

# Evaporitic-source model for igneous-related Fe oxide–(REE-Cu-Au-U) mineralization

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## ABSTRACT

**We propose that many igneous-related Fe oxide-rich (REE-Cu-Au-U-bearing) deposits form by hydrothermal processes involving evaporitic ligand sources, either coeval salars or older evaporites. These deposits are abundant in both Phanerozoic and Proterozoic extensional continental and continent-margin settings. They commonly form in global arid zones, but they also occur where magmatism is superimposed upon older evaporites. Magmatic compositions exert only second-order control, mainly on alteration mineralogy and on element abundances. Hot S-poor brines generated by interaction with evaporitic materials are consistent with geologic settings and help rationalize the distinctive element enrichments (siderophile, lithophile) and hydrothermal alteration (sodic, locally alkaline) found in these systems. This model contrasts with immiscible oxide melt and magmatic-hydrothermal origins commonly proposed for these deposits, although all three mechanisms can occur.**

## INTRODUCTION

Evaporitic environments are widespread in the geologic record, yet they have received scant attention as ligand sources for igneous-related mineralization, despite the importance of saline fluids in the transport of metals and the recognized importance of brines in many sediment-hosted mineral deposits (Kyle, 1991). Rather, the clear evidence for magma-derived brines in many igneous-related systems has dominated ideas about the genesis of porphyry, skarn, and related ore deposits.

In this paper, we propose that highly saline fluids of surficial or connate origin, derived from contemporaneous or older evaporitic material, are an important source for fluids in many igneous-related Fe oxide-rich mineral deposits (cf. Haynes et al., 1995). Such deposits number in the thousands and are distributed globally in Proterozoic and Phanerozoic rocks, yet they are enigmatic in character and origin. The presence of variable amounts of accessory rare earth elements, Cu, U, Au, Ag, and Co has made these rocks of considerable economic interest for commodities besides iron. This interest has stimulated study of them, particularly since the discovery of the enormous Cu-Au-U-rich hematitic breccias at Olympic Dam, Australia and the inferred association of world-class deposits of iron (Kiruna, Sweden) and rare earth elements (REEs; Bayan Obo, China) with this group (Pratt and Sims, 1990).

Both the characteristics and origins of iron oxide-rich systems are controversial. Fe oxide-rich deposits occur with many types of igneous rocks in a variety of settings (Barton et al., 1993). Previous genetic models have invoked immiscible melt, deuteric, and synsedimentary origins (reviewed by Hitzman et al., 1992; Hauck, 1990). The debate about origins is largely predicated on limited data sets and interpretation of local field and textural relations. We exclude some types, such as anorthosite-related Fe-Ti oxide deposits, where an immiscible melt origin fits geological and experimental data (Kolker, 1982).

## GEOLOGIC AND GEOCHEMICAL CHARACTERISTICS

Although origins are controversial, there is broad agreement that these deposits have abundant Fe oxides, a characteristic suite of accessory elements, at least some hydrothermal alteration, evidence for vigorous emplacement processes, and a genetic link to magmatism (Hitzman et al., 1992; Table 1<sup>1</sup>). These systems are typified by large masses of Ti-poor Fe oxide (commonly >10<sup>8</sup> tonnes magnetite or hematite) with lesser amounts of phosphates (apatite, REE phosphates), Cu-Fe sulfides, and sporadic Au, U, Ag, and Co minerals. Proximal and deeper mineralization consists of early magnetite ± apatite rocks commonly with abundant sodic (albite ± scapolite + hornblende) wall-rock alteration. Superimposed or distal mineralization consists of hematite ± Cu-Fe sulfides ± REE minerals with hydrolytic ± potassic alteration. Variants include districts with substantial sodic alteration and Cu or U mineralization but subordinate Fe oxide. Sodic alteration occurs in nearly all districts; it is typically voluminous, and a number of examples have local peralkalic assemblages containing NaFe<sup>+3</sup>-bearing amphibole or pyroxene. Calcareous host rocks contain calcic or magnesian skarn assemblages, with hydrous assemblages (actinolite-chlorite-carbonate) distal to and superimposed upon anhydrous assemblages (pyroxene-garnet). In form, these deposits may consist of strata-bound massive Fe oxide in volcanic and sedimentary rocks, although most commonly they form discordant, variably brecciated tabular to irregular masses. The former have been interpreted both as syngenetic and replacement bodies, whereas the latter have been interpreted as veins, dikes, and breccia fillings.

Igneous rocks are closely linked in time and space to many of these deposits, yet there is little correlation with igneous compositions or intrusive phases (Table 1). Crosscutting relations indicate that mineralization proceeded concurrently with magmatism. Associated igneous rocks range across alkalic granitoids and volcanic rocks, calc-alkalic mafic, intermediate, and felsic suites, continental flood basalts, and rift-related basalts. This lack of correlation with igneous compositions and the immense amount of hydrothermal alteration in some of the mafic systems indicates the importance of nonmagmatic controls. In contrast, in other igneous-related deposit types, such as skarn and porphyry deposits, metals and alteration correlate strongly with igneous compositions, and voluminous sodic alteration is rare (e.g., Einaudi et al., 1981).

Although similar overall, mafic and felsic systems differ in aspects of their wall-rock alteration and element enrichments. Mafic rocks have abundant early scapolitic and late chloritic and carbonate alteration. Felsic rocks typically contain abundant early albitic ± potassic and late silicic and sericitic alteration, but rarely have scapolitic alteration. Compared with mafic systems, felsic systems tend

<sup>1</sup>Data Repository item 9612, Table A, Additional Characteristics of Selected Fe Oxide–(REE-Cu-Au-U)–bearing Regions, a supplement to Table 1, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

Data Repository item 9612 contains additional material related to this article.

TABLE 1. SELECTED CHARACTERISTICS OF SOME FE-OXIDE(-REE-Cu-Au-U)-BEARING REGIONS

Region and District	Age and setting	Size* and metals, sodic alteration	Comments	References
Red Sea region (Afar, Atlantis II)	Holocene - rift basaltic volcanism, abundant evaps	>100? (>15?) FeOx + MnOx ± Zn-Cu-Pb sulfides sed; local peralk alt	Modern geothermal circulation through evaporitic beds	Zierenberg & Shanks (1983), Bonatti et al. (1972)
Chilean Andes (El Laco, Magnetita Pedernales)	Neogene - interm. volcanic centers in closed basins	>1000? (>500) FeOx in 2 districts; minor sodic ± peralk alt	Arid; volcanos adjacent to salars containing halite	Vivallo et al. (1994)
Mexican Altiplano (Cerro de Mercado, La Perta)	Mid-Tertiary - continental arc felsic volcanic centers	>300 (>100) FeOx ± REE, Cu in >20 locs; modest sodic ± peralk alt	Arid paleoclimate, sulfates in volcanic basins, Jurassic salt	Lyons (1988), J. Ruiz, 1994, personal commun.
Basin & Range, USA (Cortez Mtns., Humboldt complex)	Jurassic - back-arc mafic and felsic volcanic complexes	>1000 (>75) FeOx ± REE, Cu; >40 locs; ext sodic ± peralk alt	Arid paleoclimate, evaps in region; heavy S, saline fluids	Battles & Barton (1995), Barton et al. (1991)
Andean coastal belt, Peru & Chile (El Romeral, Raul, Candelaria, Monterosas)	Jurassic-Cretaceous - extensional arc interm-mafic volcano-plutonic centers	>3000 (350) FeOx ± major Cu(Au), minor Co, REE; >150 locs; ext sodic ± peralk(?) alt	Arid paleoclimate, Jurassic evaps; variable S, saline fluids, VMS in same arc	Vidal et al. (1990)
Mid-Atlantic, USA (Cornwall, Grace)	Triassic-Jurassic - mafic sills in rift basins	>350 (>100) FeOx ± Cu, Co (± U); >50 locs; skarn & sodic alt	Redbeds ± evaps; geochem. evidence for evap source	Rose et al. (1985)
Siberian Platform, Russia (Korshunovsk, Tagar)	Permo-Triassic - mafic intrusions with flood basalts	>3000 (>650) FeOx + minor Cu, Co in >150 locs; skarn and sodic alt	Basalts interact with Cambrian salt, saline fluids, heavy S	Smirnov (1977), Vakrushev et al. (1981), Zharkov (1984)
Turgai, Kazakhstan (Sarbai, Kachar)	Carboniferous - interm-mafic arc volcanic centers	>4000 (>1500) FeOx + minor Cu, Co; ext sodic alt & skarn	Arid paleoclimate, possible evaps	Smirnov (1977), Zharkov (1984)
Central Iran (Bafq, Gole Gohar, Hamadan)	Cambrian & younger -anorogenic felsic volcanic centers	>2500 (>1000) FeOx ± Cu, REE; >25 locs; sodic ± peralk alt	Extensive Cambrian & younger evaps; distal MnOx & Pb+Zn	Förster & Jafarzadeh (1994)
NW Canada (Great Bear, Wernecke Mtns.)	Proterozoic - interm arc volcano-plutonic centers	>50? (>10?) FeOx ± Cu, U, Ag, Co; >25 locs; regional sodic alt	No evaps reported; zoned from FeOx to distal Ag-Co-U	Hildebrand (1986), Hitzman et al. (1992)
South Australia (Acropolis, Olympic Dam, Emmie Bluff)	Mid-Proterozoic - anorogenic felsic-mafic(?) suite	>3000 (>2000) FeOx + major Cu, REE, U, Au; >5 deposits	High salinities, but no described Proterozoic evaps	Hanyes et al. (1995), Gow et al. (1994)
Northern Sweden (Kiruna, Gallivare, Ekstromberg)	Mid-Proterozoic - mafic-felsic volcanic suite, extensional(?)	>5000 (>2000) FeOx ± Cu, REE, Au, U; >20 locs; ext sodic ± peralk alt	Evidence for rifting with coeval evap source	Hitzman et al. (1992), Hauck (1990)
Northeastern USA (Benson mines, Mineville, Dover)	Mid-Proterozoic(?) - felsic-interm anorogenic suite	>1000 (200) FeOx + REE ± Cu, U; >30 locs; ext sodic ± peralk & skarn	Evaps present; some interpret FeOx to be related to Grenville	Foose & McClelland (1995)

\*In millions of tonnes; first number is total district resource, numbers in parentheses are tonnages for largest deposit within the district  
Abbreviations: alt=alteration, evaps= evaporites, ext=extensive, interm=intermediate, locs=locations, peralk=peralkaline, sed=sediments

to have higher REEs, U, Ba, F/Cl, hematite/magnetite, and hydrolytic/sodic alteration volumes (Table 1; Barton et al., 1993). Enrichments in Fe, REE, Cu, Au, and U are typically 10–100 times their abundances in probable source rocks, usually more for rare metals than for Fe or REEs. These variations are consistent with imposition of wall-rock control on otherwise similar fluids.

Ages and tectonic environments vary widely. Ages range from Early Proterozoic to Holocene (Table 1 and Fig. 1). Large deposits and districts are common in the Phanerozoic, in contrast to the suggestion that they reflect a distinctive Proterozoic geologic environment (Hitzman et al., 1992). Many tectonic environments are inferred—within and behind marine and terrestrial arcs, in failed continental rifts, in active rifts, and on stable platforms associated with hot-spot volcanism (Table 1). An anorogenic or rift-related origin is widely postulated based on the lack of extensive deformation in some of the best-known systems and the occasional association with alkalic igneous rocks (Hauck, 1990). Indeed, extensional settings of some variety are common in both Proterozoic and Phanerozoic districts, although in many cases they may be local closed basins (e.g., volcano-tectonic depressions, Table 1).

## EVIDENCE FOR AN EVAPORITIC COMPONENT

Rather than specific magmatic or tectonic correlations, a common thread is evidence for an evaporitic component. Evidence for an evaporitic component includes direct association with evaporitic materials, correlation with arid belts or evaporite-bearing basins, voluminous sodic alteration, and geochemical data that point to evaporitic rather than magmatic fluids (Table 1). In many Phanerozoic occurrences, older or broadly coeval evaporites can be demonstrated. Such evidence is less common in Proterozoic regions where evaporitic materials are only rarely observed or are inferred from distinctive metamorphic assemblages. In some regions, evaporitic sources persisted through time and contributed to multiple generations of iron oxide mineralization (e.g., Iran). Holocene generation of hydrothermal iron oxides from evaporitic sources is evident in several settings (Table 1). In the Andes, deposits have formed in volcanic centers that are emplaced adjacent to Cenozoic saline basins. Iron oxides are forming in the Red Sea region where

hypersaline hydrothermal systems result from basalts cutting Miocene and younger salt.

Further supporting an evaporitic connection is the striking correlation of Fe oxide-(REE-Cu-Au) deposits with areas having arid paleoclimates. For example, during the Mesozoic, nearly all occurrences are restricted to arid latitudes ( $25^{\circ} \pm 10^{\circ}$  N or S, Fig. 1). A notable exception is the Permo-Triassic province of the Siberian platform, which formed at  $>50^{\circ}$ N, but in an area where the Siberian traps were emplaced through  $>1$  km of Cambrian salt (Zharkov, 1984; Vakhrushev and Ryabkov, 1984). Analogous paleoclimatic relations hold for Paleozoic deposits in Laurentia and Gondwana. For example, the scapolite-rich multibillion-tonne iron provinces of the Turgai, Uralian, and Altai-Sayan regions are associated with red-bed ± evaporite-bearing mid-Paleozoic arcs that formed near  $30^{\circ}$ N (Table 1, Zonenshain et al., 1990; Zharkov, 1984).

Enormous volumes ( $>100$  km<sup>3</sup>) of intense sodic alteration are present in many of these districts (Table 1). This alteration requires far more saline fluid than can plausibly be generated from associated magmas. By comparison, corresponding volumes of intense alteration in other types of magmatic-hydrothermal systems are considerably smaller. For example, pervasive alkali exchange in porphyry Cu systems generally is  $<10$  km<sup>3</sup> except where external fluids are involved (Dilles et al., 1995). Only sea-floor hydrothermal systems, where the amount of fluid is not limited, have greater volumes of sodic alteration.

Finally, geochemical data are consistent with an evaporitic component. Fluid inclusions and the presence of marialitic scapolite indicate salinities of  $>20$  wt% NaCl (e.g., Vanko and Bishop, 1982). Available isotopic data commonly indicate nonmagmatic fluid components. In particular, sulfur isotope ratios indicate that isotopically heavy sulfur was important in the formation of sulfides in a number of deposits ( $\delta^{34}\text{S} > 5\%$ , Table 1). Early magnesian silicate + magnetite to late hematite ± pyrite ± chalcopyrite assemblages indicate oxidized, relatively sulfur-poor environments (Barton et al., 1993) as would be expected from an evaporitic fluid source (below). This external source of volatile constituents contrasts with magmatic sources indicated for transition metals and REEs from whole-rock and radiogenic isotope data (Barton et al., 1991; Johnson and Cross, 1991).

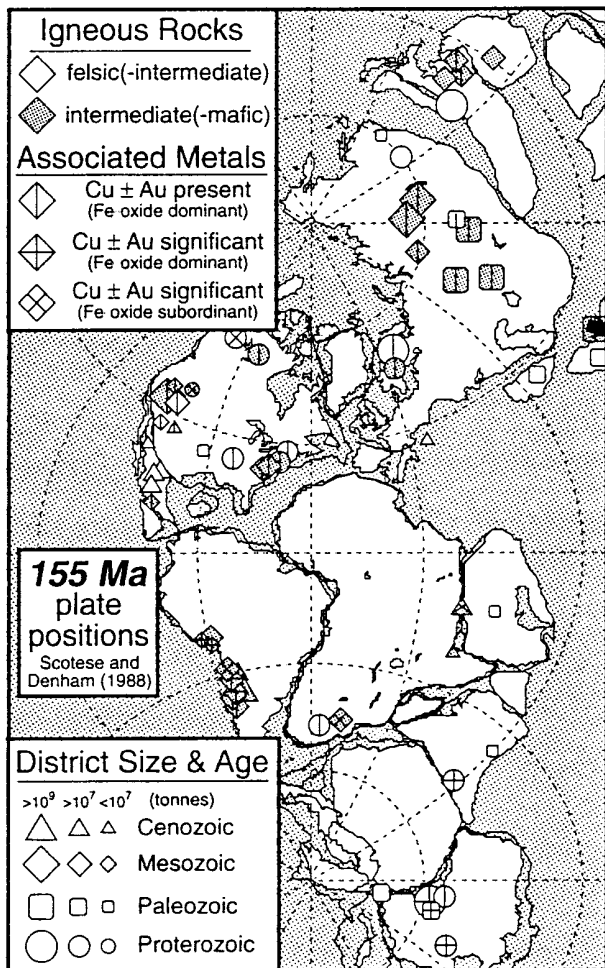


Figure 1. Distribution of some Fe oxide-(REE-Cu-Au-U) districts. See Table 1. Note correlation of most Mesozoic deposits with arid belts.

### EVAPORITIC-SOURCE MODEL

The evaporitic model invokes thermal circulation of highly saline fluids originating from coeval or older sources (Fig. 2). Magmatism provides the necessary heat to drive circulation and generate the required high temperatures. Igneous rocks also serve as the source and hosts for mineralization. Evaporitic sources provide the chloride necessary for metal transport and the Na observed in hydrothermal alteration, and they drive fluids toward oxidized, relatively S-poor compositions. NaCl-CaSO<sub>4</sub>-bearing sources will be saturated with halite and gypsum at near-surface temperatures (~30 wt% NaCl, ~0.5 wt% CaSO<sub>4</sub>; Hardie et al., 1982). Reaction of these fluids with igneous and sedimentary rocks along a circulation path would produce alteration and mineralization similar to observed patterns (Fig. 2). These patterns will resemble those created by other igneous-related hydrothermal systems, but they have some distinctive differences.

On the downwelling limb, sodic alteration follows from the high Na contents of low-temperature evaporitic fluids. Voluminous sodic alteration forms independently of other factors throughout the magmatic history; such alteration will substantially exceed the amount of potassic alteration that can form. Alteration volumes are limited by the amount of fluid that can be circulated (heat balance?), rather than by the S and Cl contents of causative intrusions, as is the case in many porphyry-type systems. If temperatures are high, scapolite + hornblende alteration will dominate, as it does in many intermediate and mafic magmatic systems; otherwise, albite + actinolite + chlorite assemblages will form, as in most felsic systems. Peralkalic

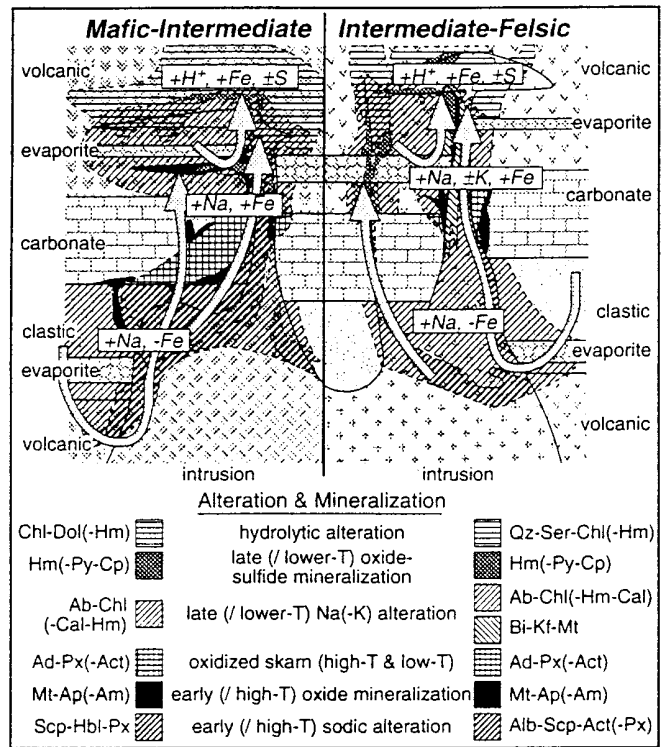


Figure 2. Schematic model of igneous-driven circulation of evaporitic fluids showing alteration zoning in mafic and felsic systems. Based on occurrences listed in Table 1.

assemblages are present in a number of Fe oxide occurrences (Table 1); they are hard to rationalize by ordinary igneous or magmatic-hydrothermal mechanisms, but the extremely high Na<sup>+</sup>/H<sup>+</sup> of an evaporitic source could drive reactions of the type 2NaCl<sub>aq</sub> + Fe<sub>2</sub>O<sub>3</sub> + 2SiO<sub>2</sub> + H<sub>2</sub>O = 2NaFeSi<sub>2</sub>O<sub>6</sub> + 2HCl<sub>aq</sub>. Coincident with sodic alteration, the fluid will gain components in which it is undersaturated (Fe, K, Ca, reduced S, REEs, SiO<sub>2</sub>), as is suggested by mass-balance data on Basin and Range occurrences (Barton et al., 1991; Dilles et al., 1995).

On the upwelling limb, cooling, wall-rock reaction, and mixing with other fluids create distinct products depending on rock type and path (Fig. 2). Sodic alteration persists where fluid-to-rock ratios are high. Hydrolytic alteration (producing K-mica + quartz in felsic rocks, chlorite in mafic rocks) forms in response to cooling and precipitation of metals from chloride complexes. In rocks with moderate K<sub>2</sub>O contents, potassic alteration (secondary biotite ± K-feldspar) can form by alkali exchange (Hitzman et al., 1992). The original sulfate-bearing fluids may be modified by partial reduction and incorporation of sulfides, but they generally have too little sulfur to precipitate sulfide minerals at higher temperatures. Early precipitation of magnetite-apatite is superseded by hematite ± copper-iron sulfides ± other REE minerals as H-O(-Cl-S) fluids become more oxidizing and sulfidizing with decreasing temperature (Barton et al., 1993).

Evaporitic brines have exceptionally high Cl/S; thus, metals greatly exceed the amount of sulfur needed to precipitate them (Fig. 3). Consequently, only the least soluble chalcophile elements (e.g., Cu) form sulfides along with the other elements that form oxides or oxysalts (Fe, REEs, U) or native elements (Au)—the suite seen in these systems. Because adequate S is lacking, Pb and Zn will be removed from the system, and Fe sulfides will be sparse. In some circumstances, reduction of these fluids might precipitate distal Ag-Co-As-U as is observed in some systems (Hildebrand, 1986). In contrast, other ore-forming fluids (e.g., magmatic or marine waters)

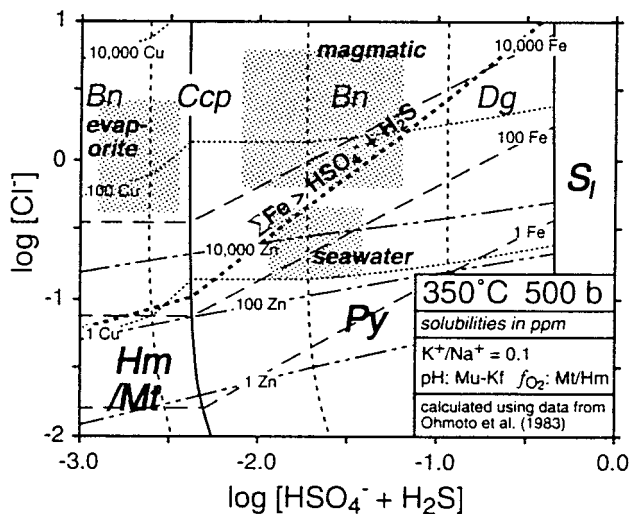


Figure 3. Distinction among deposit types by aqueous chlorine-sulfur contents. See text for discussion.

have lower Cl/S, leading to more abundant sulfide precipitation, lower oxide/sulfide ratios, and commonly significant distal Zn ± Pb sulfides (Fig. 3).

### SUMMARY AND CONCLUSIONS

The involvement of fluids with evaporitic components in magmatic environments rationalizes many features of a large group of enigmatic Fe oxide-rich mineral deposits. Incorporation of such fluids in intrusion-driven hydrothermal systems should produce distinctive metasomatism dominated by sodic alteration and oxide-rich ore mineral assemblages. Hot Cl-rich, S-poor fluids can mobilize many elements while precipitating few as sulfides. Such hydrothermal systems could form in many tectonic settings where magmas are emplaced with contemporaneous or older evaporitic sources; thus, they will primarily reflect paleoclimatic control. Igneous rocks will have only a second-order effect on mineralization, influencing relative enrichments and alteration minerals. These predictions are consistent with Fe oxide-dominated igneous-related hydrothermal systems. These systems share enrichment in REEs and commonly Cu, Au, and U. Voluminous sodic alteration, locally peralkalic, occurs in most areas along with other evidence for evaporitic fluids. They exhibit a paleogeographic control associated with evaporitic materials, be it in convergent, divergent, transform, or intraplate settings.

Alternative models are distinguishable from the evaporitic model. Skarn and porphyry systems associated with dioritic and alkalic intrusions have similar element enrichments (Fe-oxide, Cu-Au), but lack the huge volumes of intense alteration and exhibit no paleogeographic influence. Rather, they have a strong spatial and temporal correlation with intrusive centers of restricted composition. Likewise, apatite-bearing Fe-Ti oxide-rich bodies with accessory REEs clearly form in mafic, commonly alkalic magmatic systems, consistent with experiment (Kolker, 1982). They lack hydrothermal alteration and the lower-temperature mineral assemblages, whereas Ti-poor systems lack clear evidence of magmatic temperatures.

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