Vertical zoning and continuity in Fe oxide(-Cu-Au-Ag-Co-U-P-REE) (or 'IOCG') systems: Cordilleran insights

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Abstract. Recent studies of Cordilleran Fe oxide(-Cu-Au-Ag-Co-U-P-REE) (or 'IOCG') systems demonstrate that they formed in the upper 8 km of terrestrial crust. Fe±Cu mineralization extends from near at or the contemporary surface to depths of 1-4 km whereas related Na-Ca alteration (including metal leaching) spans paleodepths from 1 to 8 km. Many well exposed systems show systematic vertical zoning in Fe(-Cu) mineralogy from near-surface Hm-rich assemblages (including some syngenetic deposits) through Mt-dominated, sulfide-bearing zones (including Mt-rich, silicate-poor skarns in carbonate rocks) to sulfide-poor Mt-(Act/Cpx±Ap) mineralization (i.e., Kiruna or 'IOA' type), and ultimately with depth into Fe- and base metal-depleted intense Na-Ca alteration. This vertical zoning matches early syntheses of the IOCG clan, but differs from recent suggestions that IOA, Mt, and Hm styles necessarily represent distinct types of systems. Although there is considerable variation in the geochemically defined IOCG family, Cordilleran evidence demonstrates that these several styles typically form in regular, predictable patterns as part of zoned hydrothermal systems. Differences reflect depth, local host rocks, structural style, available S (for Cu precipitation), and composition of contemporaneous igneous rocks. These insights can apply directly to district- to regional-scale exploration.

1 Introduction

Many differences exist among deposit types within the Fe oxide(-Cu-Au-Ag-Co-U-P-REE) system (or 'IOCG' sensu lato) clan (e.g., Williams et al., 2005; Barton, 2013). We follow the original definitions: voluminous Ti-poor, hydrothermal Fe oxides with a characteristic and eponymous suite of geochemically anomalous (but not necessarily economic) minor elements. As so defined, does this clan represent a part of a broad continuum of closely related systems as early syntheses suggested (e.g., Hitzman et al., 1992; Barton and Johnson, 1996, 2000)? Or, do the deposits reflect geochemically similar but geologically distinct types of systems? Clearly some IOCG family types, such as those intimately associated with regional metamorphic features do indeed differ in fundamental ways; nevertheless, the majority of systems share many features (Barton, 2013). Should one separate deposit families simply because they can be grouped as hematite- or magnetite-dominated (both with or without economic Cu±Au; Skirrow, 2010; Williams, 2010)? Also, should one create a separate classification for Kiruna-type (aka 'IOA') deposits with Mt(Hm)(±Act/Cpx±Ap) or carbonate-hosted Mt(Hm) replacement/skarn deposits both of which lack economic Cu? These questions can be addressed by system-scale examination of well exposed IOCG family occurrences.

1.1 Models – geologically testable hypotheses

The integrated mineralization and alteration model for Fe oxide(-Cu-Au-U-P-REE) systems (Hitzman et al., 1992; Barton and Johnson, 1996, 2000) describes a pattern beginning with abundant, deep Na-(Ca) alteration which is also depleted in Fe and base metals. These metal-depleted zones grade upwards first into Mt-Act/Cpx (Kiruna-type) mineralization that is associated with varied and intense Na-Ca-(Fe-K) alteration, then into variably (some rich, some poor) sulfide-bearing Mt or Hm-rich mineralization associated with mixed K-(Ca-H) alteration, and ultimately into intense hydrolytic (H) alteration with Hm-dominated ore mineral assemblages. Sulphide abundances, including Cu-Fe sulfides commonly (but not universally) increase upwards from low contents in the Kiruna-type ores to higher values in Mt- and Hm-rich Cu ores. Variations on this theme include Mt(+Hm)-rich, silicate-poor "skarn" replacement in carbonate rocks and distal, low-T K-alteration in some coeval volcanic rocks. This model can be tested against observations in IOCG systems worldwide and against geochemical data and theory.

In this contribution we assess the above descriptive model through examination of districts where system-scale observations have been made in the Cordillera of South and North America (Table 1; see also Barton, 2009). We note evidence for formation in the upper few km of the crust and for systematic patterns across a range of geologic environments as well for Cu-rich vs. Cu-poor ores, and the possible use of this understanding for mineral exploration and for genetic interpretations.

2 Cordilleran IOCG Systems: Diversity and Vertical Zoning

Cordilleran IOCG systems show considerable diversity in form, mineralization, and geologic setting yet all exhibit the fundamental characteristics of voluminous low-Ti Fe oxides with anomalous quantities (compared to other elements) of Cu, Au, Co, U, P, and REE as well as a close association with voluminous Na-Ca-K-(Fe) hydrothermal alteration (Barton, 2009; Barton et al., 2011a; Chen, 2010; Sillitoe, 2003).

Table 1 summarizes key characteristics for a number of well exposed and well studied districts in the coastal cordillera of Chile and in the southwestern USA. Each of these districts exhibits considerable vertical exposure through a combination of structural and/or topographic relief and exploration and development.
2.1 Coastal Chile

In Chile, a complex tectonic history has juxtaposed different structural levels along and across the trend of the Middle Jurassic to Early Cretaceous arc. New regional- and district-scale alteration mapping coupled with hornblende barometry and stratigraphic reconstructions demonstrates that hydrothermal systems are concentrated in the upper half (depth range) of exposed crust which represents at least 10 km through upper part of the middle and late Mesozoic arc crust (Barton et al., 2012). These systems exhibit structural and stratigraphic controls, are intensely brecciated, and contain common coeval intermediate to felsic intrusions.

Most of the districts listed in Table 1 contain significant Cu(-Au-Fe) ore (ranging from 0.3 to 1.5 % Cu) with from >15 Mt (Ojancos Viejo) to >800 Mt (Candelaria). Mineralization occurs as Mt- to Hm-dominated breccias, veins and replacements. In the uppermost parts of these systems Hm-stable alteration consists of either intensely acid-altered tops (locally with S-poor advanced argillic assemblages, Productora, Ojancos Viejo, Jesus Maria; Kreiner, 2011) or, in some cases, syngenetic features including banded Hm-rich jaspilites (Punta del Cobre, Candelaria).

At deeper structural levels (1-5 km depth) nearly all districts have produced at least some Fe from Mt-rich ores either as a major co-product (Candelaria, Santo Domingo Sur) or smaller amounts from Mt-rich(+Act+Ap) ores. The latter ores (Kiruna type) are present in all districts where they formed relatively deep within parts of the same district-scale hydrothermal system (e.g., Cerro Negro, Productora, Jesus Maria, Mantoverde). Where carbonate rocks are present, Mt-rich, Gar-bearing replacement deposits (skarns) formed; these have varied Cu contents. The deepest portions (2-8 km) of each of these districts contain intensely Na-Ca altered, Fe-depleted igneous rocks (intrusive ≥ volcanic). Deep alteration consists of scapolite or oligoclase plus actinolite or diopside with minor titanite. The deeper (>2-5 km) Fe ores differ little from those seen in the classic Kiruna-type deposits of the same region (e.g., Romeral, Algorrobo, Cerro Iman, Los Colorados) and which occur at similar paleodepths.

<table>
<thead>
<tr>
<th>Table 1. Vertical zoning for selected igneous-related Cordilleran IOCG systems</th>
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<tr>
<td><strong>District</strong></td>
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<tr>
<td>Coastal Chile</td>
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<tr>
<td>Candelaria / Punta del Cobre, Chile</td>
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<tr>
<td>Cerro Negro, Chile</td>
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<tr>
<td>Jesus Maria, Chile</td>
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<tr>
<td>Mantoverde, Chile</td>
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<td>Productora, Chile</td>
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<tr>
<td>Ojancos Viejo, Chile</td>
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<tr>
<td>Santo Domingo Sur, Chile</td>
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<tr>
<td>Southwestern United States</td>
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<tr>
<td>Iron Springs, Utah</td>
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<tr>
<td>Cortez Mountains, Nevada</td>
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<td>Eagle-Palen Mountains, California</td>
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<td>Humboldt, Nevada</td>
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<td>Yerington, Nevada</td>
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</table>
2.2 Southwestern USA

In the southwestern USA, numerous Fe oxide-rich hydrothermal systems of Jurassic and Cenozoic age exhibit the features common to worldwide IOCG systems (Barton, 2009; Barton et al., 2011). As in Chile, many areas (Table 1) have good 3-dimensional exposures which resulted from combinations of structural complexity (notably tilted sections due to Cenozoic extension), topographic relief, and drilling.

A handful of districts have produced modest amounts of Cu(±Au), and several have major resources (e.g., >400 Mt, 0.6% Cu at Pumpkin Hollow, Nevada, Ohlin, 2010). Similarly, many districts (Table 1) have significant Kiruna-type and/or carbonate-hosted Fe resources associated with intense Na-Ca-K-Fe metasomatism. Also as in Chile, the patterns observed include deep (2-7 km depth), metal-depleted Na-Ca alteration grading upward (1-4 km) into Kiruna-type Mt-(Act-Ap) mineralization (present in all districts in igneous host rocks). Cu-Fe sulfide-bearing Mt-(Hm) breccias and replacement bodies (skarns in carbonates) occur in the upper few km (<1-3 km) with local syngeneic Fe-oxides at the surface (e.g., Humboldt, Iron Spring). Given these shared characteristics, which suggest a common process, it is noteworthy these systems formed across a broad range of tectonic settings (arc, back-arc, extension-related) and with diverse igneous compositions (mafic to felsic), thus implying distinct, independent mechanism for IOCG clan genesis.

2.3 Tops and bottoms: vertical extents, depths and implications

The vertical extent — from tops to bottoms — in the districts summarized in Table 1 ranges from 2-3 km to as much as 7-8 km. Such ranges resemble those for circulation of surface derived or basinal fluids, or the depth interval for vigorous release of magmatic fluids. There is no evidence for continuity to greater depths as implied by models calling on deep fluid sources.

Fe(±Cu) mineralization locally reached the surface and rarely extended deeper than 4 km as indicated by local syngeneic Fe deposits, barometry, stratigraphic (± structural) constraints, and evidence for phase separation (boiling) in fluid inclusions. In most districts, the Fe-rich interval was <3 km, with Mt-(Act±Ap) beneath Cu-rich intervals. The latter range from 0.5 to 1.5 km in vertical extent. Metal-depleted, Na-Ca altered bottoms formed within ~2 km to as much as 7 or 8 km below the surface. These features and their complex superposition plus other geochemical data indicate that cooling and mixing likely were important in metal precipitation in addition to the key role of wall rock reaction.

3 Comparison with other IOCG Regions

Many IOCG systems worldwide show similar patterns to those described here, including the evidence for deep to shallow Na-Ca to K(-Ca-Na) to H+ alteration, and the corresponding development of Hm- and/or Mt-dominated variably sulfide(±Cu)-bearing mineralization overlying (or overprinting) sulfide-poor Mt-(Act/Cpx-Ap) mineralization (see Barton, 2013; Williams et al., 2005 for reviews). For example in South Australia Cu(-Au-U-Ag) Hm-dominated mineralization overprints and or overlies Mt-dominated assemblages with accessory KF-Act-Ap-Bt (Skirrow, 2010). Similar patterns in alteration, ore mineral assemblages and general depth ranges can be inferred in the southern deposits of the Carajas district, Brazil (Xavier et al., 2010), and in the relatively Cu-poor domains of northern Sweden and SE Missouri (Hitzman et al., 1992). As is the case in South Australia exposures are limited, so vertical extents are difficult to establish, however geologic evidence and available drilling indicates significant zoning over intervals of <2 km. Alteration and, to an extent, metal ratios in these districts reflects the host rocks, with higher K/Na, ∑REE, F/Cl, and U in the more felsic systems (Barton and Johnson, 2000; Xavier et al., 2010).

4 Comparison with Fe(-Ti)-oxide-Apatite Systems

Kiruna-type (or ‘IOA’) mineralization is often compared with apatite-rich Fe-Ti oxide deposits. Cordilleran-type occurrences differ in fundamental ways: (1) hydrothermal alteration is intense and abundant, (2) as shown here, Mt-(Act/Cpx-Ap) ores form one part of clearly zoned systems with other ore and alteration types; (3) apatite contents are highly variable, typically 0.5-2% rarely exceeding 5 wt % over any appreciable volume (Barton and Johnson, unpubl. compil.), and (4) isotopic data demonstrate non-magmatic components (e.g., Sr and Os) in a number of Kiruna-type ores (Williams et al. 2010). In contrast, the Fe-Ti-oxide-apatite (nelsonite) deposits, lack appreciable hydrothermal features, have relatively little pyroxene ± amphibole but far more apatite (15-25 wt%, Kolker, 1982), and far better fit the experimental data on liquid immiscibility (Charlier and Grove, 2012). The Cordilleran evidence places Kiruna-type mineralization in a well-documented hydrothermal continuum with metal-depleted roots and varied tops, and not with a model which requires oxide-silicate melt immiscibility.

5. Concluding Remarks: Inferences from and Utility of Zoning Patterns

Understanding the IOCG clan remains a challenge, yet regular patterns emerge repeatedly when system-scale observations are made. In the relatively young and well exposed systems of the South and North American Cordillera, varied geologic settings yielded similar overall alteration and mineralization patterns like those described in early syntheses: vertical zoning goes from deep metal-leaching associated with intense Na-Ca alteration through a regular upward progression terminating in high-level hematite-rich and acid-altered assemblages. Such patterns are consistent with predicted reaction pathways for brine-rock interaction (Barton and Johnson, 2000). Likewise, differences are predictable: specific assemblages and accessory element contents should and do vary systematically with setting, notably...
with rock compositions or, for Cu in particular, the availability of reduced sulfur.

The regular patterns observed in the Cordilleran IOCG clan constrain possible genetic models and may aid exploration. The similarity in vertical zoning given different geologic environments (e.g., magmas, host rocks, tectonic setting) requires an origin independent of these features and one that operates in the upper 5-8 km of the terrestrial crust (as evidenced by well defined, metal-depleted bottoms at such levels). These geologic observations when combined with other geochemical and petrological data support a key role in many systems for non-magmatic brines proposed by Barton and Johnson (1996) and discussed by many since then. This is not to conclude that other IOCG environments, especially in metamorphic terrains may have different fluid sources (Williams et al., 2010; Barton, 2013). Understanding these patterns can be particularly useful in guiding mineral exploration in covered or structurally complex IOCG-bearing terrains.

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References


Barton MD (2013) Iron oxide(-Cu-Au-REE-P-Ag-U-Co) systems: Chapter 20, Treatise on Geochemistry 13, in press.


