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Footprints of Fe-oxide(-Cu-Au) systems

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Recognizing footprints of Fe-oxide(-Cu-Au) ("IOCG") mineralization depends on the perspective that the beholder has on the nature and origin of these deposits. This follows from the fact that no simple descriptive model can adequately capture the diversity of the systems that are included in this family (any more than for epithermal deposits or similar broad classes). Nor, is there any semblance of a consensus on the mode(s) of origin. Hence application of the footprint concept depends on working with a number of descriptive and genetic models. This discussion touches on features common to most descriptions of IOCG and related systems, a range of possible origins, and the implications of this range for recognizing such systems.

Characteristics of IOCG systems

Most investigators agree that IOCG-related hydrothermal systems share certain distinguishing features notably including (1) extensive alkali-rich alteration, (2) voluminous low-Ti magnetite and/or hematite, (3) a distinctive suite of minor elements (REE, Co, Ag, ± U, P), and (4) prominent structural control (*cf*. Hitzman et al. 1992). Coeval magmatism is a general, though perhaps not universal, adjunct. These features and their geophysical signatures provide the basic footprints. In contrast to the consensus aspects, various groups have argued that key characteristics could include associations with distinctive magmas (*e.g*., high-K granitoids, Pollard 2000; alkaline magmatism, Meyer 1988) or non-magmatic brines (*e.g*., evaporitic fluids or basinal brines; Barton and Johnson 1996, Haynes 2000) or distinctive tectonic environments (*e.g*., extensional or compressional settings; Hitzman 2000) or distinctive ages of formation (*e.g*., Mesoproterozoic; Meyer 1988). For this latter group of disputed characteristics, the footprint expected will reflect the animal that is being tracked (be it edible or not).

Unfortunately, no set of geologic features, apart from the abundance of Cu and Au themselves, readily distinguishes economic Cu(-Au) systems (Olympic Dam or Candelaria types) from large accumulations of magnetite or hematite that contain only anomalous amounts of these metals plus (Kiruna type or barren ironstones). It remains unsettled whether this contrast primarily reflects fundamental differences in the types system or primarily the lack of efficient traps / metal sources. Indeed, all regions that contain significant Cu(-Au) deposits also contain numerous "barren" Fe-oxide-rich occurrences, thus, regardless of its meaning, this empirical association provides the broadest signature for prospective regions.

Hydrothermal features: All regions with IOCG deposits show evidence for voluminous (commonly 10s to100s of km^2) alkali-rich alteration of both sodic-calcic – Na(Ca) and potassic – K, types (Hitzman et al. 1992; Barton and Johnson 1996). Because of their pronounced metasomatic changes, evidence of these styles of alteration can be readily recognized in high-grade metamorphic terrains where most other evidence is obscured or lost. Acid alteration (sericitic or chloritic) with accessory hydrothermal quartz is common, however it is more restricted in space and typically occurs in the vicinity of mineralization (*i.e.*, a few km in extent). Skarn assemblages form in carbonate and some mafic host rocks. The mineralogy, relative development, and geochemistry of alteration types correlate with igneous rock compositions (Barton and Johnson, 1996).

In most districts Na(Ca) alteration is widespread (commonly >100 km^2) and generally deeper and peripheral to iron-oxide-rich zones and variably developed Cu(-Au) mineralization. Na(Ca) alteration mobilizes, typically removing, base metals and ferrous metals (Dilles and Einaudi 1992, Williams 1994, Johnson 2000). K-metasomatism is of two broad types (Barton and Johnson 2000): The first contains biotite or K-feldspar commonly with calcic phases such amphibole or clinopyroxene. It is typically associated with introduction of magnetite/hematite ± Cu/Au, REE and other elements, and it forms in inferred upflow zones which are generally a few km or less in maximum dimension. A second type of K-silicate alteration that is recognized in some young systems is oxidized (Hm stable), K-feldspar-dominated (typically >8% K_2O), and laterally extensive (10s of km); this variety may represent recharge zones in certain continental and transitional marine settings (Barton and Johnson 2000). Extensive, stratiform K-rich leptites and biotite-rich rocks in some districts could be metamorphic equivalents of this latter type of K alteration.

Mineralization and time-space patterns: Economic mineralization is dominated by paragenetically late chalcopyrite ± bornite and occurs within or near (but typically not coextensive with) Fe-oxide accumulations. Distal and shallow mineralization is hematite-dominated, whereas magnetite forms deeper and earlier. Metals not precipitated in these S-poor, moderately oxidized environments could potentially form distal halos (*e.g.*, Zn-Pb, Mn, or Ag-Co-U). Individual mineralized centers rarely extend more than a few km across; yet mineralized regions can persist over regions 10s to 100s of km when defined by the intermittent distribution of magnetite- or hematite-rich rocks. Both local and regional mineralized zones correlate with major regional structural features (*e.g.*, in coastal Chile, NW Queensland, northern Sweden) and/or with volcano-plutonic structures (*e.g.*, in South Australia, northern Mexico, SE Missouri).

Few districts have been thoroughly studied thus details of temporal and spatial patterns of alteration, magmatism (where present), and mineralization remain poorly constrained. In better mapped regions such as NW Queensland, coastal Chile, or the southwestern United States it is clear that multiple IOCG-like alteration episodes occurred intermittently over tens of millions of years. Only a minority of occurrences have economically interesting Cu-Au mineralization and that is typically interpreted to be late in the regional development (*e.g.*, Hitzman 2000). For example, in NW Queensland, significant volumes of Na(Ca)-dominated rocks clearly represent multiple events; some of these are metaevaporites and predate younger, metasomatic varieties that accompanied multiple styles of Fe-oxide ± Cu(-Au) mineralization (Williams and Pollard 2001). In individual districts, histories can be complex and do not follow simple patterns. For example, in the Candelaria-Punta del Cobre district, Chile (Marschik and Fontbote 2001), district-scale mapping (≥200 km^2) demonstrates that IOCG-like hydrothermal systems independently developed with each of at least 5 separate major intrusive suites ranging in composition from granodiorite to gabbro over ~10 m.y., and that major Cu-Au mineralization formed relatively early in the progression (M. D. Barton and E. P. Jensen unpublished data).

Geophysical features: The abundance of iron-oxides, the irregular presence of sulfides, and the widely developed hydrothermal alteration has stimulated application of magnetic, gravimetric, electrical, and radiometric tools to these systems (Smith 2002). Especially when interpreted in combination with geologic constraints, gravity and magnetic signatures reflect the distribution Fe-oxide-rich bodies, as well as imaging district to regional-scale structural and igneous features (*e.g.*, Gow et al. 1993, Haynes 2000). The complex structure and diverse materials in many of these magnetically active terrains(*e.g.*, coastal Chile) complicates geophysical interpretation, which can be more straightforward in less deformed (anorogenic?) terrains such as the Stuart Shelf or SE Missouri. However, even in ideal cases geophysical interpretation can be complicated by the demonstrably varied and complex origins and fates of Fe oxides, Cu-Fe sulfides, and alteration minerals.

Nature of the beast(s): Possible origins & implications for footprints

All genetic models for IOCG systems require saline, sulfide-poor, relatively oxidized fluids to account for the abundant Fe-oxides and sparse sulfides, but they differ in the sources of these fluids, the paths that are followed, the sources of metals, and the possible traps. Many permutations are possible, however the possibilities can be reduced to two families: magmatic and non-magmatic fluid sources. These are summarized in Table 1 and illustrated in Figure 1. Alternative genetic models have been discussed in a number of recent papers, notably those assembled in Porter (2000) and cited in the bottom of Table 1.

The critical point is that the footprint expected for IOCG deposits will depend on the model or models followed. If a magmatic-hydrothermal hypothesis is preferred, then an association with certain types of magmas (*e.g.*, K-rich or alkaline) is inferred to be key, the key igneous rocks must be present, they should be found in particular tectonic settings (*e.g.*, continental arcs, back-arcs, or anorogenic settings), and there ought to be predictable and close patterns between particular intrusive centers and the distribution of hydrothermal alteration and mineralization. As an illustration of the last point, mass and energy balance and phase equilibrium considerations predict that high-temperature quartz veins should be relatively common, Fe-oxides subordinate, and Na(Ca) alteration relatively limited (Fig. 1, left; Barton and Johnson 2000). An external sulfur source will be required for metal trapping if the magmatic fluids are exceptionally S-poor.

Analogously, if non-magmatic brines are key then a somewhat different set of footprint features would be expected. For surface-derived or basin-derived fluids the warming path is an integral part of the system with attendant voluminous Na(Ca) alteration (Fig. 1, middle). Igneous bodies generally provide the heat and many of the solutes (thus "magmatic" signatures) but compositional and petrotectonic controls would be relatively unimportant, whereas larger-scale plumbing systems and paleogeographic controls that favor external brines would be critical (Barton and Johnson 1996, 2000). Considerably more variability would be anticipated than in magmatic systems and external traps likely would be key (*e.g.*, mixing with a second fluid in a favorable plumbing system). The metamorphic and orogenic collapse versions of this scenario (Fig.

1, right) have their own distinctive features, notably that neither requires a warming path and hence the relationship to Na(Ca) assemblages will be more one of original bulk composition than system hydrology. These systems may have greater lateral and vertical extent, but would be thermally expanded due to a lack of the large temperature gradients developed near magmatic centers. Except in deep and hence warmer settings, Fe metasomatism would be subdued.

IOCG deposits and the geological systems that form them present a continuing exploration and intellectual challenge. Although there is broad agreement on what generally constitutes this family of deposits, there is little consensus on the characteristics of the geological systems and the processes that form them. Alternative models make substantially different predictions about what should be related (Barton and Johnson 1996 p. 320) and hence have direct consequences for the system-scale footprints that one would expect and ultimately how those footprints might be utilized. In the absence of compelling evidence, use of multiple working hypotheses would seem to be wisest way to work in these complex systems.

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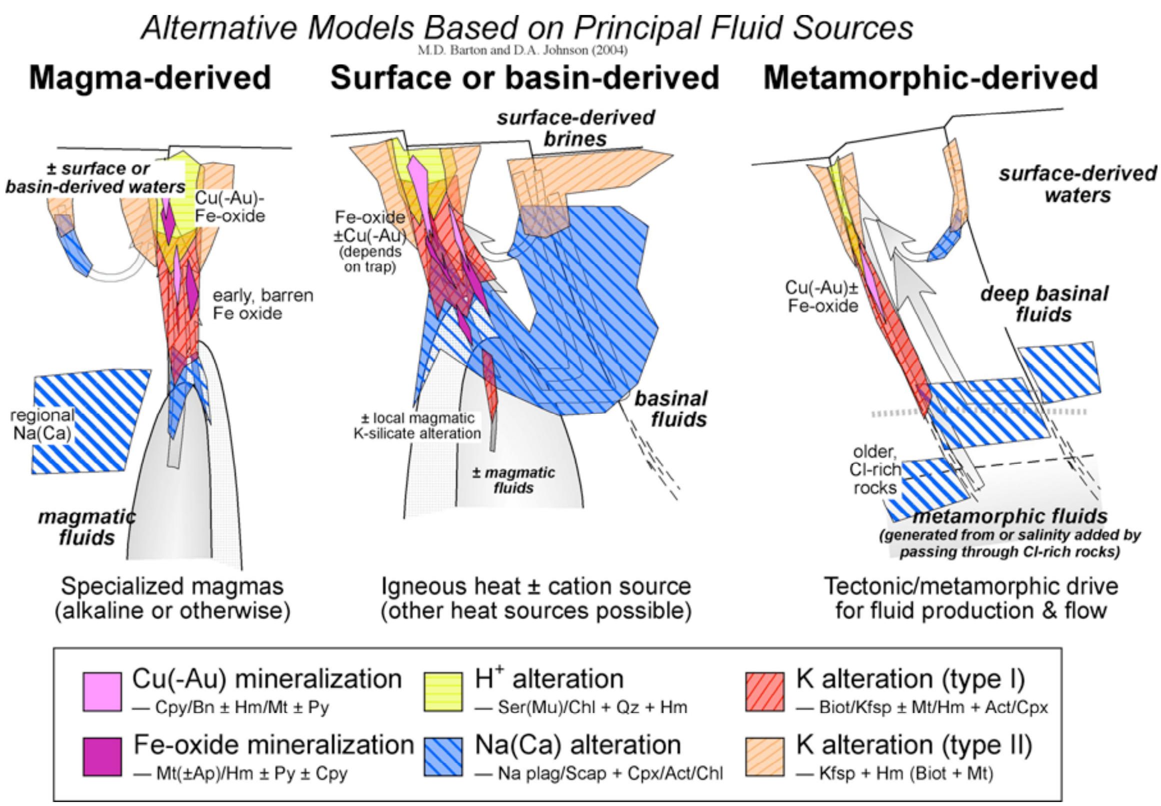

Figure 1. Schematic illustration of flow paths and hydrothermal features for alternative models for IOCG deposits. See Table 1 for synopsis of characteristics. Shading in arrows indicates predicted quartz precipitation (veining) for different paths in different quartz-saturated rocks which provides a useful first-order indication of path (*cf*. Barton et al. 1997, Barton and Johnson 2000).

Table 1. Synopsis of alternative genetic models for IOCG systems (*cf*. Figure 1).

Fluid Source	Magmatic	Non-magmatic	
		Basin / surface	Metamorphic
Fundamental processes	• Release of $S^{=}$-poor metal-bearing brine from magma; rise by buoyancy • Cooling, wall-rock reaction ± fluid mixing provide trap	• Thermal convection of non-magmatic brines; wall rock reaction provides metals • Cooling, wall-rock reaction or fluid mixing provide trap; second fluid may provide metals	• Metamorphic release of brine components by devolatilization or reaction with other aqueous fluids; rise by buoyancy • Cooling, wall-rock reaction ± fluid mixing provide trap
Igneous associations	• High-K, oxidized suites ranging in composition from diorites to granites • Carbonatite and strongly alkaline connections proposed by some	• Igneous rocks diverse (gabbro to granite); non-magmatic examples known • Key heat source in most • Material source, diversity reflected in geochemistry	• No necessary connection, though commonly present • Could be heat source in some settings • Can be material source
Hydrothermal alteration in feldspathic hosts	• Na(Ca) and other types (K, H^+) link to magmas • Regional Na(Ca) coincident but not directly related to Cu(-Au)	• K (type I), H^+ ± Na(Ca) in upwelling zones • Na(Ca) ± K (type II) in recharge zones	• Primarily K and H^+ alteration associated with deposits • Regional Na(Ca) association reflects sources
Relationship of Fe-oxides to Cu(-Au)	• Some Fe-oxides with Cu(-Au), may be deeper or higher-T equivalents • Barren Fe oxides may form from distinct fluids and commonly in older hydrothermal systems in same area	• Mt-rich are deeper, earlier, higher-T parts of ore-forming; Mt or Hm also typical with Cu • Barren Fe oxides represent lack of S trap for Cu or lack of second Cu-bearing fluid	• Fe-oxides present, but relatively minor (Bi or Chl common); Fe oxides commonly generated by breakdown of mafic minerals rather than Fe introduction
Local setting: depth / structure	• Shallow to mid crustal levels; commonly along regional structures but near causative intrusions	• In (mainly) brittle upper crust; plumbing provided by regional or volcano-tectonic structures	• Mid- to shallow crustal levels near or on major structures ; surface fluids require shallow levels
Global setting	• Arcs or extensional environments that produce characteristic magmas (oxidized high-K or alkaline)	• Regions with appropriate brine sources (arid settings or older Cl-rich materials), plumbing systems, and thermal drives	• Regions with Cl-rich low- to intermediate-grade source rocks; compressional setting (*e.g.*, basin-collapse) or prograde metamorphism
Key references	Hauck (1989), Pollard (2000), Groves and Vielreicher (2001)	Barton and Johnson (1996, 2000), Haynes et al. (1995), Haynes (2000)	Williams (1994), De Jong et al. (1998), Hitzman (2000)