

EVOLUTION & TIMING OF ALTERATION-MINERALIZATION PROCESSES IN TIGRESA-TRANSITO IOCG VEIN DEPOSITS FROM OJANCOS TECTONIC ALIGNEMENTS, ATACAMA REGION, CHILE

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Abstract: Recent electron microprobe analyses with detailed petrographical studies were carried out in IOCG shearing veins of Tigresa and Transito ore deposits hosted by the Early Cretaceous batholiths and located along the Ojancos Viejo-Ojancos Nuevo tectonic-metallogenetical alignments, south of Copiapo, Atacama, Chile. Six stages of alteration and/or mineralization in a magnetite rich, at least partly magmatic, IOCG vein to lode type environment were delineated as a result of such new data. The early stages I-II are consisting of actinolite-scapolite-titanite \pm chlorite alteration followed by K rich (biotite-K feldspar) iron oxides (magnetite, mushketovite) alteration and mineralization. Scapolite is a mixed Na-Ca marialite (2.50-4.01%Cl) corresponding to Me_{55-68} , whereas the amphibole is a tremolite-Mg rich actinolite or ferrotschermakite with Mg/Mg+Fe ratio between 0.36-0.60, suggesting mostly an igneous origin. Magnetite commonly contains TiO_2 (up to 0.54%) and V_2O_3 (up to 1.08%); additionally, titanite is constantly recording F traces, all indicating also magmatic IOCG type fluids. Early biotite is constant in chemical composition, corresponding to a rich titanium-sagenitic biotite (0.46-1.27% TiO_2) with minor amounts of V, Na, and Cl characteristic for high temperature-magmatic derived fluids. The intermediate stages III-IV enclose a Na rich metasomatic event and the main Cu sulfide mineralization. A grading from Na rich oligoclase to albite was observed and highlighted by minor-trace amounts of K and Fe. Mg-Fe rich oxidized chlorites are common in these stages and featured by fluctuant SiO_2 (28.32-33.50%) and an increasing of Cr_2O_3 (up to 0.64%) and K_2O (up to 0.47%), suggesting a possible mixing of different fluids at the end of the processes. The late stages V-VI involve a Ca-K (Fe) metasomatism and subsequent main Au mineralization in a carbonate-specular hematite \pm sericite \pm biotite environment. The late alteration of biotite is represented by low potassium-vermiculite (0.98% K_2O) with increasing amounts of Ca pointing to more widespread introduction of connate-meteoric fluids into the system.

Keywords: microprobe data, alteration-mineralization stages, Tigresa-Transito IOCG veins, Atacama, Chile.

1. INTRODUCTION: THE GENERAL GEOLOGICAL SETTING OF TIGRESA & TRANSITO VEIN/LODE IOCG ORE

The appropriate rocks/mineralization exposure and the remarkable mining history of Copiapo basin, completed with modern time discovery of the giant Candelaria IOCG ore deposit attracted for years detailed geological studies in so called Punta del Cobre District (Segestrom & Ruiz, 1962, Camus, 1980, Marschik et al., 1997, Diaz et al., 1998, Lledo, 1998, Marschik & Fontboté, 2001). In addition, the intrusive related (Copiapo Batholith) Lower Cretaceous IOCG deposits, as a part Chilean Copper

Belt, have been intensively studied in the past (Zentili, 1974, Tilling, 1976, Brown, 1987, Arevalo, 1999) or more recently using modern geochemical tools (Marschik et al., 2003, Barton et al., 2005, Marschik & Söllner, 2006, Barton et al., 2011).

As a heterogeneous group of ore deposits, the well known iron oxide-copper-gold (IOCG) environment was proven in the latest years to be magmatic, non-magmatic or hybrid in terms of source of metal fluids (Ullrich & Clark, 1998, Barton & Johnson, 2000, Williams et al., 2005, Pollard, 2006, Benavides, 2006, Hunt et al., 2007). The mesothermal vein/lode deposits of Tigresa and Transito are not an exception of the rules, hosted and related to Lower

Cretaceous intrusive rocks of Andean Batholiths in Copiapo basin, region of Atacama.

One of the salient characteristic of those two ore deposits is the position inside (Transito) or nearby (Tigresa) important tectonic alignments, i.e. Ojancos Nuevo and Ojancos Viejo (Fig 1).

The first structural consequence is an impressive shearing fabric of the veins, which are constantly dipping westward. The open space-dilatational aspects are developed locally and related mainly to later epithermal overprints carried out in a decompressional subsequent tectonic regime.

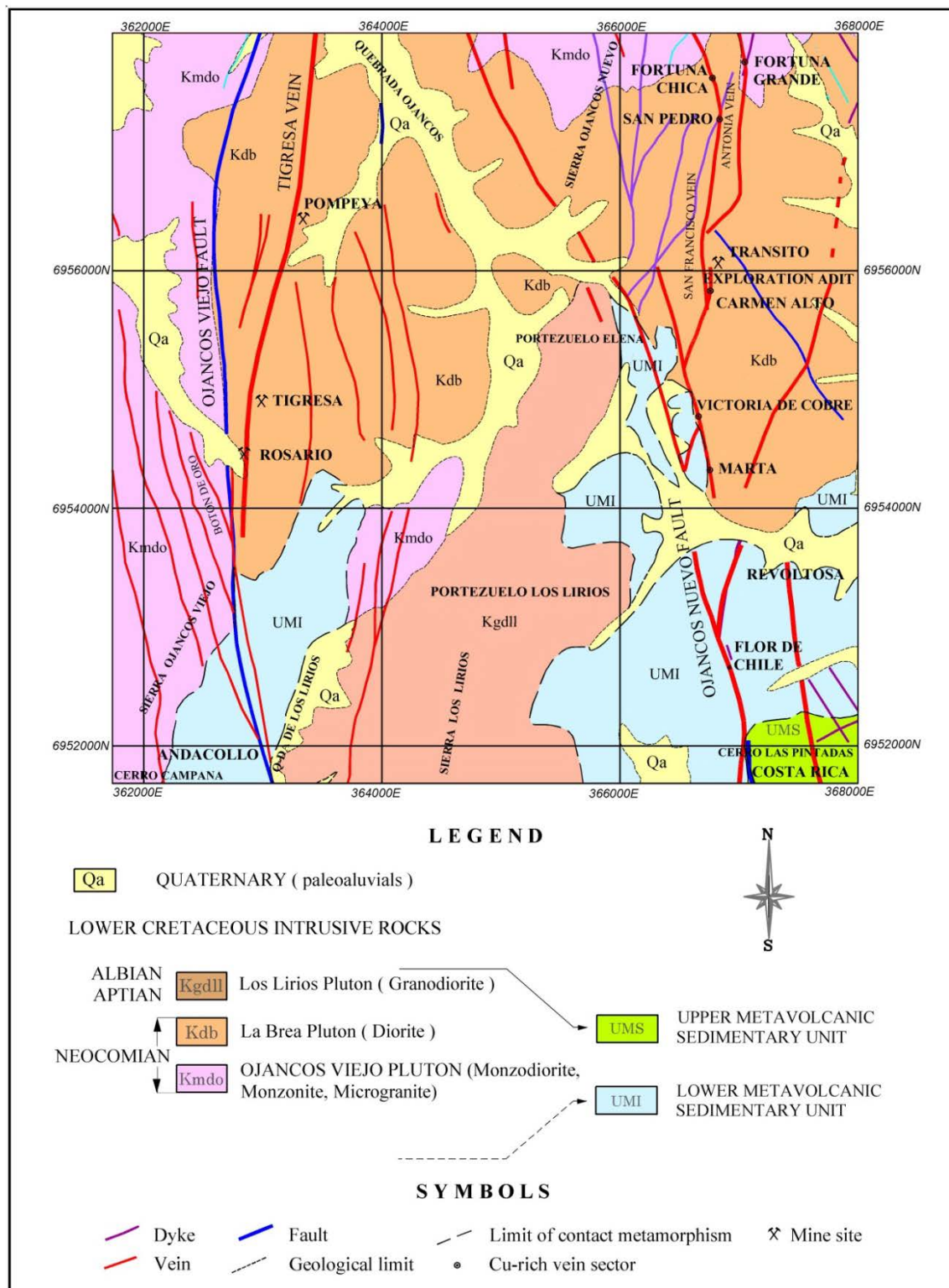


Figure 1. Geological map (simplified) of the Ojancos Viejo-Ojancos Nuevo district, south of Copiapo, Atacama, Scale 1:50.000

The Ojancos Nuevo and Viejo fractures are, as a matter of fact, oblique branches of the major Atacama Fault Systems, all together forming a convergent structure where at least partly the Upper Jurassic-Lower Cretaceous basic rocks of La Negra, Punta del Cobre and Bandurrias Formations are obducted over the continental plate and pierced by granitic-dioritic rock of Andean Batholith. During Early Cretaceous time the subduction processes have rapidly advanced eastward (The Andes), the actual position of magmatic-continental arc. Such arc migration in an intense tectonic regime is mostly controlling the deposition of mineralization in the, probably older, marginal basin of Copiapo (Thiele & Pincheira, 1987, Bonson et al., 1997). In the figure 2 is showed position and emplacement of important IOCG-porphyry mineralized structures from Atacama region, relative to arc inversion and major tectonic frame evolution.

1.1. Main features of Tigresa ore deposit

The Tigresa-Pompeya-Rosario (TPR) IOCG vein system is an almost 3km long and 2 to 12m width continuous, commonly bended-ribbon like structure. Massive Fe-Cu±Au zones, breccias-brecciated quartz bearing zones and sheeted stockwork like zones are often encountered inside the tectonic hanging-footwalls of the vein. The structure is located 200-250m away from Ojancos Viejo fault. It is linked with the main alignment by means of en-echelon system of narrower gold-hematite fractures,

where subhorizontal - Manto type dykes are responsible for at least subsequent overprinting events. The host rock of TPR vein system is La Brea coarse grained diorite, dated using U-Pb on zircon method to 116-119 M.a.±2 M.a. (Marschik & Söllner, 2006, Barton et al., 2011). The mineralization in TPR vein consists of magnetite, mushketovite, specular hematite, pyrite, pyrrhotite, chalcopyrite±cubanite±bornite in a gangue of quartz, actinolite, biotite, potassium feldspar, albite, chlorite and epidote. The dipping of the assemblage is quite variable from 40 to 70°West, suggesting a more complicated tectonic control, probably close to decollement type deformations. The exceptional-most productive zone of the vein is situated in Central Tigresa sector and comprises an almost 25m thick Cu bearing breccia- brecciated stockwork like structure. A detailed model-cross section of Tigresa type IOCG mesothermal vein, showing lateral to vertical alteration, metal zonality and mineralization style is exhibited in figure 3.

1.2. Key characteristics of Transito ore deposit

Transito IOCG mineralization is located inside of the Ojancos Nuevo Fault alignment of more than 7km long, exhibiting vein to lode (multiveins) morphology and expressive shearing aspects, converted into widespread mylonitic and brittle-ductile textures.

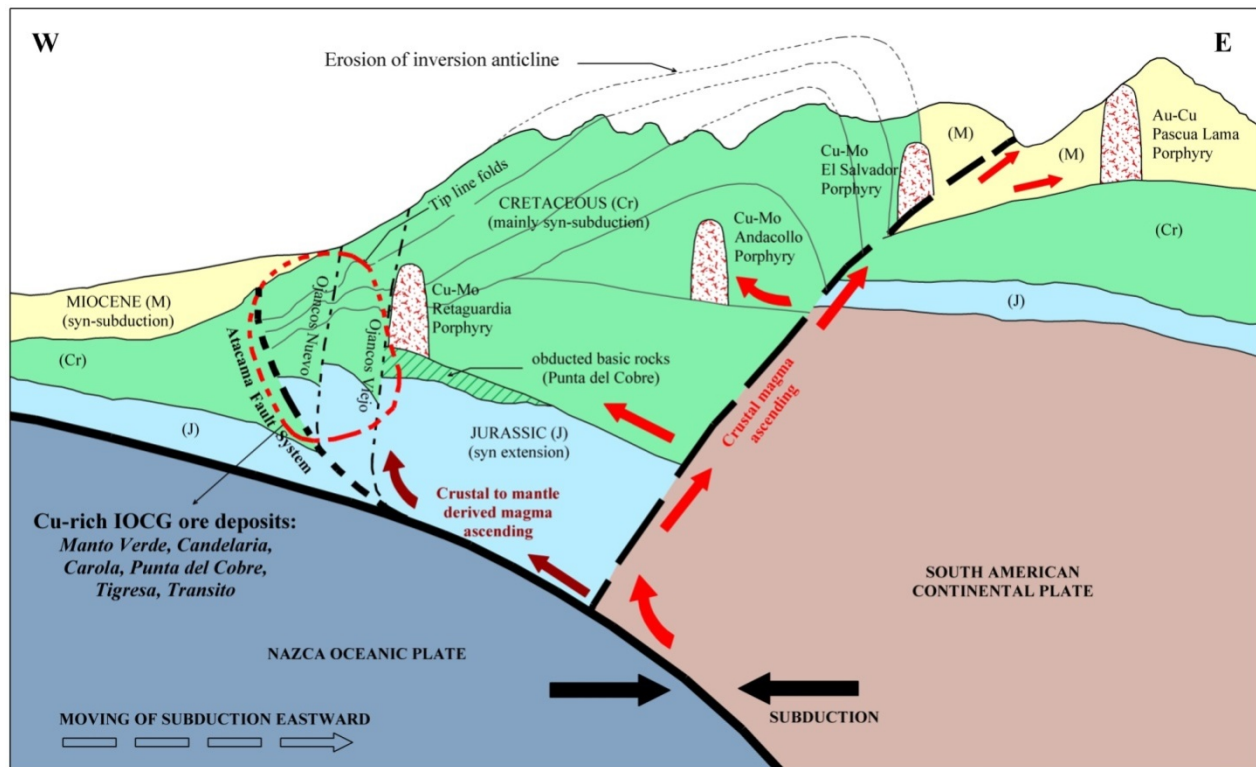


Figure 2. Cretaceous-Miocene IOCG-Porphyry emplacement and arc inversion in Atacama region, Chile (without scale)

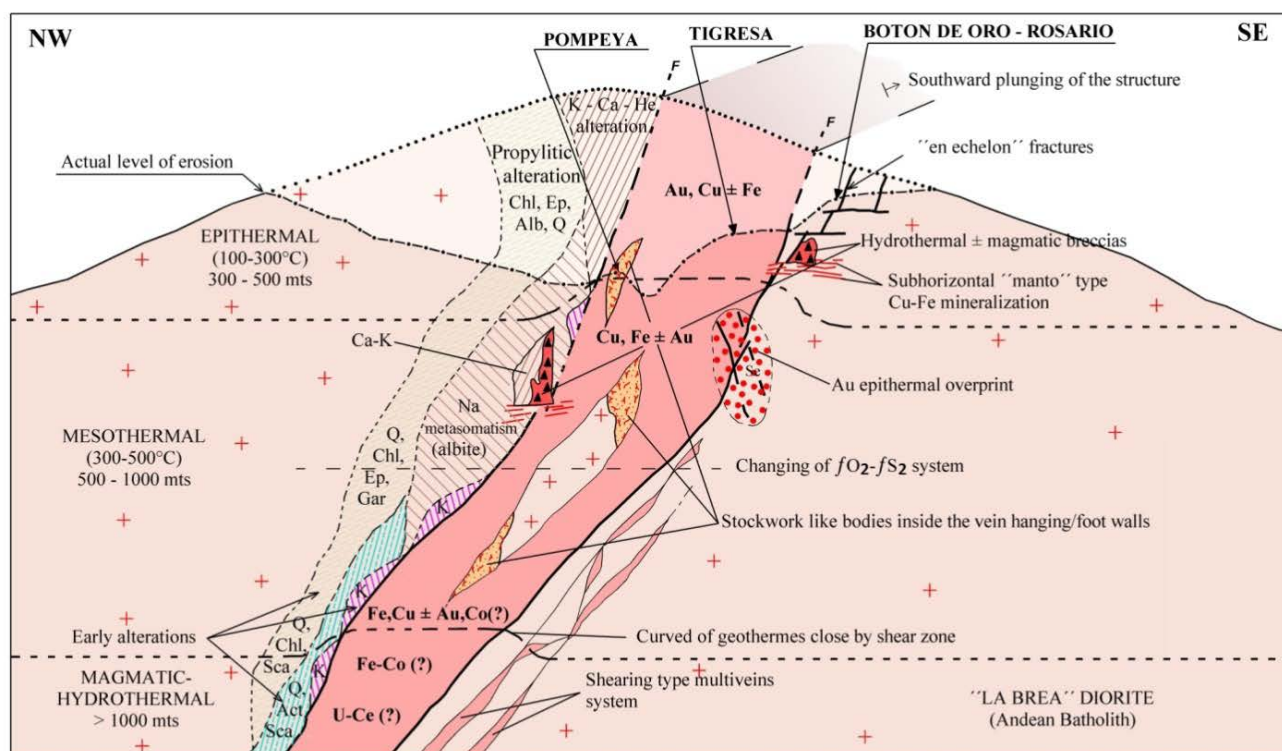


Figure 3. Hypothetical cross section (not to scale) through Tigresa IOCG mesothermal vein deposit showing lateral and vertical alterations and metals zonality; shearing-structural and hydrothermal controls are not only expressed inside the hanging/foot walls of the vein, but also by external breccia columns up to horizontal "manto" type Cu-Fe mineralization related to adjacent "en echelon" fractures.

Legend: Mgt=magnetite; He=hematite; Chl=Chlorite; Alb=albite; Q=quartz; Sca=scapolite; Ep=Epidote; Gar=garnet; Se=sericite; Ca=carbonate, k=potassic alteration; fO_2 - fS_2 =oxygen sulphur fugacity.

Many mining-exploration sectors are found along the structure, each one with distinctive features. From North to South the most important sectors are: Fortuna Grande, San Pedro, San Francisco, Antonia, Victoria del Cobre, Carmen Alto, Revoltosa, Flor de Chile and Costa Rica. The northern part is composed of two main vein branches, whereas the southern part is confined to a single lode type pattern showing different erosion levels and therefore distinctive alteration/mineralization aspects.

A multiphase metallogenetic evolution of the Transito Fracture, including possible chloritoid bearing shear zone related events, is associated with different Lower cretaceous igneous rocks emplacement, e.g. La Brea type diorites, microgranites to adamellite monzogranites, monzodiorites, tonalities, mafic (lamprophyres) and felsic (dacite-andesite) dykes. Mineralization is probably older than 110 M.a, and formed in larger time interval of 110-119M.a \pm 2.1 M.a., based on recent U-Pb zircon data (Barton et al., 2011).

In contrast with Tigresa, Transito mineralization contains additionally bornite and

molibdenite in deep sectors situated 400m below the modern surface. Also, the upper-oxidized part of the structure having over 300m thick is a rich carbonate (rhombohedral calcite)-specular hematite (specularite) environment grading into deeper quartz-magnetite-copper sulfide brittle-ductile zones and therefore showing a more expressive vertical zonation. Typical lode fabrics are encountered in several sectors, e.g. Marta, where the widest 70m thick circulated zone of the structure exhibit pervasive alterations and superposition of brecciated-mylonitic zones, stockwork like tabular patterns and massive veins-veinlets (Fig. 4).

The Ojancos Nuevo-Transito tectonic alignment is a major N-S oriented structure dipping constantly 60-70° West. The fault evolution involves normal dip-slip movements but also reverse strike-slip ones, based on the relationship along strike between shallow-volcanic and deep-plutonic rocks. The historical mining in Transito ore deposit is back to the 19th century, when several hundred thousand tons of Cu-Au ore were mined out by a British company using three main external shafts, still preserved and partly used until nowadays.

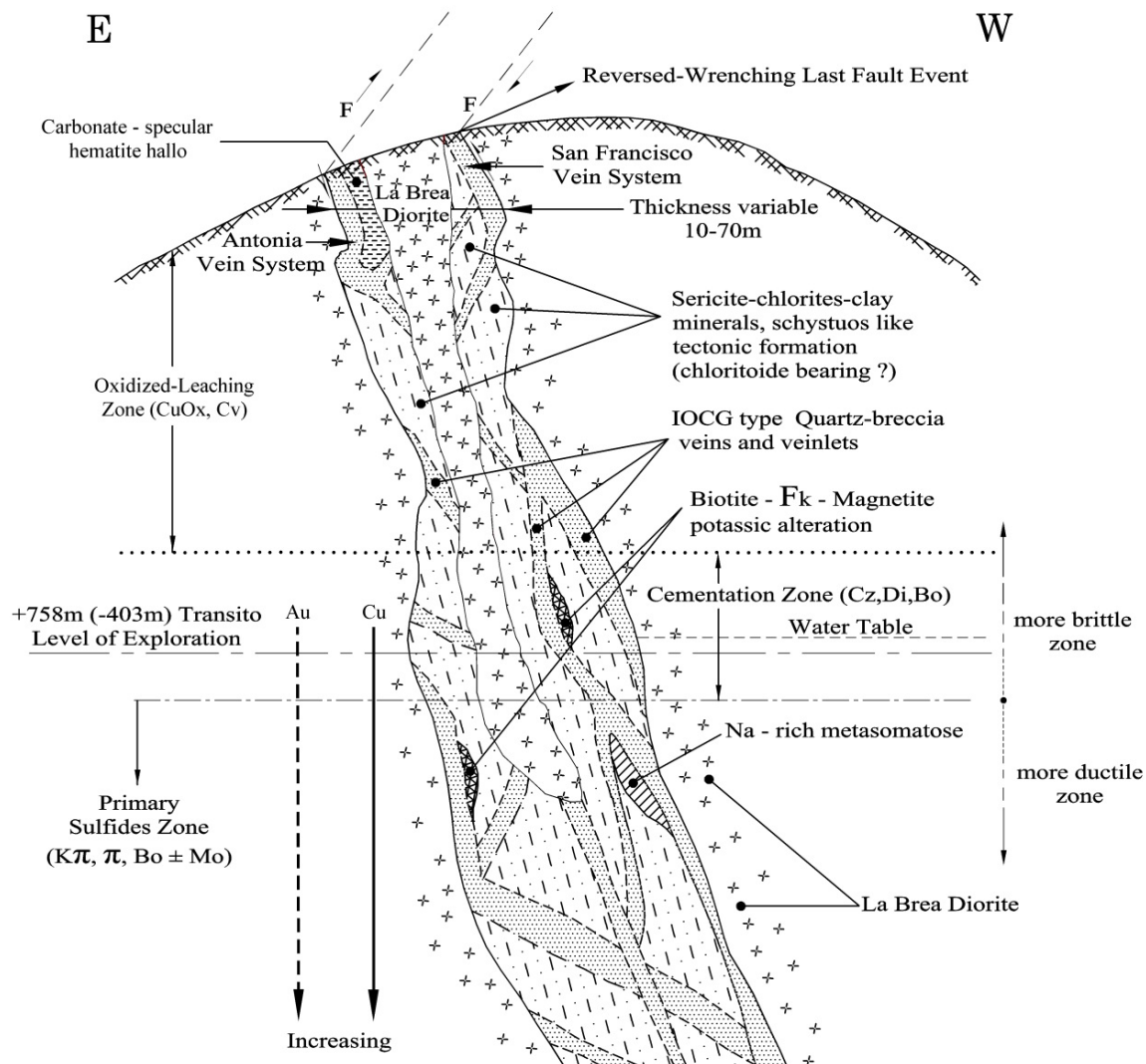


Figure 4. Sketching cross section through Transito lode pattern (not to scale) showing a possible multiphase mineralization: the first phase related to IOCG type deposit (Fe-Cu-Au) of generally higher temperature and secondly, distinctive phases of enrichment in some metals (Cu, Au) associated to the evolution of a major shearing event along Ojancos Nuevo alignment.

Symbols: CuOx=copper oxidized; Fk=potassic feldspar, Di=digenite; Cv=covelite; Bo=Bornite; Cz=chalcocite; $k\pi$ =chalcopyrite; π =pyrite; Mo=molibdenite

2. ELECTRON MICROPROBE DATA AND INTERPRETATION

To constrain mineral composition and textural relationships of Tigresa-Transito IOCG ore deposits, electron microprobe analyses were conducted on over 50 polished sections. Both the CAMECA SX50-4 and CAMECA S100-5 spectrometer electron microprobes were used in the Planetary Sciences department of University of Arizona. Internal corrections in the CAMECA software (PAP and ZAF) were used and the device was standardized prior to each session, when both WDS and EDS methods were applied. A typical analysis

was performed under conditions of 15keV accelerating voltage, 20nA beam current, 2 μ m beam size, and 30 second peak count time would require ~4 min per analysis and would yield MDLs of ~100 - 300 ppm (3 σ) for all elements and a 1 σ accuracy of 0.5 - 1.5% relative for major elements (those present at concentrations > 1wt%). For trace element analysis (elements present at concentrations < 0.1wt%), accelerating voltages of up to 25keV and regulated beam currents up to 300nA were sometimes used and can produce MDLs as low as 5 ppm in favorable cases. Silicate routines analyzed for Na, Mg, Al, Si, K, Ca, Ti, Mn, Fe, B, F, Cl, P, S, Cr, V, Sr, La, Ce, Ni, Sc and Zn. Oxide routines analyzed for Fe, Al,

Si, Ti, Mn, V, Co and Ni. The REE bearing analytical package analyzed for Na, Si, Ca, Ti, Fe, Al, V, Mn, F, La, Ce, Y, Zr, Nb and U. Na and F are known to become mobilized under the electron beam in normal operation conditions. To account Na and F were run at the beginning of the analytical package to minimize the mobilization effect. Even with appropriate standardization and running, the elements at the frontend of the routine, oligoclase and albite will often yield totals near 101-102 percent.

Representative results from Tigresa and Transito IOCG vein to lode deposits for magnetite-titanite are shown in the table1 (normalized to all cations), whilst the main vein silicate minerals are exhibited in the table 2. Sometime, as a matter of space economy, constantly “zero” values on certain elements have been eliminated from the table, without affecting the subtotal or total percent calculation.

Magnetite is the main iron oxide mineral both in Tigresa and Transito mineralization formed in early stages, according with integrated field observation and detailed mineralogic-petrographical studies. The new electron microprobe results provided valuable data, showing there are in fact two varieties of magnetite, as follows:

(a)Ti-V rich magnetite which it seems to be very early in paragenesis and is commonly associated

with actinolite in the proximal wall rock alteration selvage, this magnetite contains up to 0.54% TiO₂ and up to 1.08% V₂O₃, but also minor-trace amounts of Al, Cr, Mn.

(b)Ti-V poor magnetite associated either with biotitic alteration or iron oxide mineralization in the early stages; this type contains fluctuant-minor amounts of SiO₂ (0-2.93%), Al₂O₃ (0.07-1.73%) MgO (0-1.85%) and K₂O (0-0.54%), the highest values being recorded in the main iron oxide mineralization event.

The presence of Ti-V elements in magnetite suggests at least partly a magmatic-intrusion related origin of iron oxide fluids and a possible mafic affinity of primary-mantle derived magmas (Nyström & Henriquez, 1994). Also, Si, Al, Mg and K impurities are probably relicts of amphibole (actinolite) or potassic (biotite) alterations that affect the host rocks in early stages.

Titanite also shows a similar electron microprobe chemical pattern to magnetite, suggesting an intimate Fe-Ti association in early events. An vanadium rich titanite (up to 0.92% V₂O₃) is associated with magnetite-mushketovite mineralization, whereas titanite formed in early wall rock alteration selvage is enriched in A₂O₃ (up to 1.82%) and sometimes contains traces of Ce₂O₃ (0-0.37%) and La₂O₃ (0-0.08%).

Table1. Representative electron microprobe analyses of magnetite-titanite from Tigresa&Transito

Sample	TigB09 1-025.4	TigB93 -35.0	C6B-141 OVa2	C6B-141 OVa3	TigB005 -026.6.1	TigB005 -026.6.2	Sample	TigC09 2-033.2	Tig201 -148.9	TRS38 -003.1	Tig201 -148a1	Tig201 -148a2
Mineral	Mgt	Mgt	Mgt V	Mgt V	Mgt	Mgt	Mineral	Tit	Tit	Tit	Tit V	Tit V
Alt stage	stage II	stage II	stage I	stage I	stage I	stage I	Alt stage	stage II	stage I	stage II	stage I	stage I
Timing	early	early	earliest	earliest	earliest	earliest	Timing	early	earliest	early	earliest	earliest
SiO ₂	2.93	0.71	0.04	0.04	0.00	0.04	SiO ₂	30.31	25.01	29.96	29.62	28.48
TiO ₂	0.12	0.07	0.54	0.49	0.14	0.14	TiO ₂	37.20	37.35	37.53	37.04	37.63
Al ₂ O ₃	1.73	0.45	0.44	0.15	0.07	0.07	Al ₂ O ₃	1.82	0.78	1.25	0.74	0.60
V ₂ O ₃	0.14	0.16	1.07	1.08	0.54	0.68	FeO	0.00	0.00	0.00	0.00	0.00
Cr ₂ O ₃	0.02	0.02	0.13	0.12	0.08	0.09	Fe ₂ O ₃	0.89	1.34	1.26	1.84	1.17
La ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	MnO	0.01	0.11	0.00	0.04	0.06
Ce ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	CaO	28.27	27.05	27.41	27.86	27.51
Fe ₂ O ₃	61.17	67.37	65.78	65.79	68.12	67.37	Na ₂ O	0.00	0.02	0.00	0.00	0.02
FeO	30.43	30.60	31.28	31.06	31.05	30.96	F	0.29	0.21	0.09	0.22	0.28
MnO	0.01	0.00	0.03	0.09	0.00	0.02	ZrO ₂	0.00	0.00	0.10	0.00	0.00
NiO	0.00	0.00	0.02	0.02	0.01	0.01	V ₂ O ₃	0.27	0.06	0.16	0.95	0.92
ZnO	0.00	0.00	0.01	0.03	0.00	0.00	La ₂ O ₃	0.00	0.05	0.00	0.08	0.08
MgO	1.85	0.59	0.01	0.02	0.04	0.03	Ce ₂ O ₃	0.00	0.14	0.07	0.25	0.37
CaO	0.09	0.02	0.00	0.00	0.00	0.00	Y ₂ O ₃	0.00	0.00	0.05	0.00	0.00
Na ₂ O	0.03	0.04	0.03	0.00	0.03	0.00	Nd ₂ O ₃	0.00	0.00	0.08	0.00	0.00
K ₂ O	0.54	0.17	0.01	0.00	0.00	0.00	UO ₃	0.00	0.00	0.00	0.00	0.00
Subtotal	99.06	100.21	99.39	98.92	100.09	99.42	Subtotal	99.06	92.01	97.97	99.13	97.62

Table 2. Representative electron microprobe analyses of silicate vein fill minerals from Tigresa-Transito IOCG vein deposits

Sample	Tig201-148.9	Cr04-210.3	Pom8-179.3	TRS38-003.1	Tig201-148.9	TRS38-003.1	TigB089-063.8	CR01-117.3	TRS39-143.9	TigB93-35.0	TigC092-033.2	TigB089-063.8	TigB091-025.4
Mineral	Scap Me ₆₈ ¹	Scap Me ₆₀ ¹	Scap Me ₅₅ ¹	Scap Me ₆₆ ¹	Mg Hb ²	Act ²	Act ²	MgHb ²	MgHb ²	Act ²	MgHb ²	FspOligAn ₁₈ ³	FspAlbAn ₀₁ ³
Alt stage	stage II	stage I	stage I	stage II	stage II	stage I	stage I	stage II	stage II	stage I	stage II	stage II	stage III-IV
Timing	early	earliest	earliest	early	early	earliest	earliest	early	early	earliest	early	early	intermed
SiO ₂	56.04	53.94	53.08	57.62	50.71	55.16	55.53	49.24	52.56	50.95	47.90	64.00	66.55
TiO ₂	0.00	0.00	0.00	0.00	0.14	0.00	0.01	0.16	0.32	0.01	0.20	0.00	0.00
Al ₂ O ₃	23.25	24.25	24.93	23.21	3.95	0.94	0.54	6.12	3.54	3.08	5.81	23.37	19.94
FeO	0.00	0.00	0.00	0.00	11.51	11.92	10.43	10.28	8.16	15.89	12.90	0.00	0.00
Fe ₂ O ₃	0.22	0.13	0.04	0.43	2.26	1.30	0.00	4.29	3.00	3.82	4.55	0.48	1.18
Cr ₂ O ₃	0.00	0.00	0.00	0.00	0.08	0.06	0.03	0.08	0.04	0.01	0.04	0.00	0.00
MnO	0.00	0.00	0.01	0.01	0.08	0.13	0.05	0.19	0.06	0.26	0.10	0.00	0.00
MgO	0.01	0.00	0.00	0.01	14.67	16.00	17.22	14.02	16.96	11.48	12.47	0.00	0.00
CaO	6.54	8.84	10.18	6.25	12.56	12.65	12.97	12.34	12.64	12.26	12.45	3.70	0.26
Na ₂ O	9.18	8.38	7.59	9.32	0.47	0.17	0.08	0.59	0.43	0.25	0.63	9.58	11.52
K ₂ O	0.93	0.95	0.84	0.74	0.18	0.02	0.04	0.32	0.16	0.07	0.32	0.12	0.08
P ₂ O ₅	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F	0.00	0.00	0.00	0.00	0.05	0.03	0.01	0.08	0.06	0.13	0.12	0.00	0.00
Cl	4.01	2.74	2.50	3.60	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.01
V ₂ O ₃	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
NiO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
La ₂ O ₃	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.02	0.00	0.03	0.00	0.01	0.00
Ce ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ZnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SrO	0.09	0.06	0.06	0.09	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.04
BaO	0.00	0.00	0.00	0.00	0.02	0.00	0.03	0.00	0.08	0.01	0.04	0.01	0.00
SO ₃	0.38	0.01	0.17	0.07	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.00
H ₂ O	0.00	0.00	0.00	0.00	2.02	2.08	2.08	2.02	2.07	1.97	1.97	0.00	0.00
CO ₂	-0.09	0.17	0.20	-0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
subtotal	100.58	99.50	99.63	101.32	98.71	100.46	99.06	99.78	100.12	100.22	99.50	101.39	99.59
O=Cl.F	-0.90	-0.62	-0.57	-0.81	-0.02	-0.01	-0.01	-0.04	-0.03	-0.05	-0.05	0.00	0.00
Total	99.68	98.89	99.06	100.51	98.69	100.45	99.05	99.75	100.09	100.17	99.46	101.39	99.59

Table 2. Representative electron microprobe analyses of silicate vein fill minerals from Tigresa-Transito IOCG vein deposits (continuation)

¹ normalized to 12 cations; ² normalized to 13 cations; ³ normalized to 4 cations; ⁴ normalized to 14 oxygens; ⁵ normalized to 11 oxygens

Sample	TRS39-143.9	Tig195-056	CR01-117.3	TigC092-033.2	Tig201-157.2	TRS01-098.3	TigB091-025.4	TigB093-036.1	Pom8-179.3	TigC094-128.4	TigB093-036.1	TigC094-128.4	TigB005-026.6
Mineral	FspOlig An ₂₀ ³	FspAlb An ₀₁ ³	FspAlb An ₀₃ ³	K Fsp ³	Mg-Fe Chl ⁴	Mg-Fe Chl ⁴	Mg-Fe Chl ⁴	Mg-Fe Chl ⁴	Mg-Fe Chl ⁴	Mg-Fe Chl ⁴	Biotite ⁵	Biotite ⁵	Biotite ⁵
Alt stage	stage II	stage III-IV	stage III	stage II	stage III-IV	stage III-IV	stage III-IV	stage I-II	stage III-IV	stage V	stage II	stageII	stage V-VI
Timing	early	intermed	intermed	early	intermed	intermed	intermed	early	intermed	late	early	early	latest
SiO ₂	62.88	67.86	67.90	63.57	27.87	27.39	29.68	28.32	26.17	33.51	40.13	36.86	35.44
TiO ₂	0.00	0.00	0.00	0.00	0.03	0.02	0.02	0.04	0.02	0.12	1.27	0.46	0.51
Al ₂ O ₃	23.24	20.68	20.58	18.78	19.54	20.90	15.97	19.43	20.06	15.50	15.16	17.27	15.05
FeO	0.00	0.00	0.00	0.00	16.57	16.08	20.11	13.99	21.29	14.12	12.78	12.95	16.80
Fe ₂ O ₃	0.94	0.85	0.46	1.83	4.60	4.47	5.59	3.89	5.92	3.92	3.55	3.60	4.67
Cr ₂ O ₃	0.00	0.00	0.00	0.01	0.47	0.16	0.43	0.31	0.36	0.62	0.01	0.01	0.01
MnO	0.00	0.00	0.02	0.00	0.11	0.19	0.14	0.06	0.23	0.14	0.04	0.03	0.04
MgO	0.00	0.00	0.00	0.00	19.37	19.60	16.99	21.80	15.33	18.78	15.09	14.83	17.69
CaO	4.05	0.07	0.53	0.00	0.01	0.03	0.09	0.03	0.01	1.00	0.04	0.03	0.63
Na ₂ O	9.31	11.26	10.98	0.40	0.01	0.01	0.01	0.00	0.00	0.05	0.11	0.05	0.04
K ₂ O	0.14	0.07	0.06	15.91	0.03	0.04	0.10	0.05	0.00	0.47	8.91	9.41	0.98
P ₂ O ₅	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00
F	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl	0.00	0.00	0.00	0.03	0.02	0.01	0.01	0.01	0.01	0.15	0.14	0.22	0.42
V ₂ O ₃	0.00	0.01	0.00	0.01	0.02	0.01	0.02	0.01	0.01	0.02	0.07	0.08	0.03
NiO	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01
La ₂ O ₃	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Ce ₂ O ₃	0.01	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.00	0.01
ZnO	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.00	0.01	0.00	0.00	0.00	0.00
SrO	0.16	0.04	0.04	0.05	0.00	0.00	0.00	0.01	0.00	0.00	0.02	0.01	0.02
BaO	0.00	0.00	0.00	0.47	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.03	0.00
SO ₃	0.00	0.00	0.00	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00
H ₂ O	0.00	0.00	0.00	0.00	11.85	11.95	11.67	11.96	11.59	11.95	2.04	1.96	3.86
CO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
subtotal	100.75	100.85	100.57	101.07	100.57	100.88	100.89	99.91	101.03	100.41	99.42	97.82	96.20
O=Cl.F	0.00	0.00	0.00	-0.01	-0.01	0.00	0.00	0.00	0.00	-0.03	-0.03	-0.05	-0.09
Total	100.75	100.85	102.57	101.06	100.56	100.88	100.88	99.91	101.03	100.38	99.39	97.77	96.10

An important feature of all the titanite types is the presence of constant low amounts of F (up to 0.29%), that may be interpreted as an indicator of high temperature igneous related depositional processes, this time more close to an evolution felsic magma (Price et al., 1999). It is worth mentioning that both Tigresa and Transito ore deposits are magnetite dominated IOCG type, where magnetite is associated with mushketovite±titanite at deeper levels and specular hematite±martite in the upper part of the structures.

Early scapolite bearing assemblages are characterized by mixed Na-Ca marialite (Cl varies between 2.50-4.01%), corresponding to Me₅₅₋₅₈. The chemical composition of marialitic scapolite is quite constant in the iron oxide mineralization as well as in the wall rock alteration selvage. Minor amount of K₂O is recorded (0.74-0.93%), but also traces of Fe₂O₃ (up to 0.43%) and SrO (up to 0.09%), indicating the genetical link with potassic alteration and early iron oxide paragenesis. Even few generations of scapolite were delineated by petrographical studies both in Tigresa and Transito IOCG mineralization, the constant composition and trace elements halo supports the idea of all scapolites formed mostly on high temperature-iron oxides bearing early stages of the metallogenic processes.

The amphibole (actinolite-tremolite) alteration is widespread in Tigresa and Transito veins, affecting with different intensities over 50% of the wall rocks. Two main varieties of amphiboles were separated, based on electron microprobe chemical composition, as follows:

- (a) Mg-rich (tremolitic) actinolite in very early scapolite-magnetite bearing wall rocks alteration halo, featured by variable MgO (11.48-17.22%) and minor-trace amounts of MnO (up to 0.26%), Na₂O (up to 0.25%) and F (up to 0.13%).
- (b) Mg-rich tschermakite, commonly associated with early iron oxide mineralization; in contrast with actinolite, a more restricted MgO content is recorded (14.02-16.96%) and also specific trace amounts of K₂O (up to 0.32%) and BaO (up to 0.08%).

For those two types of amphibole the Mg/Mg+Fe ratio ranges between 0.36-0.60, mostly indicating an igneous-magmatic derived origin of the fluids (Deer et al., 1997) and a slightly tendency toward metamorphic or dynamo-metamorphic fluids in the particular case of Transito lode structure.

A complex framework is offered by the electron microprobe composition of feldspar alteration, mainly associated with copper sulfide mineralization stage both in Tigresa and Transito IOCG veins. The plagioclase chemical composition corresponds to a grading from earlier Na-rich oligoclase to later albite (An₀₁₋₂₀), with low but constant amounts of Fe₂O₃

(0.46-1.18%), suggesting that minor iron oxides are still forming in the main-intermediate copper phase. The typical traces halo of Na rich-albite metasomatism consists of K₂O (up to 0.14%) and SrO (up to 0.16%), indicating minor replacement of Na with K/Sr, even no any antiperthitic structures were observed in petrographical studies.

Secondary potassium feldspar exhibits, generally speaking, an early-after scapolite microprobe composition where minor-trace amounts of Fe₂O₃ (up to 1.83%), Na₂O (up to 0.40%) and BaO (up to 0.47%) are highlighted or intimately related to iron oxide bearing hydrothermal-acidic/aggressive solutions.

The chlorite group of minerals which normalize to clinocllore are Mg-rich oxidized chlorites, partly associated with the Na-rich metasomatism. The chemical electron microprobe composition is featured by variable SiO₂ (28.32-32.50%) and increasing of Cr₂O₃ (up to 0.62%) and K₂O (up to 0.47%) from earlier to later alteration stages. Such chemical behavior and evolution indicates, in the one hand, a larger space-time formation and distribution, and in the other hand, possible mixing of different types of fluids nearby the end of deposition processes. It is worth mentioning that chlorite-dominated associations, as well as actinolite assemblages are often occupying large zones of wall rock or vein fill, both in Tigresa and Transito IOCG structures.

Two varieties of secondary biotite were separated also in Tigresa vein system, based on microprobe chemical composition:

- (a) early biotite associated with magnetite-mushketovite, commonly showing a constant composition that corresponds to low titanium-sagenitic biotite (0.46-1.27% TiO₂) and normalize predominantly to hydrothermal phlogopite, lesser to igneous annite; trace amounts of Cl (up to 0.22%), Na₂O (up to 0.11%) and V₂O₃ (up to 0.08%) are recorded and support hydrothermal fluids, but also high temperature deposition.
- (b) late altered biotite associated with hematite, which corresponds to low potassium-vermiculite (0.98% K₂O); in contrast with the early biotite, this type contains additionally amounts of Ca (up to 0.63%) that is pointing out the introduction of meteoric-conate fluids into the system.

Even not submitted in the tables, the electron microprobe data of epidote from Tigresa and Transito deposits deserves at least few comments. Mainly associated with chlorites, the epidote group of minerals is represented by epidote-zoisite-clinzoisite and allanite (Ce₂O₃ up to 10.13% and La₂O₃ up to 4.25%). A large variation of minor-trace elements is recorded,

with strontian (up to 1.36% SrO), manganian (up to 1.01% MnO), chlorian (up to 3.02% Cl), potassian (up to 0.75% K₂O), titanian (up to 0.21% TiO₂), phosphatian (up to 0.36% P₂O₅) and vanadian (up to 0.13% V₂O₃) bearing epidote minerals. Once again, a larger space-time deposition and distribution of epidote minerals associated to chlorites is indicated, with/without related iron oxides-sulfides mineralization.

3. TIMING AND EVOLUTION OF ALTERATION-MINERALIZATION STAGES

Numerous stages of magmatic-hydrothermal alteration and mineralization are recognized in Tigresa and Transito IOCG vein to lode ore deposits based on petrographical - mineralogical relationships between metallic and gangue minerals. Also, complementary electron microprobe results to early data represent a very useful tool to characterization of the main paragenetic stages and metals bearing fluids. Alteration-mineralization stages were separated according to the mineral assemblages observed under the microscope and by electron microprobe chemical composition of the key minerals (Table 3), as follows.

3.1. Stage I- Earliest actinolite-scapolite alteration

Scapolite-Mg rich amphibole (actinolite to tschermakite) association is the most abundant, proximal to distal (regional) wall rock alteration of the IOCG veins. Accessory phases of this stage include commonly magnetite, titanite and quartz, but

also locally developed chlorite, albite, hematite±mushketovite or apatite. The field occurrence of the alteration is grey-greenish dark, especially due to the intergrown actinolite-chlorite and magnetite. The marialitic Na-rich scapolite composition is quite constant in different mineral associations, whereas hematite is found almost exclusively in breccias matrix or mylonitic-oxidized zones (e.g. Transito).

Actinolite range in size from 1mm (Tigresa) to 25mm (Transito, San Francisco sector) optically continuous crystals, while scapolite is mostly fine grained (less than 1mm) and mixed with titanite, magnetite. Generally speaking, there are no Fe-Cu sulfides related to this stage, excepts as overprints that sometime may create some misunderstanding of the earliest-no sulfide processes.

The magmatic-hydrothermal origin and high temperature deposition of the alteration minerals involved in this phase it is obvious and featured by electron microprobe composition. However, in the case study of Transito lode type system, another dynamo-metamorphic formed amphibole variety is presumable.

3.2. Stage II-Early potassic alteration and iron oxides mineralization

This phase contain most of the economical iron oxide ore, represented by dominant magnetite-mushketovite and rare hematite, associated with biotite, K-feldspar, titanite, actinolite, albite, scapolite, chlorite, minor pyrite-pyrrothite or even chalcopyrite. Also, minor amount of epidote and magnetite including micronic native gold complete the spectrum of iron oxides main event.

Table 3. Alteration/mineralization stages in Tigresa-Transito IOCG vein/lode type deposits

Mineral	Stage I	Stage II	Stage III	Stage IV	Stage V	Stage VI
Scapolite	—	—	—	—	—	—
Biotite	—	—	—	—	—	—
K-Feldspar	—	—	—	—	—	—
Titanite	—	—	—	—	—	—
Actinolite	—	—	—	—	—	—
Albite	—	—	—	—	—	—
Magnetite	—	—	—	—	—	—
Mushketovite	—	—	—	—	—	—
Hematite	—	—	—	—	—	—
Pyrite	—	—	—	—	—	—
Quartz	—	—	—	—	—	—
Chalcopyrite	—	—	—	—	—	—
Molibdenite*	—	—	—	—	—	—
Chlorite	—	—	—	—	—	—
Epidote	—	—	—	—	—	—
Calcite	—	—	—	—	—	—
Sericite	—	—	—	—	—	—
Gold	—	—	—	—	—	—
Bornite**	—	—	—	—	—	—

Legend: — abundant - - - common — local - - - rare;
Obs.*=recorded only in Transito **=recorded mostly in Transito

Secondary biotite is the main mineral of potassic alteration in the early stage, occurring mostly with magnetite or mushketovite and lesser with titanite, scapolite, quartz and pyrite. Biotite-scapolite association is locally encountered and contains also titanite, actinolite in magnetite-rich vein fill or proximal wall rock alteration.

Magnetite is present in massive or stockwork like- hydrothermal breccia zones of the veins as the dominant component of the mineralized system. Mushketovite occurred in the oxidized zones where early formed hematite was converted to magnetite. Both magnetite-actinolite and magnetite-biotite paragenesis are registered in early stage, with variable Ti-V composition that supports at least partly an igneous-magmatic origin of iron oxide fluids. However, recent fluid inclusion data (Kreiner & Barton, 2011) indicated hypersaline fluids and possible crustal rock assimilation that generated external-non magmatic fluids too.

Secondary potassium feldspar is also observed, both in Tigresa and Transito vein fill, associated with actinolite, chlorite, epidote and minor sulfides; in certain parts of the veins, orthoclase replace scapolite, somehow spatially pointing out latter copper sulfides. Incipient hydrothermal substitution of K with Na and Ba is recorded, even no clearly perthitic structure was found under the microscope.

Sometimes, minor amount of chalcopyrite, chlorite and molibdenite (only in Transito) have been encountered in biotite-magnetite paragenesis. In contrast with latter formed biotite, in the early phase is fine grained titanium bearing normalized phlogopite. Biotitic assemblages are nearly ubiquitous in breccias-brecciated vein zones, where may form sparse veinlets or selvages of iron oxides mineralization.

It is to be mentioned that the early iron oxide mineralization stage is not a sulfide free environment. Minor pyrite-pyrrothite associations are present in this stage and local chalcopyrite±cubanite are included in magnetite-mushketovite early paragenesis.

3.3. Stage III-Intermediate Na-rich metasomatism

Partly preceding the copper sulfides main stage, albite bearing alteration is the best indicator for the copper-rich zones of the structures, both in Tigresa and Transito IOCG systems. Earlier Na rich oligoclase passing to later albite is associated with chlorite and/or mushketovite and contains traces of K and Sr. The most common aspect of this

assemblage is albite replacing igneous feldspar sites and chlorite-epidote substituting mafic minerals, together with quartz, pyrite, chalcopyrite and local to rare developed epidote-calcite associations.

Oxidized Mg-Fe rich chlorites which normalize to clinocllore, with increasing traces of Cr and K, are found in this stage and the later one, but potassium may represent a biotitic overprint as well. The chemical composition of chlorite and epidote also suggests a larger space-time deposition, correlated with voluminous wall rock/pervasive alteration or vein fill. Sometime, an albite-chlorite± epidote-calcite alteration is superimposed on earlier actinolite bearing halo and may create the false impression that the amphibole is part of calcic assemblage.

3.4. Stage IV-Intermediate copper sulfide mineralization

Sulfide dominated mineral associations, either with pyrite or chalcopyrite, are discontinuous in Tigresa and Transito IOCG vein/lode systems. However, in this stage chalcopyrite becomes more abundant than pyrite. In the particular case of Transito-San Francisco sector, secondary bornite replaces or is intimately mixed with chalcopyrite and it seems to belong to this phase or even to later events. The gangue minerals of copper sulfide association are quartz, albite, chlorite and epidote. Magnetite or mushketovite-hematite is sparse to absent in this stage. An earlier shaped pentagonal pyrite is converted into cubic-euhedral pyrite, whereas chalcopyrite and bornite may contain micronics native gold.

Albite occurrence in some of the chalcopyrite bearing paragenesis suggests that the Na-rich alteration is still joining the main copper phase, i.e. is the key mineral/alteration. Also, allanite (REE>10%) may forms in this stage the core or rims of epidote associations, while chlorite become more and more enriched in potassium. The electron microprobe chemical evolution of the minerals involved here indicate that in the copper sulfide main stage is possible and presumable the beginning of fluid mixing processes, i.e. introduction of meteoric-connate fluids into the system.

An interesting approach is related to the quartz textures in copper sulfides rich paragenesis. Typical quartz of this phase is grey to milky and exhibits early crustiform to comb-layered textures, sometimes overgrown by later fibrous-radial zones. Similar feature is described in many W-Mo porphyry systems, where such quartz is pointing out the limit magmatic-hydrothermal and hypersaline-high temperature over pressured fluids separated

from magma during secondary boiling (Cline & Bodnar, 1994, Heithersay & Walshe, 1995, Lowerstern & Sinclair, 1996). The earlier molybdenite occurrence and sparse Mo grades recorded in Transito IOCG lode system argue and support a certain link with porphyry style processes.

3.5. Stage V-Late Ca-K (Fe) metasomatism

The calcite-specular hematite environment is associated with chlorite, biotite \pm epidote, sericite and variable amounts of pyrite, chalcopyrite \pm native gold in the upper part of the structures. It is well preserved in many sectors of Transito setting, but also in distal en-echelon veins-fractures of Tigresa system. Specular hematite occurs as blades and plated in cleavage planes, while calcite is rhombohedral and large crystallized, up to 5-6cm.

Trace amounts of potassium in chlorites correlate in this stage with biotite-hematite association. The late secondary biotite is low potassium vermiculite that contains also anomalous calcium. Typical transparent-bladed calcite found in Transito-Antonia zone is pointing out the boiling phenomena and meteoric component of the fluids, this time nearby epithermal temperatures and pressures.

Sericitic assemblages is characterized by the almost complete replacement of feldspars or mafic minerals with hydromicas associated with chlorite (green sericite), jasperoidal quartz/chalcedony, specular hematite and minor pyrite that may contain micronic native gold. Fracture controlled alteration nearby the main vein is more widespread in the upper part of the structures, where lower temperature-epithermal like horizon is still preserved.

3.6. Stage VI-Latest Au mineralization

This phase contains the most important part of economical IOCG type gold in Tigresa and Transito vein/lode systems, often encountered at shallow to moderate depth levels. Micronic gold has been observed under the microscope in pyrite-green sericite-clay minerals subsequent fractures which are cutting the main ore body in Tigresa or associated with specular hematite, jasperoidal quartz, biotite \pm calcite in Transito. In the first case an epithermal overprint is obvious, whereas in the second one, still preserved epithermal suite in the upper part of the structure that exhibits boiling phenomena it seems to be dominant.

The problem of an uncommon epithermal elevation for an intrusive-batholith related gold-copper mineralization remains controversial in

Tigresa-Transito IOCG systems. However, it is easier to be understood if we take into account both multiple cycles of fluids related to the evolution of magmatic system and also sequential shear zone mineralization components (e.g. Transito) that may create a more complex metallogenetical frame.

Also, the analogies between epithermal and whole IOCG style mineralization in Atacama region (Simmons et al., 2005, Barton, 2009) look for Tigresa and Transito ore deposits more restrictive, referring either to high salinity fluids or gold bearing boiled fluids formed only in the upper part of the above mentioned structures.

4. CONCLUSIONS AND REMARKS

Both ore controlling Atacama Fault System displacement, with Ojancos Viejo-Ojancos Nuevo branches, and Early Cretaceous cyclic magmatism are responsible for an extended duration of alteration and mineralization in Tigresa-Transito IOCG vein/lode systems.

The early stages 1-2 consists of actinolite-potassium rich magnetite mineralization and alteration formed mainly from deeper high temperature magmatic-hydrothermal fluids. The iron oxides phase is not sulfides free, i.e. contains minor amounts of pyrrhothite, pyrite and chalcopyrite. The whole mineral assemblage is genetically related to biotite \pm K feldspar alteration.

A Na-rich (albite) metasomatism is associated with intermediate stages 3-4 that are carrying the main copper sulfides mineralization. Chalcopyrite \pm bornite deposited this time may be derived from fluids mixing between magmatic-hydrothermal and external-crustal types, as a dominant mechanism developed at still higher (mesothermal) temperatures.

The late stages 5-6 involve Ca-K (Fe) bearing Au \pm Cu mineralization and alteration exhibited in the upper part of the structures, either as an epithermal overprint or still preserved epithermal suite. Carbonate-specular hematite \pm sericite, biotite \pm clay minerals indicate a more and more widespread introduction of meteoric fluid into the systems.

The up-dated electron microprobe and petrographical data are contouring this time a better expressed vertical to lateral zonation of Tigresa-Transito alteration, mineralization and metal of IOCG vein/lode assemblages.

Thus, the deeper and proximal levels are characterized by magnetite rich actinolite-scapolite and potassic alteration, passing upward to moderate depth through at copper sulfides bearing Na-rich (albite) alteration.

The shallower and distal levels are featured by gold-hematite-copper sulfides/oxides in a calcic to potassic alteration halo. The metal zonation from upper to deep levels is as following: Au, Cu (Fe) → Cu, Fe(Au) → Fe (Cu, Co), whereas a shear zone related mineralization event in Transito may produce a slightly increase of Cu downward. Also, U or REE (Ce, La) sometime strongly anomalous along Ojancos Viejo-Ojancos Nuevo tectonic alignments and also mentioned at deeper levels in many IOCG systems (Sillitoe, 2003, Groves et al., 2010) may be found at depths during forthcoming exploration programs in Tigresa-Transito deposits.

The upper part of Tigresa and Transito IOCG systems shows self-features of Au (Cu) epithermal ore deposits, whereas the deeper Cu-Fe levels are rather exhibiting similarities with Mo-W porphyry style mineralization. However, the whole characteristics of vein systems it should be seen as IOCG type related, instead of a mixed epithermal-porphyry styles.

Last but not least, the concept that non-magmatic fluids are inferred to be a prerequisite for economic-Cu rich IOCG deposits (Howkes et al., 2002, Oliver et al., 2004, Benavides et al., 2007) it seems to be not representative on a regional scale and therefore not the key of Cu enrichment in Chilean IOCG mineralization.

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