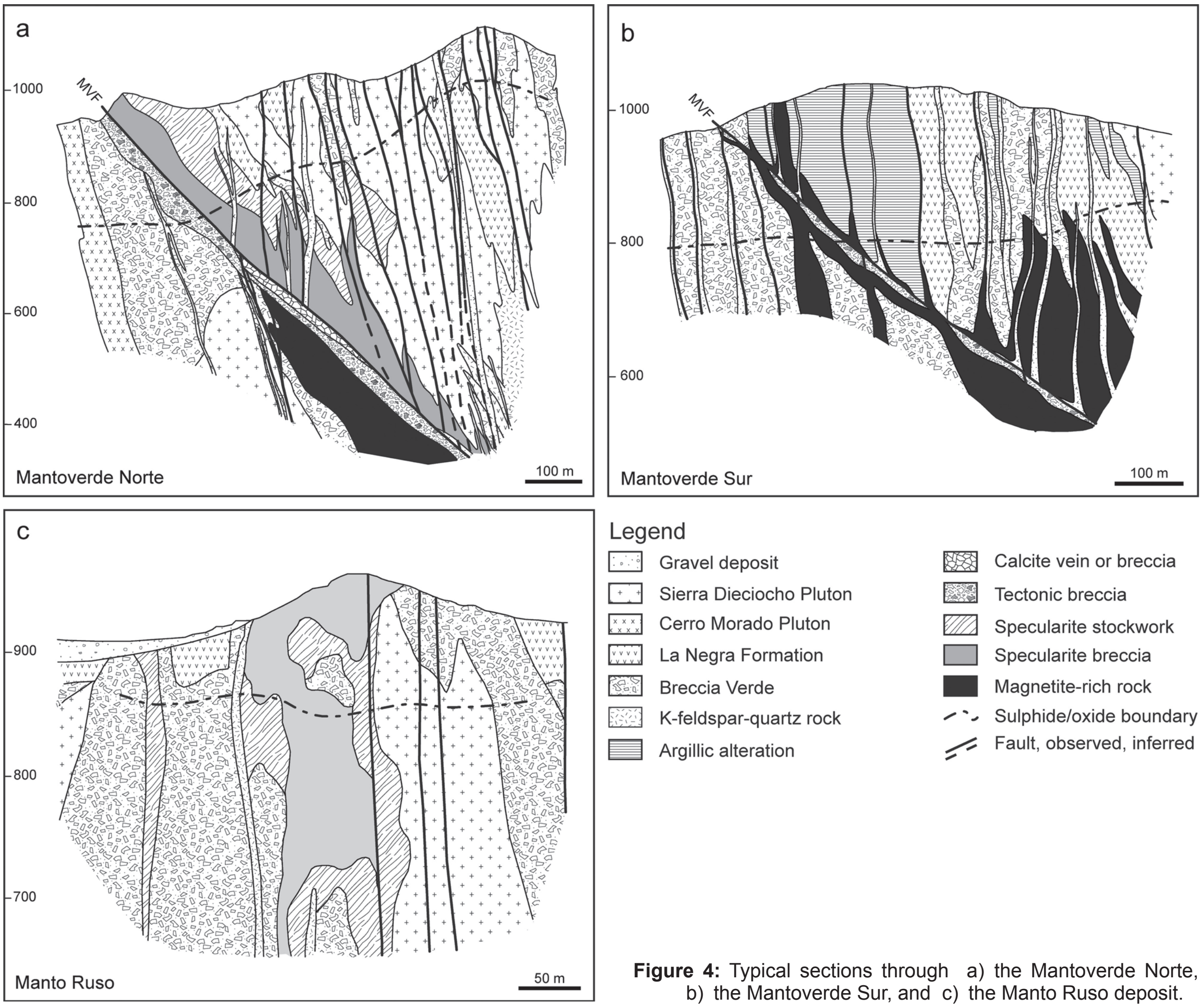

Figure 4: Typical sections through a) the Mantoverde Norte, b) the Mantoverde Sur, and c) the Manto Ruso deposit.

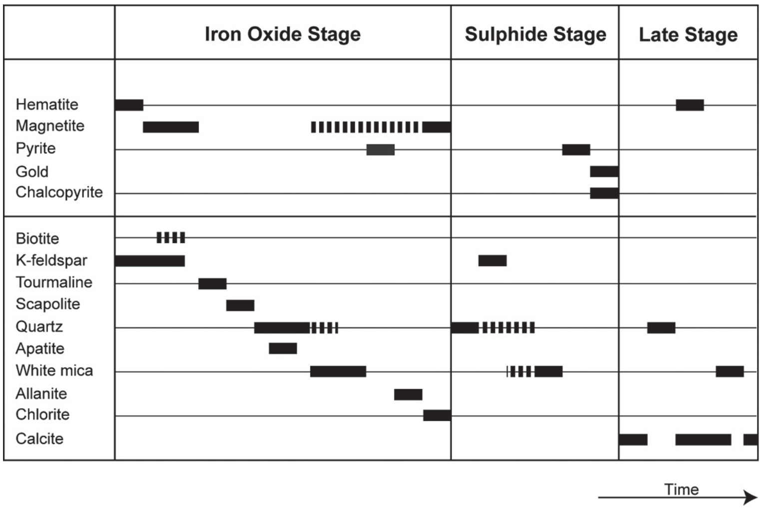

Figure 5: Simplified paragenetic sequence of the IOCG deposits in the Mantoverde district.

Norte. The rock fragments (MV 96-5-1) and the matrix (MV 96-5-2) of this latter breccia have been analysed separately. Further rock fragments from specularite breccias at Mantoverde Norte (MV 07427, MV 07514, MV 07526), Mantoverde Sur (MV 07356) and Manto Ruso (MV 07135) have been collected for comparison. The Magnetite Zone at Mantoverde Sur is represented by sample MV 07368. Analytical results of selected samples are given in Table 1.

K-metasomatism caused gains in K_2O of up to >13 wt.% in originally andesitic rocks. These gains are accompanied by losses of CaO and Na_2O. Silicification is manifested in SiO_2 contents of up to about 82 wt.%. Zn, Pb and Mo contents are generally low (Table 1), although there is one exception in which the Zn content in a sample from an ore zone is three times the reference andesite value. Light rare earth elements contents are variable, with La up to 574 ppm and Ce up to 937 ppm. In general, U and Th concentrations of altered rocks are low, averaging 1.4 or 3.6 ppm respectively and close to original values of the reference andesite (U = 1.3 ppm, Th = 6 ppm).

The normalised data of whole rocks from the various defined units are shown together in Fig. 6a. All rock units are depleted in CaO, Na_2O, Zn, Pb and Sr, and enriched in Cu and Co compared to the reference andesite composition. Except the Magnetite Zone, these units are also enriched in FeO, K_2O, Ba, Rb and light rare earth elements (LREE). Fig. 6b shows analytical data of the specularite breccia at Mantoverde Norte. Whole rock, fragments, and matrix of the breccia are compared. The data suggest that the element distribution in the rock fragments and the matrix is very similar, although K_2O, Co, Ba, Rb and LREE are more enriched in the fragments than in the matrix, whereas the iron content is low. Data from rock fragments from specularite breccias at Mantoverde Norte, Mantoverde Sur and Manto Ruso have been plotted together in Fig. 6c. The fragments have higher K_2O, Co, Ba, Rb, and lower CaO, TiO_2, Na_2O, P_2O_5, Nb, Zn, Pb, Sr, Y contents compared to the reference andesite. LREE are depleted in all but one sample (MV 96-5-1).

Microthermometry

Three microthermometric studies have been carried out to date (Campos, 1994; Collao and Ortega, 1999; Collao and Campos, 2003). These are summarised in Vila *et al.* (1996) and Benavides *et al.* (2007), respectively. Collao and Ortega (1999) report homogenisation temperatures between 460 and 550°C obtained from hypersaline fluid inclusions in quartz coexisting with magnetite. Vein quartz and quartz fragments, pre-dating the main copper mineralisation, host coexisting liquid-rich three-phase (Liquid > Vapour + Solid; L>V-S) and two types of two-phase fluid inclusions (mainly V>L and subordinately L>V; Campos, 1994 in Vila *et al.*, 1996). The three-phase inclusions have salinities between 32 and 56 wt.% $NaCl_{equiv.}$, and were homogenised between 185 and 500°C, mostly between 215 and 340ºC. Two-phase fluid inclusions have homogenisation temperatures between 180 and 334°C, and salinities inferred to be close to the saturation point (~26 wt.% $NaCl_{equiv.}$; Vila *et al.*, 1996). Based on the coexistence of vapour-rich and liquid-rich phases in quartz and the abundance of hydrothermal breccias, Vila *et al.* (1996) suggested boiling under hydrostatic conditions.

Late calcite veinlets cutting the main mineralisation in the Manto Atacama breccia contain liquid-dominated three-phase and two-phase fluid inclusions (Campos, 1994 in Vila *et al.*, 1996). The three-phase inclusions have salinities between 32 and 40 wt.% $NaCl_{equiv.}$, and homogenisation temperatures from 160 to 360°C (Vila *et al.*, 1996). Similar data for these inclusions (salinities 30 to 40 wt.% $NaCl_{equiv.}$; homogenisation temperatures 140 to 240°C) are later reported by Collao and Campos (2003). The two-phase inclusions are characterised by lower salinities (1 to 10 wt.% $NaCl_{equiv.}$) and homogenisation temperatures between 112 and 260°C (Collao and Campos, 2003). Two-phase fluid inclusions in a chalcopyrite-bearing calcite veinlet also show relatively low salinities (14 to 21 wt.% $NaCl_{equiv.}$). They homogenise mainly between 210 and 280°C, with a mean at 240°C (Campos, 1994 in Vila *et al.*, 1996).

Stable Isotope Geochemistry

Oxygen isotope signatures of iron oxides from Mantoverde Norte, Mantoverde Sur, and Manto Ruso have been recently published by Benavides *et al.* (2007). The oxygen isotope compositions of magnetite from the deeper parts of Mantoverde Norte and Mantoverde Sur are between +1.4 and +3.4 ‰ $\delta^{18}O_{VSMOW}$, i.e. slightly higher than those obtained from hematite. At Mantoverde Norte, the $\delta^{18}O_{VSMOW}$ values of hematite range from -1.9 to +0.5‰ (n= 4). A single hematite sample from Manto Ruso yields a $\delta^{18}O_{VSMOW}$ value of +1.7‰. Other hematite samples collected at some distance from the Manto Ruso deposit have $\delta^{18}O_{VSMOW}$ values of -1.7 or 1.0 ‰, respectively (Benavides *et al.*, 2007). Benavides *et al.* (2007) assume

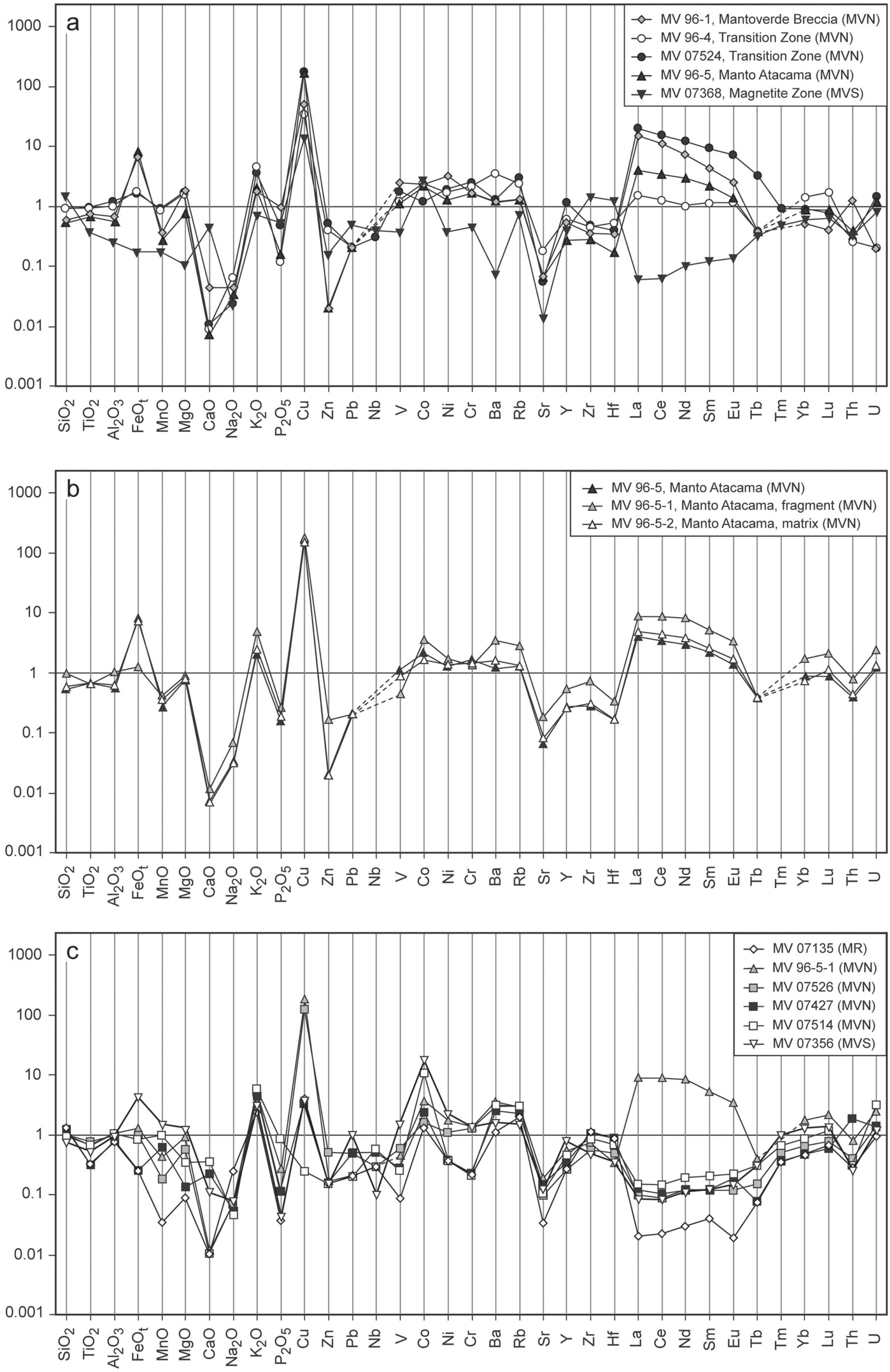

Figure 6: Andesite-normalised geochemical data of: **a)** whole rocks from various defined units in the Mantoverde district; **b)** of the Mantoverde Norte specularite breccia (Manto Atacama, MV 96-5), breccia fragments (MV 96-5-1), and breccia matrix (MV 96-5-2); **c)** rock fragments from specularite breccias at Mantoverde Norte, Mantoverde Sur and Manto Ruso (andesite reference data from the GERM Reservoir Database; Weaver and Tarney, 1984 and Ewart, 1982). Abbreviations: MVN Mantoverde Norte; MVS Mantoverde Sur; MR Manto Ruso.

Table 1: Major and trace element contents of selected samples from the Mantoverde district.

Sample	**MV 96-1**	**MV 96-4**	**MV 96-5**	**MV 96-5-1**	**MV 96-5-2**	**Standard**
Unit	Mantoverde Breccia	Transition Zone	Manto Atacama	Manto Atacama fragments	Manto Atacama matrix	
Major elements in wt.%						
SiO_2	31.71	51.06	28.66	54.80	32.60	59.20
TiO_2	0.60	0.76	0.55	0.57	0.57	0.90
Al_2O_3	10.44	16.16	8.73	17.10	10.23	17.20
FeO_t	35.54	10.05	46.24	7.34	40.61	6.10
MnO	0.04	0.10	0.03	0.05	0.04	0.12
MgO	5.61	5.05	2.31	3.00	2.55	3.40
CaO	0.23	0.05	0.04	0.07	0.04	5.90
Na_2O	0.16	0.24	0.12	0.26	0.12	4.00
K_2O	3.92	10.13	4.42	11.35	5.48	2.40
P_2O_5	0.23	0.03	0.04	0.07	0.05	0.27
LOI	3.23	2.80	1.97	2.53	2.03	
Total	91.72	96.42	93.12	97.14	94.30	99.49
Trace elements in ppm, except Au in ppb						
Au	271	16	60	825	154	
Ag	<0.4	<0.4	0.4	0.8	0.4	
Cu	2 037	1 349	6 615	7 249	6 224	40
Zn	2	38	2	16	2	97.8
Pb	<5	<5	<5	5	<5	12
Mo	<1	<1	<1	<1	<1	
Sc	20.1	30.3	24.9	20.6	24.3	
Be	<2	<2	<2	<2	<2	
As	8	7.9	5.3	5	5.3	
Bi	<5	<5	<5	<5	<5	
Sb	2	2.5	2.2	1.3	1.9	
Cs	<1	<1	<1	<1	<1	
Ta	<0.5	<0.5	<0.5	<0.5	<0.5	
V	303	150	139	57	118	125
Co	44	43	40	67	31	18.6
Ni	90	46	34	46	38	27
W	183	247	326	189	218	
Cr	74	96	75	63	66	45
Ba	740	2 100	740	2 100	1 000	605
Rb	87	155	86	194	91	66
Sr	40	108	40	110	51	601
Y	8	9	4	8	4	15
Zr	63	79	50	133	57	181
Hf	2	3	1	2	1	5.8
La	434	42.9	116	260	145	29
Ce	692	75	217	528	271	61
Nd	171	23	68	186	86	23
Sm	21.3	5.3	10.5	25	12.7	4.9
Eu	3.3	1.5	1.8	4.4	2.2	1.29
Tb	<0.5	<0.5	<0.5	<0.5	<0.5	0.65
Yb	0.8	2.1	1.3	2.6	1.1	1.5
Lu	0.1	0.4	0.21	0.52	0.27	0.24
Th	7.8	1.5	2.4	4.8	2.7	6
U	<0.5	<0.5	1.5	3	1.7	1.25
S	<0.01	<0.01	0.01	0.01	<0.01	

magnetite formation temperatures between 460 and 550°C based on homogenisation temperatures of fluid inclusions in quartz that coexists with magnetite. They calculated $\delta^{18}O_{fluid}$ values of a fluid in equilibrium with magnetite between +7.3 and +10.0‰ (fractionation coefficients of Bottinga and Javoy, 1973). Hematite precipitation is thought to occur at temperatures between 200 and 250°C (Benavides *et al.*, 2007). This temperature estimate is based on oxygen isotope fractionation between coexisting calcite and hematite. The calculated $\delta^{18}O_{fluid}$ signature of a hydrothermal fluid in equilibrium with the hematite would range from +3.0 and +8.0‰ (fractionation coefficients of Yapp, 1990; Benavides *et al.*, 2007).

Chalcopyrite in the Mantoverde district shows a wide range in sulphur isotopic composition. ($\delta^{34}S_{VCDT}$ between -6.6 and +10.0‰; this study; Benavides *et al.*, 2007). Systematic variations of these data are observed as a function of the spatial distribution of the sulphides in the orebodies and their position relative to the MVF (Fig. 7). Sulphur isotopic compositions around 0‰ $\delta^{34}S_{VCDT}$ are compatible with a magmatic-derived sulphur component and characteristic for chalcopyrite in orebodies with a close spatial relationship with the MVF in the southern and deeper central part of the Mantoverde district, representing the more internal parts of the IOCG hydrothermal system (Mantoverde Sur, southern or deeper part of Mantoverde Norte). Higher $\delta^{34}S_{VCDT}$ values (centred roughly around +6‰), suggesting sulphur contribution from non-magmatic sources, are typical of the northern part of the district, or the shallower levels (Mantoverde Norte deposit and at Manto Ruso) or lateral portions of the hydrothermal system.

Discussion and Conclusions

The geometry and spatial distribution of the Cu-Au orebodies in the Mantoverde district is closely related to the northnorthwest-striking MVF or subparallel structures, which are the principal fluid conduits for the hydrothermal system. A lithostratigraphic control may have, in addition, played a role at Manto Ruso. All identified Cu-Au ore zones in the Mantoverde district are characterised by variable proportions of potassic feldspar, chlorite, sericite, quartz and calcite alteration. Na(-Ca) alteration, commonly represented by albite, oligoclase and/or sodic scapolite (±Ca-amphibole±epidote), which is a characteristic feature of most IOCG districts and used as an exploration criteria, is only poorly developed at Mantoverde. In surface outcrops outside the mineralised zone, obvious indications of Na(-Ca) alteration are lacking, whereas in mines and mineralised zones, manifestations of this alteration are limited to certain areas with scapolite. The mineralogical characteristics of the altered rocks are reflected in their geochemical composition. Most notable is a strong gain in K_2O and losses of Na and Ca (Fig. 6). Apart from Fe, Cu and Au, IOCG deposits may be anomalous in Co, Ba, U and LREE. The fingerprint of IOCG type mineralisation is visible in the Mantoverde district, although U contents are low. Locally, LREE enrichments or depletions have been detected in the altered and mineralised rocks compared to the inferred precursor host rock composition. Therefore, LREE may not have been necessarily contributed from external sources, but may have been redistributed within the deposits.

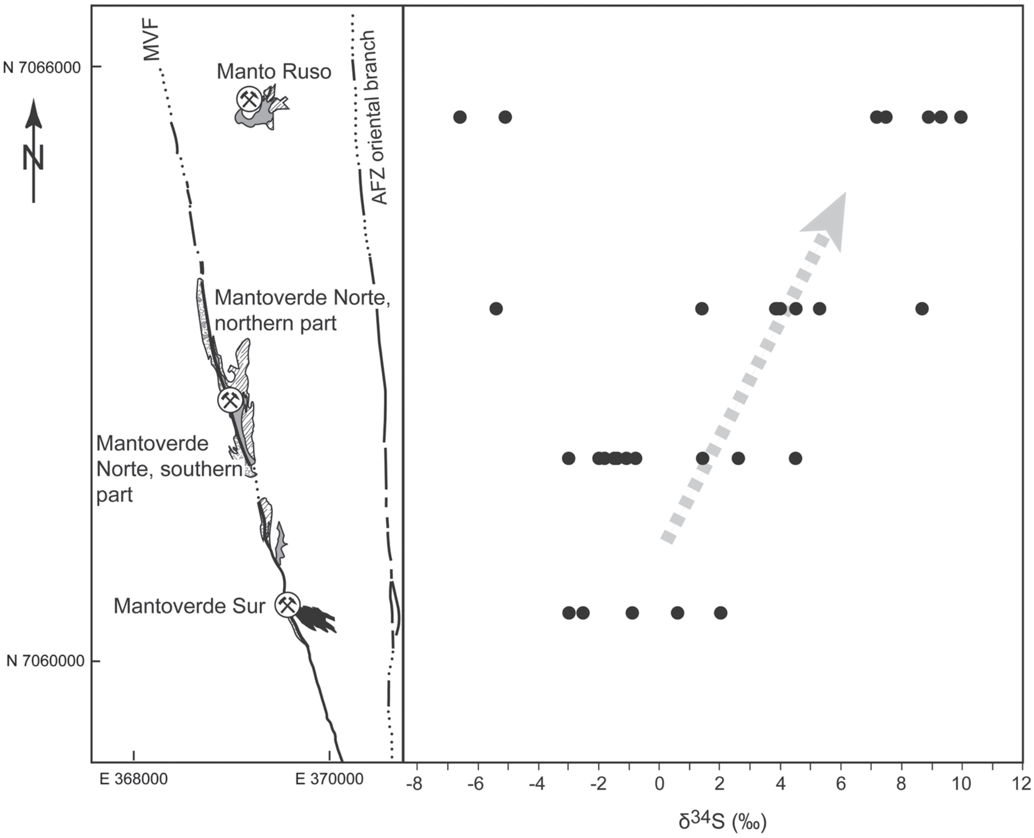

Figure 7: Sketch of the Mantoverde district with the location of main ore zones and sulphur isotope signatures of chalcopyrite from these areas (data of Benavides *et al.*, 2007 included). A general trend in enrichment of ^{34}S from south towards north is recognised (see arrow).

The potassic feldspar-chlorite-sericite-quartz-calcite alteration and the mineralisation style in the district, with hematite commonly at shallow levels giving way to magnetite at depth, resembles the upper to intermediate parts of the deposits in the Punta del Cobre district (Marschik and Fontboté, 1996). The alteration and the hematite rich and hematite to magnetite transition zones are characteristic of the more distal portions of zoned IOCG systems (Hitzman *et al.*, 1992; Marschik and Fontboté, 2001). The tilting of the structural block east of the MVF (Fig. 3), resulting in downthrow of the northeastern part of the district, and the consequent partial erosion (Orrego and Zamora, 1991; Sanhueza and Robles, 1999), explains the predominance of near-surface magnetite-rich rocks (i.e. the exposure of deeper portions of the system) at Mantoverde Sur, and that of near-surface hematite in the north (Mantoverde Norte and Manto Ruso).

Specular hematite (hm-I) formed early in the evolution of the hydrothermal system. It was replaced by magnetite to form mushketovite in the deeper parts of the system, whereas at shallow levels hm-I remained unaffected. Most of the specularite in the currently mined supergene zone in the northern part of the district is hm-I. The magnetite-specularite zonation is consistent with lower temperature and/or more oxidised conditions of the hydrothermal system at shallow levels. The main Cu mineralisation postdates magnetite formation and took place before abundant calcite veining. Therefore, microthermometric or isotope geochemical data derived from calcite and late hematite (hm-II) can only provide insights into the late (post-ore) hydrothermal stages.

The data derived from fluid inclusions suggest moderate to high salinity fluids in the hydrothermal system. A general decrease in temperature and salinity with time is noted by Vila *et al.* (1996), who suggest that boiling and/or mixing with meteoric water has occurred. Based mainly on the microthermometric and stable isotope data, Benavides *et al.* (2007) envisaged a genetic model in which metal-bearing magmatic-hydrothermal fluid mix with seawater possibly mediated by evaporites. Although this model is consistent with, and similar to, those previously suggested for Mantoverde (e.g. Vila *et al.*, 1996; Cornejo *et al.*, 2000; Zamora and Castillo, 2001) or other South American IOCG deposits (e.g. Marschik *et al.*, 2000; Marschik and Fontboté, 2001; Marschik *et al.*, 2003; Chiaradia *et al.*, 2006; De Haller, 2006), Benavides *et al.* (2007) emphasise the role of a non-magmatic (seawater) source for sulphur. They further state that exotic sulphur input is a prerequisite for economic or even subeconomic copper mineralisation in Andean IOCG deposits, referring also to the La Candelaria and Raúl-Condestable, Peru, IOCG deposits. Non-magmatic sulphur may be present in most and predominant in some Andean IOCG deposits (e.g. Raúl-Condestable; $\delta^{34}S$ from –32.7 to +26.3 ‰; De Haller, 2006). However, based on recent research results from investigations at Raúl-Condestable, De Haller (2006), in accordance with suggestions by Sillitoe (2003), pointed out that the presence of external seawater-derived evaporitic or metamorphic brines (and therefore exotic sulphur) is not seen as a general requirement for IOCG deposit formation. The fact that essentially all of the sulphides in the Candelaria-Punta del Cobre orebodies have an igneous $\delta^{34}S$ signature (–3.2 to +3.1 ‰; e.g. Rabbia *et al.*, 1996; Marschik and Fontboté, 2001; Mathur *et al.*, 2002 and references therein) makes the hypothesis of a required exotic seawater or evaporitic sulphur input appear unlikely. Sulphides with $\delta^{34}S$ signatures suggesting a non-magmatic sulphur source only occur locally at Candelaria-Punta del Cobre, in general, at shallower levels and/or at the periphery of the orebodies. Similar relationships regarding the spatial variations in the sulphur isotope signatures are also recognised in the Mantoverde district. A magmatic or igneous sulphur signature is detected in chalcopyrite at deeper levels and/or in the central portions of orebodies, close to, or within the feeder zones (i.e. where the bulk of the known hypogene Cu-Au resources have been discovered). However, the input of non-magmatic hydrothermal fluids and sulphur seems significant or may be predominant in some other currently accessible portions of the Mantoverde IOCG system.

The age of the mineralisation is only poorly constrained and estimates are based on the K-Ar ages of hydrothermal sericite and a two-point Re-Os isochron age derived from magnetite suggesting that mineralisation-alteration at Mantoverde occurred at approximately 116 to 121 Ma (Vila *et al.*, 1996; Mathur *et al.*, 2002). This age range overlaps with that obtained for granitoids of the Sierra Dieciocho plutonic complex (~120 to 127 Ma; Zentilli, 1974; Dallmeyer *et al.*, 1996). The age estimates are consistent with the remnant magnetic properties of the orebodies in the district showing normal (Manto Ruso) or inverse polarities (Mantoverde Norte; Tassara *et al.*, 2000). The mineralisation in the Mantoverde district, therefore, may have occurred coeval with a change from an interval with inverse into normal polarity at around 120 Ma (Tassara *et al.*, 2000), or alternatively with a change to a short interval of reverse polarity between 115 to 116 Ma (Chronozone M-1r; high-resolution Mesozoic timescale of Gradstein *et al.*, 1995).

Acknowledgments

AngloAmerican Mantoverde Division, Chile, is thanked for logistic support during the fieldwork and the permission to publish these data. We appreciate constructive discussions with and contributions by C. Astudillo, A. Sanguinetti, M. Zuleta, M. Cortéz, and the friendly help of L. Guerrero, L. Ramos, D. Véliz, and C. Robledo. Ana A. Rieger and Robert Marschik are particularly thankful for the hospitality and the constant support by all members of AngloAmerican Mantoverde Division. This research is funded by the DFG, which is gratefully acknowledged.

References

Astudillo, C., 2001 - Distribución y caracterización de carbonatos en Mantoverde, Provincia de Chañaral, Tercera Región, Chile; Memoria de Título (unpublished), *Universidad Católica del Norte, Antofagasta, Chile*, 113p.

Benavides, J., Kyser, T.K., Clark, A.H., Oates, C.J., Zamora, R., Tarnovschi, R. and Castillo, B., 2007 - The Mantoverde iron oxide-copper-gold district, III Región, Chile: The role of regionally derived, nonmagmatic fluids in chalcopyrite mineralization; *Economic Geology*, v. 102, pp 415-440.

Berg, K. and Breitkreuz, C., 1983 - Mesozoische Plutone in der nordchilenischen Küstenkordillere: Petrogenese, Geochronologie, Geochemie und Geodynamik mantelbetonter Magmatite; *Geotektonische Forschung*, v. 66, pp 1-107.

Berg, K. and Baumann, A., 1985 - Plutonic and metasedimentary rocks from the Coastal Range of northern Chile: Rb-Sr and U-Pb isotopic systematics; *Earth and Planetary Science Letters*, v. 75, pp 101-115.

Bottinga, Y. and Javoy, M., 1973 - Comments on oxygen isotope geothermometry; *Earth Planetary Science Letters*, v. 20, pp 250-265.

Brown, M., 1991 - Comparative geochemical interpretation of Permian–Triassic plutonic complexes of the Coastal Range and Altiplano (23º30' to 26º30'S), northern Chile; *Geological Society of America Special Paper* 265, pp 157-171.

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

Campos, E., 1994 - Análisis preliminar de inclusiones fluidas, Mina Manto Verde, Santiago; *Empresa Minera de Mantos Blancos S.A., (unpublished internal report),* 11p.

Chiaradia, M., Banks, D., Cliff, R., Marschik, R, and De Haller, A., 2006 - Origin of fluids in South American iron oxide-copper-gold deposits: Indications from δ^{37}Cl, ^{87}Sr/^{86}Sr$_i$ and Cl/Br; *Mineralium Deposita*, v. 41, pp 565-573.

Coira, B., Davidson, J., Mpodozis, C. and Ramos, V., 1982 - Tectonic and magmatic evolution of the Andes of northern Argentina and Chile; *Earth-Science Reviews*, v. 18, pp 303-332.

Collao, S. and Campos, E., 2003 - Inclusiones fluidas en Mina Manto Verde, Empresa Minera Mantos Blancos, III Región; *Anglo American Chile Ltda (unpublished internal report)*, 20p.

Collao, S. and Ortega, R., 1999 - Mineralización – Alteración e Inclusiones Fluidas en Muestras del Distrito Minero Mantoverde, Copiapó, III Región, Chile; *Anglo American Chile Ltda, (unpublished internal report)*, 30p.

Cornejo, P., Matthews, S., Orrego, M. and Robles, W., 2000 - Etapas de mineralización asociadas a alteración potásica en un sistema de Fe-Cu-Au: Yacimiento Mantoverde, III. Región de Atacama, Chile; *9. Congreso Geológico Chileno, Puerto Varas, Actas,* pp 97-101.

Dallmeyer, R.D., Grocott, J., Brown, M., Taylor, G.K. and Treloar, P.J., 1996 - Mesozoic magmatic and tectonic events within the Andean plate boundary zone, 26°-27°30'S, North Chile: Constraints from ^{40}Ar/^{39}Ar mineral ages; *Journal of Geology*, v. 104, pp 19-40.

De Haller, A., 2006 - The Raúl-Condestable iron oxide copper-gold deposit, central coast of Perú; *Terre and Environment, Section des Sciences de la Terre, University of Geneva, Switzerland,* v. 58, 123p.

Ewart, E., 1982 - The mineralogy and petrology of Tertiary-Recent orogenic volcanic rocks: with special reference to the andesitic-basaltic compositional range; *in* Thorpe, R.S., (Ed.), Andesites: orogenic andesites and related rocks, *Chichester, U.K., John Wiley and Sons*, pp 25-87.

García, F., 1967 - Geología del Norte Grande de Chile; *Symposium sobre el Geosinclinal Andino*, *Santiago de Chile, Sociedad Geológica de Chile - ENAP*, pp 138.

Gelcich S., Davis D.W.D. and Spooner E.T.C., 2004 - Onset of Early Jurassic magmatism in northern Chile: Precise U-Pb zircon ages for the La Negra Formation and the Flamenco Pluton in the Coastal Cordillera of Chañaral; *International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) General Assembly, Pucón-Chile* (abstracts in CD-ROM).

Gelcich, S., Davis, D.W. and Spooner, E.T.C., 2005 - Testing the apatite-magnetite geochronometer: U-Pb and ^{40}Ar/^{39}Ar geochronology of plutonic rocks, massive magnetite-apatite tabular bodies, and IOCG mineralization in Northern Chile; *Geochimica et Cosmochimica Acta*, v. 69, pp 3367-3384.

Gradstein, F.M., Agterberg, F.P., Ogg, J.G., Hardenbol, J., Veen, P.Y., Thierry, J. and Huang, Z., 1995 - A Triassic, Jurassic and Cretaceous time scale; *in* Berggren, W.A., Kent, D.V., Aubry, M.P. and Hardenbol, J., (Eds.), Geochronology, time scales and global stratigraphic correlation; *Society for Sedimentary Geology*, *Special Publication* no 54, pp 95-126.

Grocott, J. and Taylor, G.K., 2002 - Magmatic arc fault systems, deformation partitioning and emplacement of granitic complexes in the Coastal Cordillera, north Chilean Andes (25º30'S to 27º00'S); *Journal of the Geological Society, London*, v. 159, pp 425-442.

Hitzman, M.W., Oreskes, N. and Einaudi, M.T., 1992 - Geological characteristics and tectonic setting of Proterozoic iron oxide (Cu-U-Au-REE) deposits; *Precambrian Research*, v. 58, pp 241-287.

Hodkinson, D., Krogstad, E. J. and Brown, M. 1995 - Geochemical constraints on magma sources of Mesozoic continental arc plutonic complexes, Andean plate boundary zone, north Chile; *in* Brown, M. and Piccoli, P., (Eds.), The Origin of Granites and Related Rocks, *U.S. Geological Survey Circular* 1129, pp 66-67.

Lara, L. and Godoy, E., 1998 - Hoja Quebrada Salitrosa, III Región de Atacama: Santiago, Chile; *Servicio Nacional de Geología y Minería, Santiago, Chile, Mapas Geológicos 4*, escala 1:100.000.

Marschik, R. and Fontboté, L., 1996 - Copper(-iron) mineralization and superposition of alteration events in the Punta del Cobre belt, northern Chile; *in* Camus, F., Sillitoe, R.H., Petersen, R. and Sheahan, P., (Eds.), Andean copper deposits: New discoveries, mineralization, styles and metallogeny, *Economic Geology Special Publication* 5, pp 171-189.

Marschik, R. and Fontboté, L., 2001 - The Candelaria-Punta del Cobre iron oxide Cu-Au(-Zn-Ag) deposits, Chile; *Economic Geology*, v. 96, pp 1799-1826.

Marschik, R., Leveille, R.A. and Martin, W., 2000 - La Candelaria and the Punta del Cobre district, Chile: Early Cretaceous iron oxide Cu-Au(-Zn-Ag) mineralization; *in* Porter, T.M. (ed.) Hydrothermal Iron Oxide Copper-Gold and Related Deposits: A Global Perspective, *PGC Publishing*, *Adelaide,* v. 1, pp 163-175.

Marschik, R., Fontignie, D., Chiaradia, M. and Voldet, P., 2003 - Geochemical and Nd-Sr-Pb-O isotope characteristics of granitoids of the Early Cretaceous Copiapó plutonic complex (27º30'S), Chile; *Journal of South American Earth Sciences*, v. 16, pp 381-398.

Marschik, R. and Söllner, F., 2006 - Early Cretaceous zircon U-Pb isotope ages for the Copiapó plutonic complex and implications for the IOCG mineralization at Candelaria, Atacama Region, Chile; *Mineralium Deposita*, v. 41, pp 785-801.

Mathur, R., Marschik, R., Ruiz, J., Munizaga, F., Leveille, R.A. and Martin, W., 2002 - Age of mineralization of the Candelaria iron oxide Cu-Au deposit and the origin of the Chilean Iron Belt based on Re-Os isotopes; *Economic Geology*, v. 97, pp 59-71.

Mercado, M., 1978 - Geología de la Cordillera de la Costa entre Chañaral y Caldera, Región de Atacama; *Instituto de Investigaciones Geológicas, Santiago, Chile,* 1 Mapa Geológico, escala 1:100.000, 27, 15p.

Moscoso, R., Nasi, C. and Salinas, Z., 1982 - Hoja Vallenar y parte norte de La Serena, regiones de Atacama y Coquimbo; *Servicio Nacional de Geología y Minería, Santiago, Chile,* Carta Geológica de Chile, 55, 100p.

Mpodozis, C. and Ramos, V., 1990 - The Andes of Chile and Argentina; *in* Ericksen, G.E., Cañas-Pinochet, M.T. and Reinemund, J.A., (Eds.), Geology of the Andes and its relation to hydrocarbon and mineral resources, *Earth Science Series: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources*, v. 11, pp 59-91.

Naranjo, J.A., 1987 - Interpretación de la actividad Cenozoica superior a lo largo de la zona de Falla Atacama, norte de Chile; *Revista Geológica de Chile*, v. 31, pp 43-55.

Orrego, M. and Zamora, R., 1991 - Manto Ruso: Un Yacimiento de Cobre ligado a la Falla de Atacama, Norte de Chile; *6. Congreso Geológico Chileno, Viña del Mar, Resúmenes expandidos,* pp 174-178.

Rabbia, O. M., Frutos, J., Pop, N., Isache, C., Sanhueza, V. and Edelstein, O., 1996 - Características isotópicas de la mineralización de Cu(-Fe) de Mina Carola, distrito minero Punta del Cobre, norte de Chile; *8. Congreso Geológico Argentino, Buenos Aires, Actas,* pp 241-254.

Sanhueza, A. and Robles, W., 1999 - Estudio Estructural del Distrito Manto Verde, Informe Final; *Anglo American Chile Ltda (unpublished internal report)*, 25p.

Scheuber, E. and Andriessen, P.A.M., 1990 - The kinematic and geodynamic significance of the Atacama fault zone, northern Chile; *Journal of Structural Geology*, v. 12, pp 243-257.

Sillitoe, R.H., 2003 - Iron oxide-copper-gold deposits: An Andean view; *Mineralium Deposita*, v. 38, pp 787-812.

Tassara, A., Roperch, P. and Pavez, A., 2000 - Paleomagnetísmo de los yacimientos Mantos Blancos y Manto Verde: Implicancias tectónicas y cronológicas; *9. Congreso Geológico Chileno, Puerto Varas, Actas,* pp 166-170.

Taylor, G.K., Grocott, J., Pope, A. and Randall, D.E., 1998 - Mesozoic fault systems, deformation and fault block rotation in the Andean forearc: a crustal scale strike-slip duplex in the Coastal Cordillera of northern Chile; *Tectonophysics*, v. 299, pp 93-109.

Vila, T., Lindsay, N. and Zamora, R., 1996 - Geology of the Manto Verde Copper Deposit, northern Chile: A specularite-rich, hydrothermal-tectonic breccia related to the Atacama Fault Zone; *in* Camus, F., Sillitoe, R.M., Petersen, R. and Sheahan, P., (Eds.), Andean copper deposits: New discoveries, mineralization, styles and metallogeny, *Special Publication, Society of Economic Geologists*, 5, pp 157-170.

Weaver, B. L. and Tarney, J., 1984 - Empirical approach to estimating the composition of the continental crust; *Nature*, v. 310, pp 575-577.

Yapp, C., 1990 - Oxygen isotopes in iron (III) oxides 1. Mineral-water fractionation factors; *Chemical Geology*, v. 85, pp 329–335.

Zamora, R. and Castillo, B., 2001 - Mineralización de Fe-Cu-Au en el distrito Mantoverde, Cordillera de la Costa, III Región de Atacama, Chile; *2. Congreso Internacional de Prospectores y Exploradores (ProExplo 2001), Lima, Perú,* (abstracts in CD-ROM).

Zentilli, M., 1974 - Geological evolution and metallogenetic relationships in the Andes of northern Chile between 26° and 29° S; Ph.D. Thesis, (unpublished)*, Queen's University,* 394p.