A Synopsis of Iron Oxide ± Cu ± Au ± P ± REE Deposits of the Candelaria-Kiruna-Olympic Dam Family

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INTRODUCTION

The Fe oxide-rich family summarized in this synopsis includes a wide spectrum of deposits whose only major common characteristic is the presence of abundant hematite and/or low Ti-bearing magnetite. These deposits exhibit highly varied styles of mineralization, alteration and chemistry, and they occur in geological settings that range from rifted continental crust to volcanic-arc environments. Consequently the validity of the family as a deposit classification is still controversial. It could be argued, for example, that the Australian Cu-U-Au-Ag Olympic Dam deposit is so unique that it has little in common with the sulphide-poor, magnetite-only deposits such as El Romeral in Chile. Conversely, like the well-known skarn family which also includes a spectrum of equally diverse deposits, the Fe oxide family may prove to be a valid grouping, as advocated by Hitzman *et al* (1992), Williams (1999) and other workers. It is hoped that this synopsis will, among other things, stimulate debate on this question.

SYNONYMS

Synonyms for this class of mineral deposits include: Olympic Dam, Kiruna, Ernest Henry or Candelaria types; iron oxide breccias and veins; apatite iron ore; volcanic-hosted magnetite; iron oxide-rich deposits; Proterozoic iron oxide (Cu-U-Au-REE) deposits.

COMMODITIES

The important economic commodities in these deposits are Fe, Cu, Au, Ag, U and P. There is also a potential for byproduct REE's, Ba, Mo and Co.

EXAMPLES

Olympic Dam (Gawler district, South Australia); Ernest Henry, Osborne (Cloncurry district, Australia); Kiirunavaara (Kiruna district, Sweden); Candelaria, Punta del Cobre, El Algarrobo, Boqueron Chanar, Manto Verde and El Romeral (Chilean Iron Belt); Monterrosas, Eliana, Raul, Condestable, Marcona (Peru); Cerro de Mercado (Durango district, Mexico); Pea Ridge, Pilot Knob and Boss-Bixby (Missouri, USA); Sue-Dianne and Great Bear (Northwest Territories, Canada); Wernecke Breccias (Yukon, Canada); Iron Range (082FSE014 - 028, British Columbia); Vergenoeg (South Africa); Mangula (Zimbabwe); Shimyoka, Kantonga, and Kitumba prospects (Mumbwa district, Zambia); Bafq (Iran).

Other possible examples include the Heff prospect (092INE - 096, British Columbia), Salobo and Igarape Bahia (Carajas district, Brazil), and the Bulagidun prospect (North Sulawesi, Indonesia).

CAPSULE DESCRIPTION

Hydrothermal hematite and/or low-Ti magnetite-rich mineralization which may be hosted by sedimentary, igneous or metamorphic rocks. These deposits exhibit a wide range of morphologies, including multiphase breccia pipes and sheets, veins, stockworks, diatremes and both concordant and crosscutting tabular bodies. Mineralization varies from sulphide-poor magnetite±apatite ore bodies (*e.g.* Kiirunavaara, El Algarrobo, El Romeral) to more sulphide-rich hematite±magnetite deposits±Cu±Au±Co±U±REE's (*e.g.* Olympic Dam, Ernest Henry and Candelaria).

TECTONIC SETTING

Proterozoic deposits are found in rifted cratonic settings whereas many Phanerozoic examples lie close to major linear structures in an Andean, continental margin, volcanic arc setting.

DEPOSITIONAL ENVIRONMENT/ GEOLOGICAL SETTING

The depth-range in which these deposits form is uncertain. Some deposits (*e.g.* Salobo) may have developed in a very shallow, possible exhalite environment; others (*e.g.* Olympic Dam; Cerro de Mercado) formed at near surface levels <1 km), whilst depths down to 6 km are speculated for some magnetite-albite dominated systems (Oreskes and Hitzman, 1993). Deposits are commonly associated with long-lived brittle-ductile fractures, nar-

row grabens or rifts that may, in part, be coeval with host-rock deposition.

AGE OF MINERALIZATION

Proterozoic to Tertiary. Many of the better known deposits are mid-Proterozoic (1.2 to 1.9 Ga). However, the Chilean and Peruvian Iron Belt examples are of Cretaceous age.

HOST/ASSOCIATED ROCK TYPES

The Fe oxide mineralization crosscuts, or is conformable with, a wide variety of sedimentary, igneous and metamorphic rocks, including mafic flows, felsic volcanic breccias, tuffs, clastic sedimentary rocks, granites, gabbros, diorites, granodiorites and syenites. Prograde garnet-pyroxene±scapolite skarn mineral assemblages may develop where the fluids are Ca-rich and high temperature, or where reactive calcareous host-rocks are present. Some deposits are associated with very coarse grained actinolite-apatite veins and breccias (crystals >3 cm long), and large volumes of sediment-hosted hematite-rich "ironstone" or iron oxide-bearing volcanic rocks.

DEPOSIT FORM

Highly variable. Sub-horizontal to steeply inclined, discordant to concordant pod-like zones, dike-like veins, lenses, tabular bodies, pipes and stockworks. The iron-rich veins and tabular zones may reach hundreds of metres in width and have a strike length of many kilometres.

TEXTURE/STRUCTURE

The Cu-Au mineralization may be hosted in the Fe oxide matrix as disseminations, micro-veinlets and as rare mineralized clasts. Textures indicating replacement and microcavity filling are common (*e.g.* tuff lapilli may be selectively replaced by iron oxides). Intergrowths between minerals are noted. Hematite and magnetite may display well developed crystals, interlocking mosaics, and tabular or bladed textures. Hematite varies from specular to massive to botryoidal (kidney ore). Some deposits are characterized by matrix-supported hydrothermal, polymictic and multiphase breccias. Breccia textures are highly variable; they may grade from core zones containing 100% Fe to weakly fractured and Fe-veined host-rock on the margins. Breccias may be difficult to recognize in hand sample as the same apparent Fe oxide phase may comprise both the fragments and matrix. Many breccias contain clasts of magnetite, hematite, fresh to altered country rock, quartz, calcite and older breccia material supported in a matrix of younger iron oxides and /or calcite. If Ca-rich host-rocks are present, fragments of garnet-pyroxene±scapolite skarn over-grown by iron oxides may be seen. Breccia fragments are generally angular to sub-angular although rounded and mechanically milled clasts are not uncommon. They range up to >10 m in diameter, but tend to be <15 cm wide. Contacts with the unbrecciated host-rocks are frequently gradational over scale of centimetres to metres. Hematite breccias often display a diffuse wavy layered texture of red and black hematite, and some microbreccias have thin, hair-like veins of hematite. Replacement (pseudomorphing) of early magnetite by hematite (martite) may be a common feature.

ORE MINERALOGY

These vary from low sulphide-bearing magnetite-apatite deposits with actinolite±pyroxene (*e.g.* Kiirunavaara, El Romeral) to more sulphide-rich, polymetallic hematite-magnetite deposits (e.g. Olympic Dam, Candelaria). The principal ore minerals are hematite (includes specularite, botryoidal hematite and martite), low-Ti magnetite, bornite, chalcopyrite, chalcocite and pyrite. Subordinate minerals include digenite, molybdenite, covellite, native copper, carrolite, cobaltite, Cu-Ni-Co arsenates, pyrrhotite, pitchblende, uraninite, coffinite, autunite, brannerite, bastnaesite, monazite-xenotime, florencite, native silver and gold and silver tellurides. At Olympic Dam, the native gold, uraninite, coffinite, bastnaesite and florencite are very fine grained; gold is disseminated either in the breccia matrix or as inclusions in the sulphides whereas bastnaesite and florencite occur in the matrix as grains, crystals and crystal aggregates.

GANGUE MINERALOGY

Gangue is intergrown with ore minerals as veins, as clasts in breccias or as disseminations. Principal gangue minerals include albite, K-feldspar, sericite, carbonate, chlorite, quartz, amphibole, pyroxene, massive silica, biotite and apatite. Lesser amounts of fluorapatite, fluorite, barite, epidote, rutile, titanite, monazite, ilvaite, tourmaline and allanite may also occur. The amphiboles include hastingsite and tschermakitic varieties as well as Cl-rich hornblende. Hematite breccias are frequently cut by veins, up to 10 cm wide, containing fluorite, barite, siderite, hematite and sulphides.

ALTERATION MINERALOGY AND ZONING

Hitzman *et al*. (1992) note that at greater depths, alteration in these systems comprises large (>1 kilometre wide) zones of Na-Fe metasomatism (early albite-actinolite-magnetite, apatite and late epidote); if Ca-rich host-rocks are present, Fe-rich garnet-clinopyroxene ±scapolite skarn assemblages may form (*e.g.* Heff prospect, British Columbia; Candelaria, Chile; Kiruna, Sweden; Shimyoka and Kantonga prospects, Zambia).

Overlying the Na-Fe alteration, at intermediate depths, are extensive haloes of K-Fe-rich alteration (K-feldspar, secondary biotite, sericite, magnetite, actinolite, chlorite); intense chloritization may result in almost total destruction of the hydrothermal biotite. The upper parts of the hydrothermal systems tend to be marked by lower temperature Si-Fe-K assemblages (massive silica-quartz-sericite-specular hematite-chlorite).

Olympic Dam has intense sericite and hematite alteration with increasing hematite towards the centre of the breccia bodies at higher levels. Close to the deposit, the sericitized feldspars are rimmed by hematite and cut by hematite veinlets. Adjacent to hematite breccias the feldspar, rock flour and sericite are totally replaced by hematite. Chlorite or K-feldspar alteration predominates at depth. Quartz, fluorite, barite, carbonate, rutile, orthoclase and epidote are also present.

The Kiruna orebodies contain scapolite and albite with actinolite-epidote alteration in the mafic wallrocks; up to 20 wt % apatite is also reported. Some Chilean and Peruvian Phanerozoic examples contain tourmaline (*e.g.* Manto Verde, Monterrosas) and this mineral also occurs at Kiirunavaara and Olympic Dam.

WEATHERING

In certain weathering environments, pervasive kaolin-clay alteration may develop as well as some supergene alunite veins. In arid environments, a blanket containing secondary Cu, Cu-Mn and U phosphates, oxides, sulfates and chlorides may be present (*e.g.* turquoise, torbernite, brochantite, antlerite, atacamite). Supergene enrichment of Cu and U is possible; examples include the pitchblende veins in the Great Bear Magmatic Zone.

ORE CONTROLS

There are strong structural ore controls in most deposits although in some (*e.g.* Candelaria) stratigraphy also plays an important role. Deposits are hosted by rocks adjacent to brittle-ductile fractures or narrow grabens that have undergone repeated transcurrent and extensional movement. They may cluster along linear arrays more than 100 km long and >10 km wide and be spaced 10-30 km along the trend. Many older deposits (*e.g.* Kiirunavaara, Olympic Dam, Ernest Henry) are hosted by mid-Proterozoic continental crustal rocks and past exploration has focused largely on fractures that cut these packages. However, recognition of younger deposits (*e.g.* Bafq, Chilean and Peruvian Iron Belts) demonstrates that fault zones in Phanerozoic volcanic arcs are also important exploration targets.

GENESIS

Recent work (*e.g.* Oreskes and Einaudi, 1990; Hitzman *et al*., 1992; Oreskes and Hitzman, 1993;

Borrok *et al*., 1998; Gow *et al*., 1994) suggests that these deposits are hydrothermal in origin. However, there is disagreement about this interpretation and whether or not these diverse orebodies should be grouped as a single deposit type. Barton and Johnson (1996) suggest that evaporites provided a source for chlorides and the sodium alteration in some deposits; this involves a process of non-magmatic fluids circulating through evaporites, and being drawn into an intrusion-centered hydrothermal system. A magmatic-volcanic (syngenetic) versus epigenetic origin of the Kiruna (Sweden) and El Laco (Chile) magnetite mineralization is still hotly debated (*e.g.* Parak, 1975; Nystrom and Henriquez, 1994). In some cases the mineralization appears to be younger than, and unrelated to the hosting igneous rocks (*e.g.* Ernest Henry, Candelaria), but recent studies at Olympic Dam (Johnson and Cross, 1995; Campbell *et al*., 1998) suggest that the hosting granite is only slightly older (*circa* 8 Ma) than the mineralization. Sm-Nd data from Olympic Dam (Johnson and McCulloch, 1995) indicate a mantle-derived origin for the mineralization. However, many examples lack an identifiable plutonic source; hence the origin of the hydrothermal fluids and composition of the assumed parent magmas are unknown.

ASSOCIATED DEPOSIT TYPES

On a wide district scale, these Fe oxide± Cu±Au±REE deposits may be associated with volcanic-hosted U orebodies, alkaline and calc-alkaline porphyry Cu-Au deposits, supergene U and/or Cu blankets or veins, and hematite-rich massive iron-stones. Some sedex-type Pb-Zn-Ag deposits are found in the same geological setting as Fe oxide deposits, although there is no proven genetic relationship. Examples of this broad regional association include Broken Hill and Olympic Dam, Mount Isa and Ernest Henry (Australia), Kabwe and the Shimyoka, Kantonga, and Kitumba prospects (Zambia), and Sullivan and the Iron Range prospect (British Columbia). In the latter case, however, the age of the Iron Range prospect relative to the Sullivan deposit is unknown.

COMMENTS

Hitzman *et al*. (1992) note that the magnetite in these deposits is generally low in Ti (<0.5% TiO_2), in contrast to the magnetite associated with anorthosites, gabbros and layered mafic intrusions. Some carbonate-hosted Fe oxide-Cu-Au±REE deposits with a skarn gangue resemble calcic island-arc Fe skarns; both deposit types contain low-Ti magnetite, Fe-rich and Mn-poor garnets and hedenbergitic clinopyroxenes, and sporadic Cu, Au and Co geochemical anomalies. Also, both types tend to have early albitic alteration, sporadic younger K-feldspar development and similar textures (hydrothermally brecciated magnetite and magnetite veins and dikes). Unlike Fe oxide-Cu-Au deposits, however, island-arc Fe skarns are strongly controlled by pluton margins, they

contain relatively little hematite and lack anomalous REE's and U.

GEOCHEMICAL SIGNATURE

Anomalously high values for Fe, Cu, U, Au, Ag, Co, REE's (Ce, La, Nd, Pr, Sm, Gd)±P±F±B±Mo±Y±As ±Bi ±Te±Mn ±Se and ±Ba in associated rocks and in stream sediments. The light REE's tend to be concentrated in minerals such as allanite, epidote, bastnaesite, florencite, monazite, xenotime or apatite.

GEOPHYSICAL SIGNATURE

Large positive gravity anomalies related to the Fe oxides. Regional aeromagnetic anomalies related to magnetite and/or coeval igneous rocks. Radiometric anomalies (detectable by ground and airborne gamma-ray spectrometer surveys) occur with polymetallic deposits containing U mineralization or K alteration. IP was a useful tool in exploring the Candelaria deposit (Ryan *et al.*, 1995).

OTHER EXPLORATION GUIDES

Promising areas are those with narrow rift structures and deep-seated brittle-ductile fault zones. Favorable features along such structures include the presence of: (1) extensional or trans-tensional movement, (2) zones of albite, K-feldspar, sericite, chlorite, apatite, epidote, tourmaline, fluorite, actinolite, garnet±pyroxene±scapolite skarn or silica-rich alteration, (3) Fe oxides, particularly in breccias, stockworks and veins, (4) sodic or potassically-altered intrusions, (5) U oxides and/or REE-enriched alteration, and (6) secondary Cu phosphates. The favorable linear belts may exceed 100 kilometres in length and be tens of kilometres wide.

TYPICAL GRADE AND TONNAGE

Deposits may exceed 1000 Mt grading >20 % Fe. Reserves for the following deposits are:
- Olympic Dam - 2000 Mt grading 1.6% Cu, 0.06% U_3O_8, 3.5 g/t Ag and 0.6 g/t Au with a measured and indicated resource in a large number of different ore zones of 450 Mt grading 2.5% Cu, 0.08 % U_3O_8, 6 g/t Ag, 0.02% Co and 0.6 g/t Au with ~2000 g/t La and ~3000 g/t Ce (Reeves *et a*l., 1990);
- Ernest Henry - 166 Mt averaging 1.1 % Cu and 0.5 g/t Au (quoted in Williams, 1999);
- Sue-Dianne - 8.16 Mt averaging 0.8% Cu, up to 150 ppm U and locally significant gold (Gandhi, 1989);
- Kiruna district - > 2000 Mt grading 50-60% Fe and an average apatite content of 0.9 % (quoted in Williams, 1999);
- Candelaria - 366 Mt averaging 1.08 % Cu, 0.26 g/t Au and 4.5 g/t Ag (Ryan *et al.*, 1995).

ECONOMIC LIMITATIONS

The larger, sulphide-poor Fe oxide deposits are a potential economic source for Fe and P in areas with easy access and existing infrastructure. However, the more sulphide-rich Fe oxide deposits with Cu-Au-Ag mineralization are currently more attractive economically.

IMPORTANCE

These deposits continue to be significant producers of Fe and represent an important source of Cu, Au, P, U and possibly REE's.

ACKNOWLEDGEMENTS

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