Hydrothermal Alteration and Mineralization Zoning in Iron-Oxide(-Cu-Au) Vein Deposits, near Copiapó, Chile

Douglas C. Kreiner and Mark D. Barton
Center for Mineral Resources, Department of Geosciences, University of Arizona, Tucson, Arizona 85721, U.S.A.

Abstract: Recent work in the Copiapó region of northern Chile provides insight into vertical and lateral zoning of vein-type Iron-oxide(-Cu-Au) (IOCG) deposits as a function of structural levels. Two vein systems hosted in La Brea diorite phase of the Copiapó batholith were investigated via drill core and surface mapping. Geologic field relations and alteration assemblages indicate that these vein systems represent two different structural levels. Vein systems at Transito are characterized by magnetite-chalcopyrite mineralization and high-T Na(-Ca) alteration which is consistent with deeper structural levels of the IOCG forming environment. In contrast, at Tigresa moderate to low-T alteration assemblages of chlorite-albite and mushketovite + chalcopyrite mineralization are consistent with higher structural levels. These data and other geologic evidence indicate that the Tigresa vein formed near the upper contact of the host La Brea diorite. Few IOCG systems have well documented vertical and lateral zoning. The contrasting, relatively simple vein systems at Transito and Tigresa demonstrate that the economic mineralization can persist over considerable (>500m) vertical intervals and overlaps with multiple styles of hydrothermal alteration. These relationships are broadly comparable to the patterns seen in some larger manto and breccia type IOCG systems where deducing time-space patterns can be far more difficult.

IOCG, alteration, mineralization, zoning, Chile.

1 Introduction

The origin of the iron-oxide Cu(-Au) (IOCG) family of deposits is controversial (cf. Barton and Johnson, 2000; Williams et al., 2005). An understanding of simple zoning in alteration and mineralization is lacking. Contrasting genetic models make fundamentally different – yet testable – predictions at multiple scales (Williams et al., 2005; Barton and Johnson, 2000). The main challenge for both academics and industry is to understand the reasons for the development of iron-rich but otherwise "barren" (nonetheless Cu-Au-anomalous) "Kiruna-type" deposits (which are numerous) as compared to well-mineralized Cu-Au rich deposits (which are rare). Both deposit types are present in the same region and commonly in the same district (Sillitoe, 2003; and Williams et al., 2005).

This paper summarizes recent documentation of alteration and mineralization zoning about IOCG vein systems based on new work in northern Chile and provides valuable insight into the district and deposit-scale zoning of alteration and mineralization. The excellent exposure in the Copiapó batholith allows for the comparison of several structural levels of vein systems, which exhibit contrasting styles of alteration and mineralization as a function of structural level.

2 Geologic Framework

The Mesozoic of northern Chile and southern Peru hosts one of the world's principal IOCG belts. The deposits are hosted both in supracrustal, mainly volcanic, rocks and intrusive rocks of the Coastal Batholith (Sillitoe, 2003). Although exhibiting structural control, the larger IOCG deposits vary from stratabound (manto-type) to discordant breccia bodies, mainly in supracrustal rocks. These texturally varied bodies typically exhibit complex superposition of events. In contrast, intrusive rocks generally have somewhat simpler, smaller, but locally economic vein deposits.

2.1 Copiapó Batholith and Framework Rocks

The Copiapó batholith is a composite batholith of Early Cretaceous (99-119 Ma [U-Pb]) age (Marschik and Sollner, 2006; M.D. Barton et al., unpubl. data). The plutons are broadly dioritic in composition, but range from pyroxene diorite to tonalite. The plutons intrude Jurassic volcanic and Cretaceous volcanic and marine sedimentary rocks, including evaporite-bearing layers (Marschik and Fontbote, 2001).

Each pluton in the Copiapó batholith has an associated and mappable alteration system resulting from its emplacement (Barton et al., 2007). Sodic(-calcic) alteration formed with all major intrusive units, whereas, high-T potassic alteration including local porphyry-style alteration formed only around the more felsic intrusions. The most prominent development of Na(-Ca) alteration and perhaps the most important IOCG mineralization is associated with La Brea diorite.

La Brea diorite is the largest volumetric intrusion in the district, and hosts the vein systems discussed in this paper. It is a coarse-grained pyroxene(±hornblende) diorite with accessory magnetite, ilmenite, zircon and apatite. The latest phase of this intrusion is an aplitic to porphyritic quartz diorite to granodiorite that forms shallowly dipping sill and dike-like bodies. All phases of the intrusion are altered and mineralized.

2.2 IOCG Deposits

The largest IOCG occurrences in the vicinity of Copiapó include the volcanic-hosted stratabound to discordant breccia bodies of La Candelaria and similar deposits of the Punta del Cobre district (Marschik and Fontbote, 2001). There are, however, several well defined IOCG vein districts located in and around Copiapó that provide geologically simpler systems suited for comparative study (Segerstrom, 1963). Among the latter, the two veins studied here are Tigresa, located in the Ojancos Viejo district, and Transito (on the San Francisco vein system), located in the Ojancos Nuevo district.

The Ojancos Nuevo district is hosted by both La Brea diorite and older supracrustal rocks that flank the batholith and host a broad contact metamorphic aureole. These rocks have intense, wide-spread sodic-calcic alteration, including large swaths of scapolite-rich assemblages. Within the batholith in this district, mineralization is vein-hosted and varies from magnetite-actinolite-chalcopyrite to mushketovite-chalcopyrite(-specularite). Structural patterns suggest that this area may represent relatively deep (~2-4 km paleodepth) levels of exposure.

Ojancos Viejo is hosted almost entirely by La Brea diorite but has a cap of supracrustal rocks exposed in the southern end at the structurally highest levels. A large north-striking fault of uncertain displacement cuts the western side of the district and juxtaposes contrasting styles of alteration and mineralization. The western block contains high-temperature scapolite-actinolite-epidote alteration whereas the eastern block (with most mineralization) contains actinolite-albite-chlorite(-epidote). In the southern end, intrusion-hosted scapolite-actinolite-epidote alteration abuts sericite-albite(-pyrite-hematite) alteration in the volcanic rocks.

3 Deposit-scale zoning

3.1 Transito

The Transito mine of Minera Carmen Bajo is along the San Antonio-San Francisco vein system. It has been mined over >500 m vertically and intermittently along >5 km strike length. The vein contains complex relationships and overprinting patterns, with dominantly sodic and calcic alteration minerals. The vein has a width of 2-4 meters and a zone of sheeted to mild stockwork magnetite + chalcopyrite mineralization extending 3-5 meters on either side of the vein structure.

Na(-Ca) alteration is distributed throughout the structure, with intense scapolite veining and breccias developed in the main structure. Included in this are unusual veins containing scapolite-mushketovite. Multiple generations of scapolite are present, including early scapolite + actinolite cut by later magnetite ± actinolite ± chalcopyrite. Younger scapolite ± biotite cuts and brecciates magnetite ± sulfide mineralization and earlier scapolite. Actinolite-albite alteration of the host La Brea diorite is widespread with intensity increasing towards the vein structure and is commonly found distal and above the scapolite-rich assemblages. Calcic(-Na) alteration is localized along the structure where epidote ± actinolite ± albite forms a 10 m wide envelope. Epidote tends to be late, and overgrows, or destroys earlier alteration and is in places texturally destructive and desilicates the host rock. Massive epidote alteration is cut by later actinolite±albite assemblages. Potassium silicate alteration is not widespread in this deposit. Biotite commonly occurs in the matrix with scapolite-rich breccias. Potassium feldspar is localized in the more felsic differentiate of La Brea and is also present replacing scapolite during retrograde reactions.

The system is extremely dynamic with numerous breccia bodies. The breccias contain magnetite-, scapolite- and quartz-dominated matrix. There is evidence that scapolite-rich and later magnetite-rich breccias are post-early mineralization and contain clasts of magnetite-actinolite-chalcopyrite vein material and are cut by subsequent magnetite-chalcopyrite, quartz-chalcopyrite, and late sulfide-bearing assemblages.

3.2 Tigresa

The Tigresa vein is one of several dozen veins in the Ojancos Viejo district, all of which have either NNE or NNW strikes. Like Transito, Tigresa contains complex overprinting and telescoped alteration patterns. The main structure ranges from 1-3 m in width surrounded by a 3-5 m zone of intense sheeted to stockwork veining. Mineralization is dominated by mushketovite+ chalcopyrite cross cut by later quartz±chalcopyrite.

Na(-Ca) alteration is abundant in varying intensities in the vicinity of Tigresa. Actinolite-albite alteration of La Brea diorite is common with numerous actinolite veins present. Ca-(Na) alteration is poorly developed at Tigresa, with only minor epidote present, typically as late texturally destructive replacement and veins. K-silicate alteration is well-developed and can be intense within a few meters of the structure. Potassium feldspar is found only within a few 10's of m of the deposit and is both present in veins and replacing primary plagioclase sites in the host diorite. Potassium feldspar is intermediate to late in age, and is seen cutting early mineralization, but is in some cases cut by younger mushketovite+actinolite ± chalcopyrite veins. Potassium feldspar±mushketovite and potassium feldspar± chalcopyrite veins are present, and typically one of the latest generations of veins. Biotite+chlorite is abundant as breccia matrix and veins. This assemblage is intermediate to late, and cuts nearly all mineralization. Calcic(-K) alteration is found on the margins of the vein and only appears to be developed at the middle to upper levels. Potassium feldspar+actinolite+epidote is the common assemblage of this alteration type. This assemblage occurs with minor sulfides present as veins and locally as vein halos on mushketovite-potassium feldspar veins. This assemblage is late, and only cut by the latest chlorite±sulfide veinlets. The zone of Ca(-K) alteration overlaps with the zone of K-silicate alteration, but clearly postdates the earlier potassic assemblages. The dominant alteration in the envelope on the Tigresa structure is intense chlorite±magnetite±sulfide replacing mafic sites, and chlorite+albite replacing feldspar sites in the diorite and is 20-30 m in width.

As was the case with the Transito vein, Tigresa is also a very dynamic system with multiple generations of breccias occurring. The two most abundant types of breccia are chlorite dominated matrix, which has at least one early to intermediate generation and magnetite-dominated matrix. The magnetite matrix breccia commonly is seen to cutting and being cut by the earlier generations of chlorite-matrix breccia. The breccias are only present within a few meters of the vein.

4 Discussion

Tigresa and Transito represent different structural levels of IOCG vein systems. This has been determined by systematically examining the alteration assemblages, geologic relationships, and structural settings of the deposits. The veins are located in different districts, and are not hypothesized to be vertically continuous, however they are both hosted in the same unit, and possess many similar features. Thus it is believed they represent two distinct structural levels of IOCG veins.

Regional Al-in-hornblende indicates that plutons of the Coastal Batholith were emplaced at < 10 km depth, with many likely emplaced within the upper few km of the crust (Dallmeyer et al., 1996; Barton, unpubl. data). The proximity (<500 m vertically) of Tigresa to supercrustal volcanic rocks infers a relatively shallow level of formation (< 2 km paleodepth). In addition, the presence of chlorite + albite after plagioclase, and chlorite after mafic minerals is favored at moderate to low temperatures (<200° C [cf. Seedorff et al., 2005]). Conversely, Transito is inferred to have formed at greater depth (2-4 km paleodepth), evidenced by the presence of scapolite + actinolite mineral assemblages requiring high temperatures for formation (>400° C [cf. Vanko and Bishop, 1982]).

Deeper structural levels of these deposits are characterized by high-T Na(-Ca) alteration assemblages (Fig. 1), including the presence of abundant scapolite-actinolite-epidote and quartz + epidote ± magnetite mineralization. This zones upwards into moderate-T Na(-Ca) alteration of actinolite-albite with magnetite + chalcopyrite ± mushketovite mineralization. Overlying this is a zone dominated by low-T alteration of chlorite + albite ± hematite and mineralization dominated by mushketovite + chalcopyrite + specularite. The highest levels of these systems may contain hydrolytic assemblages (Fig. 1) (quartz-sericite±pyrite and albite-pyrite±specularite), as are present in the upper levels of the Ojancos Viejo district and specularite + calcite mineralization. Potassic alteration is not well developed at deeper structural levels and becomes much more abundant at moderate to high structural levels (Fig. 1).

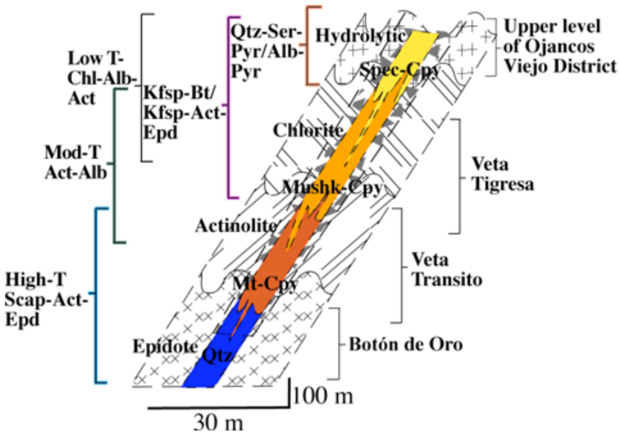

Figure 1. Schematic idealized sketch of vertical and lateral zoning of IOCG vein systems. Major features shown: alteration types on left, level of exposure in study on right, envelope (pattern), mineralization (solids) and breccia (triangles).

Lateral zoning has also been observed. Deep structural levels are marked by intense scapolite-actinolite alteration within a few meters to 10's of meters of the vein. At moderate to high structural levels, there tends to be a halo of several meters to 10's of meters of chlorite±magnetite±hematite alteration along the main structures. Potassic feldspar is abundant at these levels, elevated by a few percent to >10% above the concentration in the regionally altered rock. At both deep and shallow structural levels, Fe-oxide + chalcopyrite veining and the presence of magnetite-dominated breccias increase in intensity into sheeted or dense stockwork patterns within 10's of meters of the main vein structures.

It is postulated, as a result of this work, that one important component on the formation of "barren" and "well-mineralized" ore bodies may be a function of structural levels combined with geochemical controls. This hypothesis is supported by work in northern Chile and may be applicable to IOCG systems worldwide.

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