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GOLD POSITION AND DISTRIBUTION IN LOWER CRETACEOUS IOCG DEPOSITS OF THE COPIAPO BASIN, ATACAMA REGION, CHILE

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Abstract: Detailed geological, petrographic and metallogenic data, including stable isotopes and fluid inclusions have been derived for vein-stockwork mineralization, stratabound to Manto type and replacement-lens shaped to skarn/contact ore bodies of the Lower Cretaceous IOCG Copper Belt near Copiapo, Atacama (Ojancos Viejo-Ojancos Nuevo tectonic alignments). At least three types of gold association can be distinguished in this IOCG environment, as follows:

1. Early iron oxide (magnetite) related gold (M type) is included in early mesothermal magnetite and mushketovite associated with fine grained biotite with/without potassic feldspar. The fluids of the M type gold bearing stage were hypersaline (41-59%wt.NaCl eq.) with temperatures ranging from 350^0 to $>500^0$C. The source of fluids was mainly magmatic ($\delta^{34}S$ from -5.3 to 4.7) with possible crustal rock (e.g. evaporite) assimilation during the magma ascent.
2. Later copper sulfides (chalcopyrite) related gold (C type) is genetically linked with, the mostly mesothermal, main copper event and associated with proximal Na-rich (albite) alteration. C type gold was deposited from magmatic or near magmatic fluids ($\delta^{34}S$ from -6.9 to 4.1) which, also were highly saline (32-59%wt.NaCleq.) at temperatures varying between 250^0 and 400^0C.The evolution of the mineralized system may have included the introduction of an external saline brine and the possible mixing of two different types of fluid.
3. Late pyrite or hematite (specularite) related gold (P/H type). This gold type is recorded either as a subsequent epithermal overprint or a still preserved epithermal suite in the upper part of the structures. The key proximal alteration is a sericite bearing intermediate argillic halo or carbonate – hematite dominant assemblage. The fluid temperatures were between 180^0-290^0C, with moderate salinities (15-20%wt. NaCleq.).The mixing of magmatic ($\delta^{13}C$ from -3 to -9; $\delta^{34}S$ between 0-2) and meteoric fluids ($\delta^{18}O$ between9-11; $\delta^{34}S$ extreme values of 7.6 and 8.3), including boiling phenomena characterize this gold bearing stage.

Keywords: Au typology, Lower Cretaceous, IOCG deposits, Ojancos Viejo/Nuevo, Copiapo, Chile.

1. INTRODUCTION: MAIN FEATURES OF THE IOCG TYPE ENVIRONMENT

Iron Oxide-Copper-Gold (IOCG) deposits are located and being discovered worldwide, ranging in age from Archean-Proterozoic (Brazil, Australia, Scandinavia) to Cretaceous mineralized systems (Chile, Peru, China, South Africa). The size of these deposits varies from less than1Mt to 500Mt, a benchmark value of 20Mt being used to separate single genetical and/or morphological types from composite systems (Sillitoe, 2003).

The real meaning of the IOCG type deposits is based on the absence of any genetic significance and grouping together those ore deposits which carry iron oxides, copper and gold as valuable mining commodities. However, it is clear that the most important features are metasomatic deposits (higher temperature skarn and lens shaped-replacement bodies) to manto/stratabound type, followed by hydrothermal breccias and mesothermal veins-stockworks, around or inside intrusive bodies such as plutons, stocks, dykes or sills.

Therefore, the Fe-Cu metallic association is frequent in IOCG deposits (except the Kiruna iron oxide subtype, Hitzman et al., 1992, Gandhi, 2004), while Au is very variable and furthermore has different metallogenic positions, i.e. having possible distinctive source and fluid origin (Foster et al., 2007). Often, there are various types of gold in the same IOCG deposit, their behavior and distribution of each one also being different.

The present paper intends to investigate gold characteristics such as gold-bearing minerals and relations between such minerals and gold bearing fluids, using integrated, isotope and mineralogical studies in order to evaluate the position and distribution of gold in the complex alteration-mineralization system of IOCG metallogeny of the Copiapo Basin (Atacama, Chile).

Figure 1. Location of Porphyry – IOCG Metalogenic Belts in Chile and Peru

In terms of fluid inclusions and isotope composition, some of the Chilean Fe-Cu-Au deposits of Punta del Cobre district (Marschik et al., 1997; Marschik & Fontbote, 2001) or even related to the Copiapo (Andean) Batholith (Barton et al., 2005) have been considered previously to occupy a transitional position between the Iron Coastal Belt and the Andean Porphyry Copper Belt. Note that the Chilean Iron Belt is the equivalent of the magnetite-apatite Kiruna subtype of IOCG deposits (Fig.1).

An important question is why the IOCG type Iron Belt of Chile does not contain, generally speaking, economic resources. An explanation may come from the so called Coastal Batholith with different characteristics and therefore, different fluids, in contrast to the Copiapo batholith which generated the IOCG Lower Cretaceous Copper (rich) Belt. Furthermore, the radiometric ages of the coastal plutons like Los Animas (153-161 Ma) and Las Tasas (125-131 Ma) which were involved in the Manto Verde ore deposits (Vila et al., 1996, Zamora & Castillo, 2001) are older than the plutons of Los Lirios (95-111 Ma), Ojanco (111 Ma) or even La Brea (117-123 Ma) belonging to the Copiapo (Andean) Batholith (Marschik & Söllner, 2006; Barton et al., 2011). Each pluton of the Andean Batholith has a distinctive, magmatic-hydrothermal rather than purely hydrothermal system (Barton & Johnson, 2000) associated with its emplacement and fluids of different origin (Barton et al., 2010).

Also, a misunderstanding involves some of the so called iron rich, nonetheless Cu-anomalous deposits located inside the early Cretaceous IOCG Copper Belt near Copiapo. In fact, the most important part of these structures contains anomalous copper, but the true problem is the size of each ore body (bulk mineable ore) and the position relative to the fluid-feeder zone paleochannel, i.e. both features are not of such interest to the bigger, higher capacity mining companies. At the same time, deposits of less than 0.5 Mt are successfully operated by the native workers (so called "pirquineros") on a very low scale. Only a few deposits near Copiapo, but inside the Chilean IOCG Copper Belt, carry just iron oxides and therefore Fe as the single mining commodity. However, if we take into account the vertical zonality known in the Ojancos Viejo/Nuevo region with shallow Cu (Fe, Au), middle Fe, Cu (Au) and deep Fe (Cu), the understanding of erosion level of the mineralized system is critical. Obviously, the deepest levels may contain just iron oxides, whereas the copper and gold bearing horizons have been eroded.

One of the major characteristics of IOCG deposits, valid not only in Chile but also in Peru (Justa, Raul Contestable), Brazil (Salabo, Cristalino, Alemao) or Australia (Olympic Dam, Ernest Henry), is the bimodal, main deposition of mineralization (Porter, 2000; 2002; Williams et al., 2005). The earlier iron oxide rich suite (magnetite, mushketovite, martite and hematite) is crosscut by a later copper sulfide rich assemblage (chalcopyrite, cubanite and bornite). However, there are IOCG structures in Atacama-Chile (e.g.Transito, Table 1) or Queensland-Australia (Ernest Henry; Ryan, 1998) where a multiphase-multievent evolution of the system has contributed to the final metallogenic edifice. The totally different size and depth of oxidation-leaching in certain zones of the same ore deposit and reactivation processes, especially related to later mafic intrusive, support this concept of the complex, often multiphase IOCG mineralization.

The IOCG deposits of the copper-rich Chilean Belt are localized especially along and around the Atacama Fault System (AFS), one of the biggest tectonic lines in Northern Chile and Peru, trending N20^{0}S (locally N-S) and interpreted as a result of an oblique subduction of the Aluk Oceanic Plate beneath the South American Continental Plate (Pardo-Casas & Molnar, 1987; Arevalo et al., 2006). The plate convergence in the early Cretaceous generated both a regional shearing visible in the most important part of the IOCG structures near Copiapo, but also a dominant sinistral strike-slip movement leading to a westward dip of most ore bodies. A quite similar tectonic-metallogenic evolution is accepted for the Domeyko Fault Zone, but later than the Atacama fault event, the Inca compression here producing during Eocene-Oligocene time several important Andean porphyry copper deposits (Oyarzun, 2000).

The AFS consists of more than 1000km long and 5 to 20km thick, syntectonic – rhythmic layered schistose like rocks which are often strongly altered. World class IOCG type deposits are located inside the fault zone (Manto Blanco, Manto Verde) or in the vicinity (Candelaria). In this very specific Lower Cretaceous environment, magma derived fluids were focused also into dilatational-open space sites (Bonson et al., 1997). Other small to medium size deposits of the same Fe-Cu+/-Au style were formed during Lower-Middle Cretaceous nearby/around AFS, i.e. in the Punta del Cobre district (Carola, Mantos del Cobre, Santos, Trinidad- Socavon Rampa, Teresita) or inside the Copiapo (Andean) batholith (Ojancos Viejo district with Tigresa-Pompeya-Rosario, Resguardoand Ojancos Nuevo district with Flor de Chile-Transito Mine-San Francisco, Estrella, Fig.2).

Table 1.The metallogenic-tectonic multiphase evolution of the Lower Cretaceus Ojancos Nuevo alignment (Transito IOCG lode deposit)

MAIN MAGMATIC/TECTONIC EVENT	MINERALIZATION PHASE	KEY ALTERATION	BRECCIA TYPE	SIGNIFICANT MINERALOGICAL& PETROCHEMICAL FEATURES
I. Diorite La Brea type (diorite, monzodiorite)	**Fe+/- Cu, Au** Early iron oxide stage is dominant	Biotite, magnetite, actinolite, scapolite +/- potassic feldspar, quartz	Magmatic& hydrothermal breccia	-Biotite ubiquitous -Diorite crustal magma (calc-alkaline)
II. First major fault moving event (normal fault) -monzodioriteemplacement(?)	**Fe (Cu**) Remobilization	Silica remobilization (quartz)	Tectonic breccia	-Chloritoid(?) bearing laminated–mylonitic rocks -friable quartz breccia
III. Mafic dykes (lamprofires)	**Fe +/-Cu** Early iron oxides stage is dominant	Biotite, mushketovite-hematite, chlorite, actinolite	no	-Subcrustal or contaminated magma(?) -Pyroxene ubquitous
IV.Microgranite to monzogranite-adamellite porphyry	**Cu, Au,Fe** Later cooper sulfide stage is dominant	Quartz, albite, chlorite, epidote +/- potassic feldspar	Phreato-magmatic breccia	-Quartz ubiquitous -granitic crustal magma (subalkaline-alkaline)
V.Felsic dykes (dacite-trachytic andesite porphyry)	Apparently barren	Without related alteration	no	-Diorite-syenite subalkaline magmas -Amphibole ubquitous
VI.Second major fault moving event (reverse/strike-slip fault) - tonalite emplacement(?)	**Au, Cu+/-Fe** Late epithermal stage (Au remobilization and overprints are dominant)	Calcite, sericite, smectite, hematite-specularite, chalcedony, colloform quartz	Phreatic, phreato-tectonic breccia	-Calcite ubiquitous -Interaction with meteoric water (boiling) in the upper part of the structure and advanced argillic alteration near the paleowater table

The mainly diorite, monzodiorite and tonalite rocks of the Copiapo plutons intrude Neocomian sedimentary-carbonate rich and volcano-sedimentary formations deposited under either marine or terrestrial conditions. The pile includes the Punta del Cobre, Bandurrias, Abundancia and Nantoco Formations (known as the Chanarcillo Group). The permeable contact zones are thermally and/or metasomatically affected and host important skarn deposits related to the IOCG type, such as Las Pintadas, the type locality of atacamite (Filip & Orlandea, 2015).

Another key feature of many Chilean IOCG deposits is the presence of wall rock consisting of pervasive, proximal potassic alteration (magnetite-hematite, biotite, potassic feldspar) somehow connected with the iron oxide phase or with the main copper sulfide event (Marschik, 1996). More or less distal, sodium rich (albite) metasomatism is recorded always associated with high grades of copper. The strong, pervasive potassic alteration delineated in the giant deposit of Candelaria led some authors to the idea that the ore body may represent a redistributed mineralization of an originally deep seated porphyry copper deposit, where Punta del Cobre Belt could represent the external part of the system (Ryan et al., 1995; Hopf, 1990). However, on the one hand the abundant magnetite correlated with the lack of disseminated mineralization (or an intense Na±Ca) metasomatism) and on the other hand the hard to imagine huge scale “remobilization” (without a major tectonic-shearing control) rule out such a presumed metallogenic evolution.

The overall range of deposits yielding economic volumes and grades occur in the Copiapo area, i.e. IOCG Cu-rich deposits range from small size deposits such as Transito and Tigresa (volumes ranging from 1 to 12 Mt), to medium size deposits such as Carola and Punta del Cobre (volumes ranging from 50 to 60 Mt) and to world class deposits such as Candelaria and Manto Verde (volumes up to 400-600 Mt). The main commodity is copper (0.9 to 1.5% Cu) accompanied by gold as a significant byproduct (0.2 to 0.5 g/t).

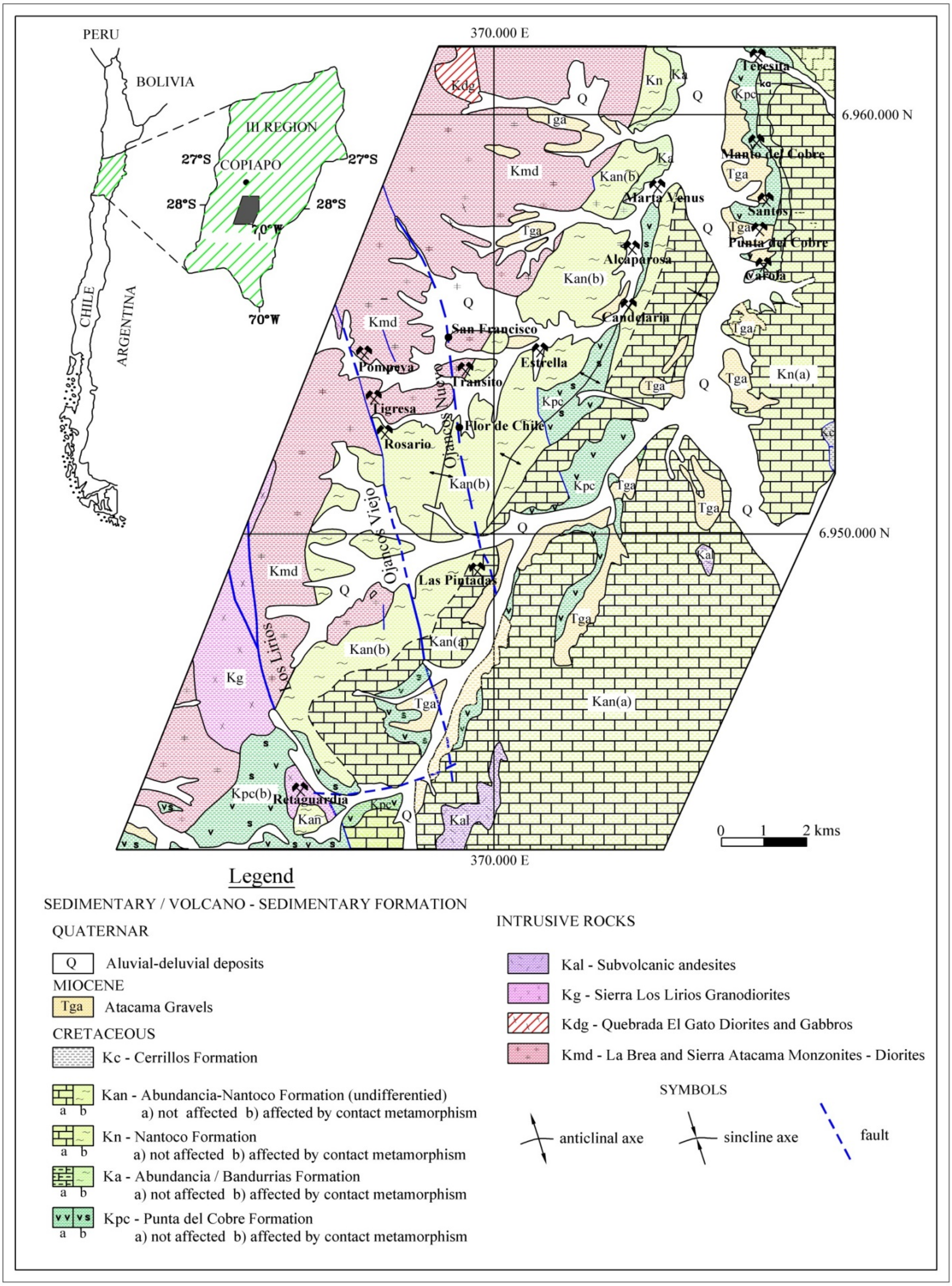

Figure 2.Geological map of Los Lirios–Ojanco–Punta del Cobre districts with location of the main Cu rich IOCG ore deposits in production (modified after Marschik, 1996)

2.STABLE ISOTOPES AND FLUID INCLUSIONS STUDIES

2.1.Stable isotopes data

Thirty eight pyrite-chalcopyrite samples were selected for sulfur(S) isotopic analyses and twenty samples were chosen for calcite C-O isotope determinations. The samples were collected from representative IOCG mineralization near Copiapo and along the Ojancos Viejo-Ojancos Nuevo metallogenic alignments, e.g. Tigresa, Pompeya, Rosario, Boton de Oro, Resguardo, Transito, Estrella, and Las Pintandas.

C-O isotope analyses were performed by the Environmental Isotope Laboratory of the University of Arizona using the following methodology: δ^{18}O and δ^{13}C of carbonates were measured using an automated carbonate preparation device (KIEL III) coupled to a gas ratio spectrometer (Finigan MAT252). Powdered samples were reacted with dehydrated phosphoric acid under vacuum at 70^0C. The isotope ratio measurement was calibrated based on repeated measurements of NBS-19 and NBS-18 and precision is ±0.1 per mil for δ^{18}O and ±0.06 per mil for δ^{13}C (1 sigma).

Sulfur isotopes were analyzed by the same Environmental Isotope Laboratory of University of Arizona using the following method: δ^{34}S was measured on SO_2 gas in a continuous flow gas ratio mass spectrometer (ThermoQuest Finigan Delta Plus XL); the samples were combusted at 1030^0C with O_2 and V_2O_5 using an elemental analyzer (COSTECH) coupled to the mass spectrometer. Standardization was based on international standards OGS-1 and NBS-123 and several other sulfide and sulfate materials that have been compared between laboratories. Calibration is linear in the range -10 to +30 per mil and precision is estimated to be ±0.15per mil or better (1s) based on repeated internal standards.

2.1.1. C-O isotope results

Two distinctive groups of samples have been separated from the 20 samples analyzed for δ^{13}C (Table 2), as follows:

Table 2. C-O isotope results from the Ojancos Viejo-Ojancos Nuevo tectonic-metallogenic alignments

Sample	***Location***	***Details***	***Associations***	***Minerals***	***δ^{13}C ‰***	***δ^{18}O ‰***
C3B-017b	Copiapo\OjancoViejo	Resguardo Mine	Cc-Lim	Cc	-9,75	11,57
C3B-472d	Copiapo\OjancoViejo	Resguardo Mine	Cc-Cpy	Cc	-9,71	12,54
C3B-528d	Copiapo/Ohanco Nuevo	Transito/SF vein	Cc-Hem	Cc	-7,56	13,12
C5B-008	Copiapo\Ojanco Nuevo	Transito/Costa Rica	Cc pure	Cc	-8,68	9,64
C5B-030	Copiapo\Nantoco	Las Pintadas surf.	Cc-Lim-Sulf	Cc	-3,71	14,50
C6B-007a	Copiapo\CerroBuitre	Transito/N of SF vein	Cc-Sulf	Cc	-7,87	11,14
C6B-007a	Copiapo\CerroBuitre	Transito/N of SF vein	Cc pure	Cc	-6,82	12,00
C6B-008a	Copiapo\CerroBuitre	Transito/N of SF vein	Cc-Hem-Chl-Cpy	Cc	-5,28	11,84
C6B-025.8	Copiapo\Ojanco Nuevo	Transito/ SF vein	Cc pure	Cc	-8,00	10,11
C6B-129	Copiapo\Ojanco Nuevo	Transito/ SF vein	Cc-Cpy	Cc	-5,20	12,64
C6B-131a	Copiapo/Ojanco Nuevo	Transito/ SF vein	Cc pure	Cc	-7,49	10,48
C6B-152d	Copiapo\Candelaria	Estrella surf.	Cc-Chl-Cpy (-Py)	Cc	-5,06	11,08
C7B-TRSf	Copiapo\Ohanco Nuevo	Transito Mine	Ccpure	Cc	-5,79	10,52
C8K-013d	Copiapo\Ohanco Nuevo	Cerro Buitre surf.	Cc-Hem-Py	Cc	-7,25	11,61
C8K-016f	Copiapo\Ojanco Nuevo	Transito/ SF vein	Cc-Hem	Cc	-6,51	10,45
C8K-042d	Copiapo\Ojanco Nuevo	Transito /SF vein	Cc pure	Cc	-6,50	11,41
C8K-045a	Copiapo\OjancoViejo	Ohanco Viejo surf.	Cc-Act	Cc	-9,89	11,12
C8K-045c	Copiapo\OjancoViejo	Ohanco Viejo surf.	Cc-Act	Cc	-7,28	10,35
C8K-265b	Copiapo\OjancoViejo	Ohanco Viejo surf.	Cc pure	Cc	-7,01	10,44
TRS040-009.9	Copiapo\Ojanco Nuevo	Transito /SF vein	Cc pure	Cc	-9,47	20,70

abbreviations: Cc=calcite, Lim=limonite, Hem=hematite-specularite, Sulf=sulfides, Chl=Chlorite, Act=actinolite Cpy=Chalcopyrite, Py=Pyrite; precision:±0.1 per mil for δ^{18}O and ±0.06 per mil for δ^{13}C

(a) The first group consists of 16 samples with values of $\delta^{13}C$ between -3 and -9 per mil, where the most important part of sulfide bearing carbonate (calcite) veins are included. With a mean of -6 per mil this range suggests a deep seated or magmatic source for the CO_2 carbon (according to Taylor, 1986);

(b) The second group of only 4 samples includes $\delta^{13}C$ values lower than -9 per mil, mainly coming from pure calcite or iron oxide bearing calcite veins. Such values indicate that a few of the carbonates incorporated CO_2 which may have been produced by oxidation or hydrolysis of organic matter, typically low in $\delta^{13}C$.

A range of $\delta^{18}O$ data from 9 to 20.7 per mil in carbonate veins was recorded for all of the samples collected (Table 2). These values indicate a fluid regime initially dominated by $\delta^{18}O$ enriched fluids, rather than magmatic fluids or those that interacted with $\delta^{18}O$ rich rocks at higher temperatures (Villas et al., 2001). A slight, but widespread, depletion tendency of $\delta^{18}O$ corresponding to values between 9-11 per mil might be related to fluid mixing (as also indicated by fluid inclusions). The evolution toward lower $\delta^{18}O$ values may have been attained by increasing infiltration of cooler solutions into the system. In this case, mixing with $\delta^{18}O$ depleted meteoric fluids is possible.

2.1.2. S isotope results

The results from 38 analyzed samples are summarized in Table 3, where the main stages-episodes of IOCG mineralization observed in the field or concluded from mineralogical and petrographical study are also highlighted. A few samples of relatively low purity (15 to 20%) were included to cover all of the mineral associations observed, but the mineral stage related isotope values suggest the data are not adversely affected. This major delineation of $\delta^{34}S$ behavior in the complex mineralization framework allows us to highlight some important features:

(a)The mostly positive $\delta^{34}S$ values, i.e. from -1.8 to +4.7 per mil, in the pyrite formed during the early iron oxide bearing stage indicate the participation of oxidized sulfur, which could be produced by non-organic, high temperature reduction of sea-water sulfides. The chalcopyrite $\delta^{34}S$ variation in the same early stage ranges between -5.3 to +1.8 per mil, suggesting also a near magmatic origin with a possible contribution of reduced non-magmatic sulfur.

(b)The $\delta^{34}S$ isotopic results varying from -6.9 to +4.1 per mil from pyrite and chalcopyrite deposited in the later copper sulfide stage indicate that most of this sulfur is magmatic or leached from magmatic rocks, whereas enrichment with reduced or slightly oxidized sulfur is also possible.

(c)Pyrite belonging to the carbonate-hematite late-final stages shows $\delta^{34}S$ values between 0 and +2 per mil, indicating that the sulfur is magmatic, either derived directly from a magmatic source or from non-magmatic fluids that leached sulfur from magmatic rocks. The extreme values of -7.6 and -8.3 per mil recorded in the late chalcopyrite of the carbonate rich stage indicate a limited, although important, contribution of reduced-meteoric sulfur in the fluid phase.

The concentration of $\delta^{34}S$ values near zero is consistent with the variation presented by Archean volcanic hosted massive sulfide deposits characterized by $\delta^{34}S$ of ±1 per mil (Ohomoto&Goldhaber, 1997; Xavier et al., 2005; Dreher, 2004; Dreher et al., 2007). However, most IOCG deposits have $\delta^{34}S$ values in the 0±5 per mil range (Williams et al., 2005), so that a sharp distinction between these deposits based on $\delta^{34}S$ data remains quite difficult.

The main conclusion of this study is that C-O and S isotope data obtained do not clearly discriminate between fluid sources, the most important part being magmatic or leached from magmatic rocks. Also, previous sulfur isotopic data stemming from pyrite and chalcopyrite of the Punta del Cobre, Candelaria and Carola IOCG ore deposits showed a range of $\delta^{34}S$ from -0.7 to 2.9 per mil, corresponding to a magmatic-intrusive related sulfur source (Rabbia et al., 1998; Marschik el al., 2000). However, repeated mineralization episodes in the same area and the high salinity of the fluid (see fluid inclusion study) may allow some assimilation of crustal rocks by the granitic-dioritic magma and therefore a sequential, possible non-magmatic source of the ore fluids.

2.2. Fluid inclusion data

The samples were collected mainly from the Tigresa – Pompeya - Rosario vein/stockwork system (Ojancos Viejo) and the Transito – Antonia - San Francisco lode system (Ojancos Nuevo), where the recently intense exploration and mining operations allowed a more reliable vertical testing from deeper to shallower levels for each IOCG type ore body.

Reconnaissance fluid inclusion observations were made in all polished-thin sections and host minerals including garnet, apatite, pyroxene, early quartz (early iron oxide stage), later quartz (copper sulfide stage), late carbonate-quartz (hematite-specularite final stage).

Table 3.Sulfur isotope results from the Ojancos Viejo-Ohancos Nuevo tectonic-metallogenical alignments

Sample #	***Location***	***Mineral***	***Purity***	***δ^{34}S ‰***	***Mineral Associations***	***Mineral stage***
C3B-007c	Copiapo\OjancoViejo\Rosario	chalcopyrite	~15%	**-0,4**	Mgt-Cpy(-Act)	minor sulfides in EIOS
C3B-007e	Copiapo\OjancoViejo\Rosario	chalcopyrite	~80%	**-3,6**	Mushk-Cpy-Chl	minor sulfides in EIOS
C3B-007e	Copiapo\OjancoViejo\Rosario	pyrite	~90%	**2,3**	Mushk-Py-Chl	minor sulfides in EIOS
C3B-017	Copiapo\OjancoViejo\Resguardo	chalcopyrite	~90%	**-8,3**	Cc-Cpy-Py	sulfides in LES
C3B-472d	Copiapo\OjancoViejo\Resguardo	chalcopyrite	>90%	**-7,6**	Cc-Cpy	sulfides in LES
C3B-472e	Copiapo\OjancoViejo\Resguardo	pyrite	~95%	**3,8**	Qtz-Py	sulfides in LCSS
C6B-007a	Copiapo\OjancoNuevo\Transito	chalcopyrite	~20%	**-6,9**	Qtz-Cpy	sulfides in LCSS
C8K-013d	Copiapo\OjancoNuevo\Transito	pyrite	~15%	**-4,8**	Otz-Py	sulfides in LCSS
C8K-038e	Copiapo\OjancoViejo	pyrite	~40%	**1,1**	Mushk-Mgt-Py	minor sulfides in EIOS
C8K-044d	Copiapo\OjancoViejo	pyrite	~95%	**-1,9**	Qtz-Py-Mgt	minor sulfides in EIOS
C8K-045a	Copiapo\OjancoViejo\BotonOro	pyrite	>90%	**0,0**	Cc-Py	sulfides in LES
C8K-199a	Copiapo\OjancoViejo	pyrite	~80%	**1,1**	Qtz-Mushk-Cpy-Py	minor sulfides in EIOS
C8K-199b	Copiapo\OjancoViejo	chalcopyrite	~90%	**1,0**	Chl-Cpy	sulfides in LCSS
TigB002-025.4	Copiapo\OjancoViejo\Tigresa	chalcopyrite	~90%	**-3,8**	Mgt-Act-Chl-Cpy	minor sulfides in EIOS
TigB002-025.4	Copiapo\OjancoViejo\Tigresa	chalcopyrite	~90%	**-5,2**	Mgt-Cpy	minor sulfides in EIOS
TigB003-047.5	Copiapo\OjancoViejo\Tigresa	pyrite	~80%	**0,3**	Cpy-Py-Chl-Ep	sulfides in LCSS
TigB003-047.5	Copiapo\OjancoViejo\Tigresa	pyrite	~80%	**-0,1**	Mushk-Mgt-Qtz-Py	minor sulfides in EIOS
TigB010-033.1	Copiapo\OjancoViejo\Tigresa	pyrite	~90%	**-1,8**	Mushk-Mgt-Act-Cpy-Py	minor sulfides in EIOS
TigB010-033.1	Copiapo\OjancoViejo\Tigresa	pyrite	~90%	**2,0**	Cc-Cpy-Py	sulfides in LES
TigB017-034.5	Copiapo\OjancoViejo\Tigresa	chalcopyrite	~85%	**-4,7**	Mgt-Cpy(-Py)	minor sulfides in EIOS
TigB030-030.4	Copiapo\OjancoViejo\Tigresa	chalcopyrite	~80%	**-1,8**	Qtz-Mgt-Mushk-Cpy-Py	minor sulfides in EIOS
TigB030-030.4	Copiapo\OjancoViejo\Tigresa	chalcopyrite	~80%	**-2,3**	Mushk-Mgt-Cpy	minor sulfides in EIOS
TigB088-013.2	Copiapo\OjancsViejo\Tigresa	pyrite	>90%	**3,0**	Qtz-Mushk-Mgt-Cpy-Py	minor sulfides in EIOS
TigB088-013.2	Copiapo\OjancoViejo\Tigresa	chalcopyrite	~95%	**1,5**	Mgt-Mushk-Cpy-Py	minor sulfides in EIOS
TigB088-046.3	Copiapo\OjancoViejo\Tigresa	chalcopyrite	>90%	**0,8**	Mgt-Chl-Cpy	minor sulfides in EIOS
TigB088-046.3	Copiapo\OjancoViejo\Tigresa	chalcopyrite	>90%	**-5,9**	Qtz-Mushk-Chl-Cpy	sulfides in LCSS
TigC092-111.7	Copiapo\OjancoViejo\Tigresa	pyrite	>90%	**4,1**	Py-Cpy-Qtz-Chl	sulfides in LCSS
TigC094-121.7	Copiapo\OjancoViejo\Tigresa	pyrite	>90%	**4,7**	Fk-Mgt-Act-Py(-Cpy)	minor sulfides in EIOS
TRS01-098.3	Copiapo\OjancoNuevo\Transito	pyrite	~80%	**1,4**	Scap-Act-Cpy-Py	minor sulfides in EIOS
TRS01-098.3	Copiapo\OjancoNuevo\Transito	chalcopyrite	~70%	**-2,0**	Scap-Act-Cpy-Py	minor sulfides in EIOS
TRS03-161.9	Copiapo\OjancsNuevo\Transito	chalcopyrite	~50%	**-5,3**	Mgt-Cpy-Qtz(-Py)	minor sulfides in EIOS
TRS03-161.9	Copiapo\OjancoNuevo\Transito	pyrite	~70%	**-1,7**	Epd-Chl-Cpy-(-Py)	sulfides in LCSS
TRS03-170.4	Copiapo\OjancoNuevo\Transito	pyrite	>90%	**-1,5**	Mgt-Fk-Cpy-Py	minor sulfides in EIOS
TRS03-170.4	Copiapo\OjancoNuevo\Transito	pyrite	~80%	**-1,1**	Act-Cpy-Py-Mgt-Qtz	minor sulfides in EIOS
TRS03-196.0	Copiapo\OjancoNuevo\Transito	chalcopyrite	~50%	**-3,7**	Mgt- Mushk-Cpy-Py	minor sulfides in EIOS
TRS38-008.4	Copiapo\OjancoNuevo\Transito	pyrite	~65%	**3,7**	Mgt-Py(-Cpy)	minor sulfides in EIOS
TRS38-008.4	Copiapo\OjancoNuevo\Transito	pyrite	~60%	**1,8**	Scap-Py(-Cpy)	minor sulfides in EIOS
TRS39-169.2a	Copiapo\OjancoNuevo\Transito	pyrite	~85%	**3,9**	Mushk-Cpy-Py-Act	minor sulfides in EIOS

abbreviations: Mgt=magnetite, Mushk=mushketovite ,Scap=scapolite, Chl=Chlorite , Ep=epidote, Act=actinolite Cpy=Chalcopyrite, Py=pyrite, Qtz=quartz, Cc=calcite, Fk=potassic feldspar; EIOS= early iron oxides stage, LCSS= later copper sulfides stage, LES= late epithermal stage; precision: ± 0.15 per mil

Heating and sequential freezing experiments were carried out at the University of Arizona, using an USGS-design gas flow heating-cooling stage. Salinities are expressed as weight percent NaCl eq. or, where observed, NaCleq.+CaCl$_2$. The calculation used the disappearance of the last ice crystal in two phase inclusions, the disappearance of the last halite crystal in multiphase inclusions or the low temperature eutectic point, when observed. Calculations were performed using the software AqSo for the system H$_2$O-NaCl, whereas salinities in the system H$_2$O-NaCl-CaCl$_2$ were calculated using the techniques developed in Steele-MacInnis et al., (2011).

Representative microthermometry and salinity data based on 35 selected samples (Table 4) suggest that the following main types of fluid inclusions can be distinguished:

Type1. These inclusions are multiphase liquid-vapor-halite plus opaque or daughter minerals such as sulfate/carbonate (LVH-O, LVH-D) or combinations of the above mentioned types (LVH-DO). The homogenization temperatures (Th) of this type range from 221^0C to >500^0C, whilst the salinity varies between 21.4-59.4%wt.NaCleq. (hypersaline). No more than 12% of the total recorded inclusions belong to this type.

*Type2.*These correspond to the three phase liquid-vapor-halite inclusions (LVH) and are the most abundant type recorded, (around 60% of the total amount of inclusions). Homogenization temperatures of these inclusions vary in the same range as for type1, but the majority are in the range 300^0 to 400^0C. The salinity is also quite similar to that for type 1, with values recorded in the 29.1-59.6%wt. NaCleq. interval.

*Type3.*This type includes the two phase liquid-vapor or vapor-liquid (VL or LV), and exceptionally, CO2-rich inclusions. The homogenization temperatures of the inclusions range between 189^0-415^0C and show moderate salinities in the interval 15.2-20.2%wt. NaCl eq. Up to 28% of the total observed inclusions belong to this type.

Inclusions formed in the deeper portion (early iron oxide stage) of the IOCG structures (e.g. Pompeya) homogenize by T_m halite, which almost always occurs after T_h vapor and between 350^0->500^0C (mostly between 375^0-415^0C). The dominant inclusion type here is type 2 (LVH), but also smaller amounts of type 1 (LVH-O, LVH-D, LVH-DO) and type 3 (LV, VL) are recorded. Note that the salinity is unusually very high, i.e. between 41.0-59.4% wt. NaCleq.

At intermediate levels, which correspond to the main copper sulfide stage (e.g.Tigresa) inclusions homogenize by the same method between 250^0-400^0C and cluster between 300^0-350^0C. Dissolution temperatures of halite indicate a higher salinity, ranging from 32 to 59.6% wt. NaCleq. Type 2 (LVH) and type 3 (VL,LV) inclusions are dominant, whereas only a few multiphase type 1 inclusions have been identified.

Inclusions in the shallowest, calcite-hematite (± clay minerals, sericite, quartz), upper parts of the IOCG structures, exhibiting epithermal overprints or the original epithermal environments (e.g. Boton de Oro, Tigresa, Transito), homogenize between 180^0-290^0C and cluster between 220^0-250^0C. The main inclusions recorded here are type 3 (LV,VL) and freezing point depressions in simple, two phase inclusions indicate a moderate salinity, varying from 15 to 20%% wt. NaCleq.

The high salinity of the (mostly) halite bearing fluid inclusions (32-59.6wt.% NaCl), associated with homogenization temperatures ranging from late magmatic to early hydrothermal (mesothermal) regimes could be explained as brines formed by direct exolution from a crystallizing magma. Due to the decrease of temperature and pressure, a part of the fluid may remain immiscible, but the acceleration of CO_2 degassing from the magma could have resulted in fluid mixing, where a pulse of Fe-Cu rich, highly saline, intrusive related (magmatic) fluids are clearly recognized. The continuous reduction in the P-T conditions to the late epithermal phase is marked by moderate salinities and homogenization temperatures around 200^0C. Introduction of meteoric fluids into the mineralized system plus boiling are responsible for this change of brine composition seen at lower temperatures.

The types of fluid involved in the evolution of the IOCG deposits near Copiapo, Atacama, have similar properties to the fluids involved in many IOCG systems worldwide. Temperatures of deposition ranging from 200^0 to over 500^0C and high salinity fluids are associated with a strong magmatic/mantle like noble gas signature (^{40}Ar/^{39}Ar>1000) and a Br/Cl ratio suggesting mixing between Cu rich magmatic fluids and Cu poor external fluids (Porter, 2010 a, b, Baker et al., 2008). Such behavior also seems to be appropriate for the Copiapo basin, the mixing of the fluids being probably one of the mechanisms of mineral precipitation (Barton & Johnson, 1996).

3.TYPOLOGY OF IOCG GOLD; RELATIONSHIP WITH Cu-Fe STAGES AND ALTERATION EVENTS

Comprehensive mineralogical and petrographic studies, combined with geological-tectonic and metallogenic field observations have been carried out on the Lower Cretaceous IOCG Copper Belt near Copiapo, Atacama by the authors during the last five years. In addition, new intense exploration and mining activities conducted in the last few years have provided valuable new data about the gold position and distribution in the IOCG environment. Small to medium size deposits (1 to 20Mt) suchas Pompeya-Tigresa-Rosario, Boton de Oro, Resguardo (Ojancos Viejo district), Carmen Alto-Transito-Antonia-San Francisco (Ojanco Nuevo district) and Las Pintadas (Punta del Cobre District) are included here.

Tabel 4. Representative fluid inclusion results from the Ojancos Viejo-Ohancos Nuevo tectonic-metallogenical alignments

Sample	*Type*	*Tm halite*	*Th V*	*Tm ice*	*Te*	*h Inclusion*	*wt% NaCl*[1]	*wt% CaCl$_2$*[2]	X_{NaCl}	X_{CaCl2}	*Na:Cl molar*
TigB088-013.1	LVH	347.2±4	257.1±2			347,2	42,0		12,36		
TigB088-013.1	LVH	299.3±5	300.3±2			300,3	38,0		10,46		
TigB088-013.1	LVH	321.1±2	266.2±0.5			321,1	39,7		11,25		
TigB088-013.1	LV		292.5±0.5			292,5	0,0		0,00		
TigB088-013.1	LVH	179.1±1	246.8±0.5			246,8	31,0		7,67		
TigB088-013.1	LVH-D	271.1±2	229.1±0.5	-28.3±		271,1	27,8	10,5	0,12	0,02	5,0
Pom08-213.1	LVH-DO	>500	387.1±2	-28.7±5		500,0	59,4	0,8	0,31	0,00	143,8
Pom08-213.1	LVH-D	440.2±2	296.2±2	-30.4±5		440,2	49,7	4,2	0,25	0,01	22,5
Pom08-213.1	LVH	>500	250.3±1			500,0	59,8		25,49		
Pom08-213.1	LV		415.3±0.5			415,3	0,0		0,00		
Tig198-099.9	LVH	>500	264.8±2	-22±5	-48.9±5	500,0	59,7	0,1	0,31	0,00	789,6
Tig198-099.9	LVH	399±1	265.3±3			399,0	47,2		15,28		
Tig198-099.12	VL		397.3±			397,3	0,0		0,00		
Tig143-102.9	LVH-D	355.4±	250±5			355,4	42,7		12,76		
Tig143-102.9	LVH	375±5	270.8±1			375,0	44,7		13,80		
Tig143-102.9	VL		335±5			335,0	0,0		0,00		
Tig143-102.9	LV		219.4±2			219,4	0,0		0,00		
Pom07-133.0	LVH-D	421.6±0.5	450±20	-32.3±1	-44.5±1	450,0	46,6	5,7	0,23	0,01	15,6
Pom07-133.0	LVH	317.5±3	243.7±0.5	-30.4±2		317,5	32,3	10,2	0,14	0,02	6,0
Pom07-133.0	LVH-D-CO_2	390±5	255±5	-32.2±0.1		390,0	41,9	7,4	0,20	0,02	10,7
Pom07-133.0	LVH-D	408.5±1.5	260.7±1	-30.9±3	-44.8±3	408,5	44,8	6,0	0,22	0,02	14,1
Pom07-133.0	LVH	375±5	269±2			375,0	44,7		13,80		
Pom07-133.0	VL		395±10			395,0	0,0		0,00		
TigB032-056.7	LVH	315.8±2	279.3±2			315,8	39,3		11,05		
TigB032-056.7	LVH	283.3±2	269.2±1			283,3	36,8		9,96		
TigB032-056.7	LV		260±10			260,0	0,0		0,00		
C2B-700	LVH	500±	373±2	-23.6±1		500,0	59,6	0,4	0,31	0,00	307,3
C2B-700	LV		189.3±3			189,3	0,0		0,00		
C3B-552b	LV		252±1	-12±3		252,0	16,0		3,25		
C3B-552b	LV		259.2±0.5	-14±3		259,2	17,8		3,70		
TigB088-013.1	LV		320±5			320,0	18,1		3,79		
TigB088-013.1	LVH-D	<313.5	331.7±0.5	-22.9±0.5	36.6±0.5	313,0	35,9	3,3	0,15	0,01	20,9
TigB088-013.1	LVH	270±10	337.2±	-21.4±1		337,2	34,7	0,5	0,14	0,00	129,8
TigB088-013.1	LVH	274±0.5	295±5	-26.4±1		295,0	29,1	8,6	0,12	0,02	6,4
TigB088-013.1	VL		321.8±1	-17±1		321,8	20,2		4,33		

[1] Calculated using Tm halite or Tm ice; [2] Calculated using Tm halite and T eutectic depressions following the methodology of Steele-MacInnis et al., (2011)

This work has documented the gold behavior in medium size to giant deposits (20 to 600Mt) e.g. Candelaria (Marschik et al., 2000, Marschik & Fontbote, 2001), Manto Verde (Zamora & Castillo, 2001, Benavides et al., 2007) or Carola-Punta del Cobre (Pop et al., 2000, Segerstrom 1967; 1968).

The morphologies of IOCG bodies vary from shear veins and stockworks, hydrothermal breccias to replacement-lens shaped and stratabound-Manto type ore bodies. Composite systems of the above mentioned types are common too, especially in the case of the giant deposits.

Petrographic studies, assay records and inducted coupled plasma-mass spectrometer analysis (ICP-MS) of major sulfides-oxides suggest that in all of the ore types the gold is present as native gold, genetically related to specific minerals like magnetite-mushketovite, chalcopyrite-pyrite or hematite-specularite. Gold grains exhibit micron sizes from <1 to 100 micrometers. Around 75% of the gold encountered in polished sections is intimately associated/included with/in chalcopyrite or pyrite and only 25% of the gold is included/in contact in /with magnetite-mushketovite or hematite-specularite.

At least three separate types of gold have been observed and described here.

3.1. M type gold associated with iron oxides (early IOCG stage)

This micron size gold (<1 to 40 micrometers) is included in early magnetite or mushketovite (Mtype) with massive to brecciated-mylonitized structures where actinolite-scapolite are abundant. All the magnetite, actinolite, scapolite, quartz groundmass is cut by later stage quartz-sulfide veins-veinlets or breccia bodies. However, minor sulfides such as early pyrrhotite, pyrite, cubanite and chalcopyrite seem to belong to this stage in many structures (e.g. Transito, Tigresa, Candelaria, and Manto Verde) but no gold was observed in these early sulfides. It has been proposed that in some IOCG systems the copper introduction occurred exclusively late in the paragenesis and is unrelated to iron oxide precipitation (Marschik & Fontbote, 2001, Williams et al., 2005). However, there is much evidence of minor amounts of copper sulfide as chalcopyrite intimately intergrown with early magnetite (Barton, 2009; Barton et al., 2011).

The iron oxide mineral assemblage also includes accessory phases of titanite, apatite or garnet without a genetic relationship with gold deposition. Mushketovite occurs in zones where early formed hematite assemblages are overprinted by magnetite associations. In this case, when hematite is converted to mushketovite, milky massive quartz and early sulfides are found with the magnetite bearing paragenesis (e.g. Pompeya). M type gold is often recorded in mushketovite blades which are intergrown with magnetite, suggesting changes of temperature and oxygen fugacity.

The key-proximal wall rock alteration which always points to the presence of gold in this stage contains fine grained secondary biotite with/without potassium feldspar. Biotite commonly appears under the microscope from green to blue-green color and is predominantly a low titanium phlogopite, whereas K-feldspar (orthoclase-perthite) sometimes replaces scapolite (e.g. Transito-San Francisco mineralized system).

The stable isotopes study of early iron oxides stage, especially δ^{34}S values variation from -5.3 to 4.7 per mil in minor sulfides of this stage, suggests that iron oxides and M type gold are deposited from magmatic or near magmatic deep seated oxidized fluids.

Fluid inclusions data also support this concept, indicating that M type gold included in magnetite-mushketovite is formed at mesothermal temperatures between 350^0-500^0C (mostly 375^0-415^0C). However, the high salinity recorded in halite bearing fluid inclusions, i.e. from 41 to 59%wt. NaCleq., remains unusual and perhaps controversial too. The hypersaline fluids could be explained as a result of direct exolution from crystallizing magma or due to assimilation of crustal rocks (e.g. evaporites) during magma ascent.

3.2. C type gold associated with copper sulfides (later IOCG stage)

This type of gold is often encountered in polished section with a size between 10-100 micrometers and is related to the main copper event, being almost entirely included in chalcopyrite (C type) which is typically massive and anhedral. As an exception, the C type gold was also observed in rich Co/Ni bearing pyrite with pentagonal habit, in contrast to the cubic-euhedral pyrite which appears to be depleted in gold.

Magnetite and hematite-mushketovite are sparse to absent in the sulfide dominant associations. The gangue minerals are represented by quartz (at least two generations), albite, K-feldspar (perthite), chlorite, epidote and subordinate actinolite. Calcite is not common in this stage, while milky-white to semitransparent opaque quartz is present either with a porous-sheared-friable aspect or as rounded to subangular clasts in breccias and brecciated zones.

However, the direct link between the C type gold bearing copper sulfide stage and albite-Na rich alkaline metasomatism, as a proximal selvage of the ore body, is clear. Potassic alteration (K-feldspar ± biotite) that is also spatially related to the ore, is actually genetically associated with the early or later formed iron oxide mineral assemblage, with/without hematite.

The $\delta^{34}S$ isotope results from samples of sulfides belonging to the main copper stage in the Tigresa ore body indicate magmatic or magmatic derived fluids ($\delta^{34}S$ from -6.9 to 4.1 per mil) and a weak enrichment with reduced sulfur is emphasized.

Fluid inclusions in this stage remain hypersaline, ranging from 32 to 59%wt. NaCleq., with variable but common $CaCl_2$ concentrations and molar ratios of Na:Cl of 10-100. The homogenization temperatures of inclusions associated with C type gold bearing sulfides are between 250^0-400^0C and cluster between 300^0-350^0C, i.e. gold seems to be mostly mesothermal in this mineralization episode.

During the decrease in temperature and pressure from the early iron oxide stage to the later copper sulfide stage, highly saline fluids are associated with degassing of CO_2 from the magma. Such evolution may require the introduction to the system of an external saline brine and the mixing of two different fluids, at least one derived from a magmatic source.

M and C types gold are directly formed during hypogene IOCG processes. They occur in the most important part of the mineralized systems in the vicinity of Copiapo-Atacama, hosted in the Andean Batholith or the Punta del Cobre District, i.e.volcano-sedimentary rocks. The source of Fe, Cu and Au is also predominantly magmatic, although an external saline brine and therefore crustal rock assimilation during magma ascent is possible.

3.3 P/H type gold related to late stage pyrite or hematite

The P/H type gold varies in size from 50 to 100 micrometers and is found in the upper to intermediate part of the IOCG deposits, either as an epithermal overprint (Tigresa) or still preserved in lower temperature, epithermal suites related to more hypabyssal rocks (Transito). Gold in this stage is associated with pyrite or hematite-specularite (P/H type) in a sericite, illite±kaolinite, chlorite, quartz bearing intermediate argillic hallo or in carbonate rich, colloform to jasperoidal quartz veins and stockwork like patterns.

This gold type was recorded as small inclusion in pyrite in argillized fractures cutting the main ore body or in hematite-specularite carbonate rich environments located in the upper part of the structures. Also, the presence of P/H type gold in hematite-sericite-carbonate haloes was reported in larger deposits near Copiapo, e.g. Carola, Candelaria, Manto Verde (Pop et al., 2000, Marschik & Fontbote, 2001, Vila et al., 1996). However, it is almost absent in many skarn to stratabound deposits and silver may become significant in the precious metal assemblage of this IOCG type system.

The C-O stable isotope results of the gold bearing late carbonate rich stage suggest the regime was initially dominated by near magmatic fluids ($\delta^{13}C$ from -3 to -9 per mil), with a slightly, but constant, tendency of mixing with meteoric fluids ($\delta^{18}O$ variation between 9-11 per mil). The $\delta^{34}S$ results show values mainly between 0-2 per mil, indicating that the sulfur is derived from a magmatic source; extreme $\delta^{34}S$ values of 7.6 and 8.3 correspond to a limited, but well marked contribution of more reduced sulfur in this stage.

Fluid inclusions show homogenization temperatures closer to an epithermal environment, i.e. between 180^0-290^0C (mostly between 220^0-250^0C). A moderate salinity varying from 15 % to 20%wt. NaCleq. correlates with boiling phenomena and a likely mixing with meteoric fluids.

Therefore, P/H type gold is probably epithermal and in places later than the main IOCG events, i.e. epithermal overprints. The key alteration in this case is a sericite bearing intermediate argillic halo which seems to be related to a low sulfidation type environment. A still preserved epithermal suite in the upper parts of some IOCG systems may also contain P/H gold in carbonate rich-hematite veins or stockwork bodies. Evidence of boiling and introduction of meteoric fluids into the system are well expressed at Transito (Antonia vein) where semitransparent-bladed calcite was found in a ribbon like hematite-specularite-jasperoidal and colloform quartz assemblage of the same low sulfidation style.

4.CONCLUSION, REMARKS AND EXPLORATION TOOLS

Fluid mixing seems to be a critical process for IOCG ore deposition near Copiapo – Atacama, Chile. A combination of stable isotope and fluid inclusion studies, together with geological, mineralogic-petrographic and tectonic-metallogenic data suggest that the majority of IOCG deposits were formed by the mixing of an external brine with a dominant pulse of Fe-Cu-Au rich, highly saline, magmatic fluids (intrusion related). Evidence supporting the mixing model includes:

(a) Fluid inclusions display a wide range of salinity and temperature; different fluid inclusion types occur in the same paragenetic stage, but there is an overall decrease in salinity from the early to late ore stages;

(b) Fluids associated with the investigated IOCG deposits are typically H_2O-salt-CO_2 fluids that evolved by unmixing of the carbonic phase and by mixing with fluids from external sources;

(c) C-O and (especially) S isotopic data do not clearly discriminate between the fluids, i.e. the most important portions are magmatic or derived from magmatic fluids; even a small contribution of external fluid component remains uncommon in such a batholith related environment.

Based on a multiphase evolution in the IOCG deposits located near Copiapo, Atacama, at least three types of gold were delineated in this mineralized environment, as follows:

(1) Early iron oxide (magnetite) related gold (M type), generally having a lower economic importance. Commonly the M type gold is included in early mesothermal magnetite or mushketovite associated with well expressed potassic alteration, i.e. fine grained secondary biotite ± K- feldspar. The fluids of this gold bearing stage were hypersaline (41-59%wt. NaCleq.) with homogenization temperatures ranging from 350^0 to $>500^0$C and cluster between 375^0-415^0C. The stable isotope data, especially δ^{34}S values between -5.3 to 4.7 per mil suggest that M gold type was probably formed from magmatic or near magmatic, intrusion related, oxidized fluids. However, high salinity brine as a result of direct exolution from crystallizing magma may be caused by evaporite-type crustal rock assimilation during magma ascent.

Even though a constant low Fe:Au ratio was observed in some structures, e.g. Tigresa, Transito, Carola, Candelaria, the fire assay records indicate that M type gold grades are between 0.05 -0.30 g/t and therefore not always economic if not overprinted by other gold types. A dark, fine grained biotitization with a microgranular aspect and accompanied by actinolite, scapolite, grayish-opaque early quartz and pyrrhotite bearing minor sulfides are present near the magnetite-mushketovite assemblage which contains M type gold.

(2) Later sulfide (chalcopyrite) related gold (C type gold) belong to the main mesothermal copper stage. Its distribution is very variable, but is well recovered in the copper concentrate flotation. C type gold is included mostly in chalcopyrite, much less in pentagonal Ni/Co bearing pentagonal pyrite. Gold in the copper sulfide stage is associated with Na rich (albite) alteration, together with small amounts of milky quartz, potassic feldspar, chlorite, epidote and later actinolite. Isotopic δ^{34}S data indicate magmatic or magmatic derived fluids (-6.9 to 4.1per mil), while an enrichment in reduced sulfur is also significant. The fluids of this gold bearing stage were still highly saline, varying from 32% to 59%wt. NaCleq. and homogenization temperatures range between 250^0-400^0C (mostly 300^0-350^0C), meaning that gold formation with copper sulfides was probably still mesothermal. The evolution of the system may require the introduction of an external brine and mixing of two different fluid types.

A constant Cu:Au ratio between 1:0.02- 1:0.5 (Cu%, Au g/t) is observed in several IOCG systems near Copiapo (Tigresa-Pompeya, Trinidad, Socavon Rampa, Candelaria). The C type gold grades based on fire assay records vary between 0.2-4.0 g/t. When present, the delineation of the sectors which contain this gold type become critical during exploration, due to the economic added value. The key albite bearing alteration forms mottled to breccias-like textured whitish zones, where fault related palygorskite or kaolin overprints are often encountered.

(3) Late pyrite or hematite related gold (P/H type gold) is recorded as an epithermal overprint or still preserved epithermal suite in the upper part of some IOCG patterns (Manto Verde, Tigresa, Transito), commonly with a significant economic value. Gold is included either in late pyrite (epithermal overprint-fractures which crosscut the main ore body) or in specular hematite-carbonate rich, preserved epithermal suites nearby the surface. The key alteration for the pyrite-included gold overprint is a sericite bearing intermediate argillic assemblage, whereas gold included in hematite-specularite is related to a carbonate rich (rhombohedral calcite) epithermal suite in the upper part of the structures. The main features and mineralization style of this environment are more closely associated to gold in low sulfidation type systems. The C-O-S stable isotope results indicate for this stage the mixing of magmatic fluids (δ^{13}C between -3 and -9 per mil, δ^{34}S between 0-2 per mil) with meteoric fluids (δ^{18}O from 9 to 11 per mil,, δ^{34}S extreme values of 7.6 and 8.3 per mil). The fluid inclusion data also indicate homogenization temperatures corresponding to an epithermal phase, i.e. between 180^0-290^0C (mostly 220^0-250^0C) with moderate salinities varying from 15% to 20%wt. NaCleq. and boiling due to the mixing of fluids.

The typical features of the P/H gold type environment which can be seen in the field are bladed calcite, green sericite-bearing oblique shear fractures with a friable clay mineral halo or jasperoidal to colloform quartz, and large crystallized calcite-bearing veins or stockworks in the upper part of the IOCG structures. Fire assay results indicate that the P/H type gold is by far the most valuable economically, ranging from 1-2 g/t up to 20 g/t. The highest grades are associated with oblique shear fractures which crosscut the main ore body, although gold tends to be deposited in quite restricted-permeable zones near the intersections.

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