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IRON OXIDE-Cu-Au DEPOSITS: WHAT, WHERE, WHEN, AND WHY

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Abstract - The magnetite-apatite deposits ("Kiruna-type") and the iron oxide-Cu-Au deposits form end members of a continuum. In general the magnetite-apatite deposits form prior to the copper-bearing deposits in a particular district. While the magnetite-apatite deposits display remarkably similar styles of alteration and mineralization from district to district and throughout geologic time, the iron oxide-Cu-Au deposits are much more diverse. Deposits of this family are found in post-Archean rocks from the Early Proterozoic to the Pliocene. There appear to be three "end member" tectonic environments that account for the vast majority of these deposits: (A) intra-continental orogenic collapse; (B) intra-continental anorogenic magmatism; and (C) extension along a subduction-related continental margin. All of these environments have significant igneous activity probably related to mantle underplating, high heat flow, and source rocks (subaerial basalts, sediments, and/or magmas) that are relatively oxidized; many districts contain(ed) evaporites. While some of the magnetite-apatite deposits appear to be directly related to specific intrusions, iron oxide-Cu-Au deposits do not appear to have a direct spatial association with specific intrusions. Iron oxide-Cu-Au deposits are localized along high- to low-angle faults which are generally splays off major, crustal-scale faults. Iron oxide-Cu-Au deposits appear to have formed by: 1) significant cooling of a fluid similar to that responsible for precipitation of magnetite-apatite; 2) interaction of a fluid similar to that causing precipitation of magnetite-apatite with a cooler, copper-, gold-, and relatively sulfate-rich fluid of meteoric or "basinal" derivation; or 3) a fluid unrelated to that responsible for the magnetite-apatite systems but which is also oxidized and saline, though probably cooler and sulfate-bearing. The variability of potential ore fluids, together with the diverse rock types in which these deposits are located, results in the wide variety of deposit styles and mineralogies.

Introduction

The iron oxide-Cu-Au class of deposits have become a prime exploration target in the past decade. This exploration has resulted in the discovery of two major deposits which are currently in production (Ernest Henry, Candelaria), a number of smaller producing deposits (primarily in the Cloncurry district), and several currently undeveloped deposits (notably Sossego). Despite these exploration successes we still lack a comprehensive genetic model that can help distinguish productive from barren or subeconomic systems. There are fundamental disagreements between many explorationists and researchers on several key features of this deposit class, particularly in regard to the source of the fluids responsible for alteration and mineralization and the role of specific magmas. In recent years the debate over this family of deposits has been increasingly focused on whether the fluids responsible for these systems are dominantly magmatically derived (Pollard et al., 1998; Wyborn, 1998; Skirrow, 1999; Perring et al., 2000) or wall-rock controlled (Haynes et al., 1995; Barton and Johnson, 1996).

Understanding of this class of deposits has been hindered by the scarcity of examples and by the large scale of the systems themselves. Due to the present dearth of national geological surveys worldwide capable of conducting large-scale, regional mapping programs, we do not properly understand the overall geological setting of many of the known deposits. In the Cloncurry district, sufficient geological studies, largely by workers associated with James Cook University, have been undertaken to begin to piece together the larger picture of a district. However, the Cloncurry district may not be representative of all of the tectonic settings of this family of deposits.

This paper will attempt to update our overall understanding of this family of deposits by first describing the characteristics which connect the deposits. In contrast to the conclusions in the paper by Hitzman et al. (1992), it now appears that though magnetite-apatite ("Kiruna-type") and iron oxide-Cu-Au deposits share many features in common, they may have fundamentally different origins. This paper will examine a number of districts in the context of a new model for this broad deposit family. The paper concludes with a discussion of the sources of ore fluids and the exploration implications of this new model.

Characteristics of the Iron Oxide-Cu-Au Ore Deposit Family

Hitzman et al. (1992) grouped magnetite-apatite ("Kiruna-type") and iron oxide-Cu-Au deposits together genetically. The paper was significant in demonstrating the shared features between these deposit types and in providing a framework for describing alteration assemblages associated with the deposits. It was noted that although the exact alteration mineralogy within individual deposits depends on host lithology and depth of formation there is a general trend from sodic alteration at deep levels, to potassic alteration at intermediate to shallow levels, to sericitic (hydrolytic) alteration and silicification at very shallow levels.

The past decade has significantly increased our database with regards to this class of deposits (Fig. 1). While there does appear to be a genetic link between the magnetite-apatite deposits ("Kiruna-type") and the iron oxide-Cu-Au deposits, evidence suggests that they form end members of a continuum. Geochronological data indicates that these deposit types are not necessarily coeval where they occur in the same district. Generally the magnetite-apatite deposits formed prior to the copper-bearing deposits. While the magnetite-apatite deposits display remarkably similar styles of alteration and mineralization from district to district and throughout geologic time, the iron oxide-Cu-Au deposits are much more diverse than some other well-known ore deposit classes such as porphyry copper or volcanogenic massive sulfide deposits. This diversity is more akin to that observed in the so-called "Mississippi Valley-type (MVT)" family of carbonate-hosted Zn-Pb deposits. The diversity strongly suggests that, as in the MVTs, a variety of geological processes can influence their formation.

Presently, the characteristics deemed important for the iron oxide-Cu-Au class (including the magnetite-apatite deposits) are:

(1) Age. Deposits are found in post-Archean rocks and are known from the Early Proterozoic to the Pliocene (El Laco, Chile; Rio Grande, Argentina). The deposits in the Carajas district of Brazil (e.g., Salobo) may be Archean though the geochronology of the sequences hosting these deposits is still somewhat controversial. There is no specific time that appears more favorable for the iron oxide-Cu-Au deposits rather than the magnetite-apatite deposits.

(2) Tectonic setting. There appear to be three "end member" tectonic environments that account for the vast majority of these deposits. These are characterized by: (A) intra-continental orogenic collapse; (B) intra-continental anorogenic magmatism; and (C) extension along a subduction-related continental margin. All of these environments have significant to voluminous igneous activity, high heat flow, and source rocks (subaerial basalts, sediments, and/or magmas) that are relatively oxidized.

(3) Association with igneous activity. The vast majority of deposits are spatially and temporally related to significant magmatic events. Some of the magnetite-apatite deposits appear to be directly related to specific, spatially related intrusions. Iron oxide-Cu-Au deposits do not appear to have a direct spatial association with specific intrusions at the structural level of mineralization. Magmas associated with the deposits do not appear to be of a specific composition.

(4) Association with evaporites. Many of the districts hosting these deposits appear to have contained marine or lacustrine halite facies evaporites.

(5) Structural control. Deposits, especially the iron oxide-Cu-Au deposits, are localized along high- to low-angle faults which are generally splays off major, crustal-scale faults.

(6) Morphology. Deposits display a variety of morphologies from stratabound sheets to irregular stockwork breccia zones. Virtually all of the deposits formed by replacement of host rocks. Rarely, ore fluids appear to have reached the earth's surface and formed iron oxide sinters.

(7) Mineralogy. This class of deposit is characterized by an abundance of iron oxide minerals and a relative lack of iron sulfides. Both the magnetite-apatite deposits and iron oxide- Cu-Au deposits may contain significant carbonate, Ba, P, or F. The iron oxide-Cu-Au deposits may contain a suite of minor metals including U, Ag, Mo, Co, As, and Zn; trace metal content is probably controlled by the surrounding host rocks. Almost all of the deposits of the class contain anomalous concentrations of REEs.

(8) Alteration. The host rocks for these deposits are generally intensely altered. The exact alteration mineralogy depends on host lithology. Magnetite-apatite deposits are generally spatially associated with zones of sodic or sodic-calcic alteration. These systems may grade upward into hematite-rich systems associated with potassic or hydrolytic alteration as noted by Hitzman et al. (1992). These magnetite and hematite deposits may, or may not, be temporally related to later iron oxide-Cu-Au mineralization. Iron oxide-Cu-Au deposits are generally associated with sodic-potassic, potassic, or hydrolytic alteration depending on the degree of interaction with meteoric or connate fluids. Alteration zones, particularly the early sodic and sodic-calcic styles of alteration, tend to be extremely large (10's to hundreds of square kilometers).

(9) Ore fluid composition. The ore fluids responsible for the magnetite-apatite deposits appear to have been relatively saline, oxidized, sulfide-poor, aqueous fluids with temperatures above 250°C. Formation of the iron oxide-Cu-Au deposits appears to have involved either retrograde reaction of the fluids responsible for the magnetite deposits or fluid mixing with a separate, saline, oxidized, sulfate-bearing, lower temperature fluid, commonly with significant CO_2.

Deposits Associated with Orogenic Basin Collapse

This setting consists of a continental rift or rifted continental margin which contains a thick (+5 km) sequence of sedimentary rocks including mafic volcanic rocks (Fig. 2). It is critical that the basin sequence has an overall high oxidation state. Thus, the sedimentary sequence commonly

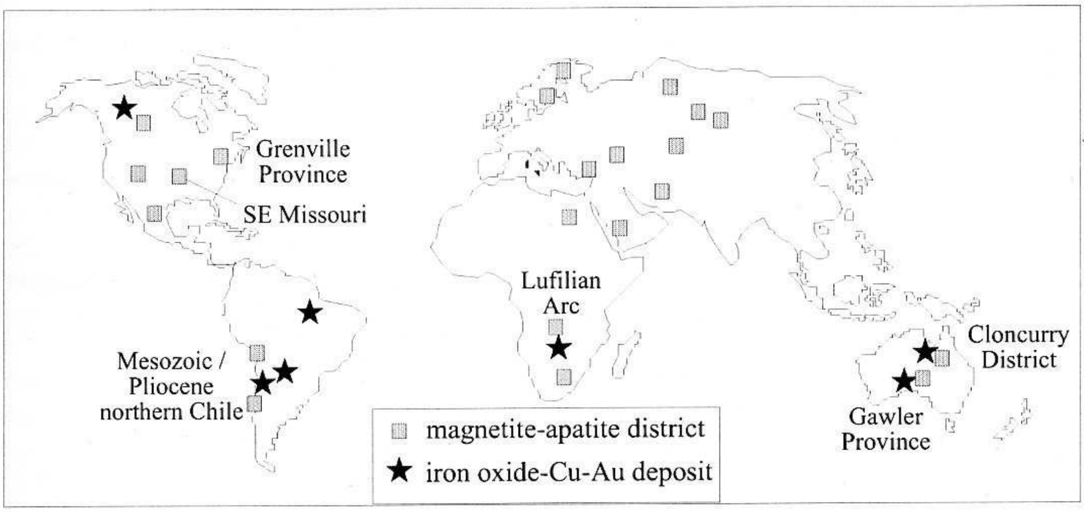

Figure 1. Location of magnetite-apatite and iron oxide-Cu-Au deposits.

contains thick subaerial volcanic sequences together with siliciclastic sequences, dominantly red beds, and lacustrine to shallow-marine carbonate sequences. The basins also contain, or contained, significant evaporites including halite-facies evaporites. This type of sedimentary fill is most commonly found in intracratonic rift basins characterized by a long-lived sag phase where rifting did not result in the formation of oceanic crust.

Orogenic collapse is the result of regional compression as well as significant crustal underplating by mantle-derived mafic magmas in the original basin area. The heat from this underplating, combined with deep burial, results in greenschist to granulite facies metamorphism of the sedimentary and volcanic sequence as well as crustal melting and the generation of intermediate to felsic intrusive rocks together with mantle-derived mafic intrusive rocks. Orogenic collapse of these basins produces basin inversion and complex deformation of the sedimentary pile. Deformation can involve both external, thin-skinned structure and internal, thick-skinned structure. Such structures are well documented in the Mesozoic Cordillera of the western U.S. (non-collisional orogen; Hamilton, 1989). The transition between thin- and thick-skinned deformation coincides with a shift to higher metamorphic grades, and has been interpreted as related to ramping of the basal cover detachment down into basement when the thermally weakened magmatic arc is approached (Armstrong and Dick, 1974; Burchfiel and Davis, 1972). In intra-continental areas, continental crust which was thermally weakened and extended due to mantle underplating may play the role of the magmatic arc in other orogenic belts. Thus orogenic collapse can often result in the development of a decollement separating the deforming sedimentary pile from the more ductily deforming lower crust. Fault splays off the master decollement focus fluid release from the deforming sediments and from the voluminous magmas emplaced below the decollement.

Crustal underplating produces high heat flow which can apparently result in the establishment of crustal-scale hydrothermal cells. Initial fluids in these large-scale cells are probably derived from dehydration of the sedimentary sequence. Later fluids may be derived from both exsolved magmatic fluids together with inflow of meteoric water at shallow to moderate depths. Initial fluids have high salinity due to evaporite dissolution. Later fluids may be able to maintain relatively high salinities through progressive release of chlorine fixed in metamorphic minerals and high salinity fluids derived from the crustal melts. The high overall oxidation state of the initial sedimentary sequence ensures that the fluids generated during orogenesis and later magmatism remain relatively oxidized.

Cloncurry District, Australia

The Cloncurry district forms the eastern portion of the Mount Isa inlier in northwest Queensland. It is perhaps the best studied terrane containing iron oxide-Cu-Au deposits. The area contains two main sequences of supracrustal rocks which appear to have formed in a large intracratonic sag or rift basin, one deposited between 1780 and 1720 Ma (Cover Sequence 2 of Blake, 1987) and a younger sequence deposited after 1670 Ma (Cover Sequence 3 of Blake, 1987; Page & Sun, 1998). The earlier sequence consists of mafic metavolcanic rocks in a mixed clastic-carbonate-evaporite metasedimentary sequence of shallow marine and/or lacustrine derivation (Blake, 1987) which appears to grade eastward into a more siliciclastic and mafic metavolcanic sequence (Beardsmore et al., 1988). The younger sequence, which is approximately coeval with the carbonaceous, shallow-water dolostones of the Mount Isa area to the west, consists of variably metamorphosed mafic volcanic flows and sills, sandstones, arkoses, and shales. The exact structural relationship of these rocks to the older sequence is in some doubt and there is a suggestion it may be allochthonous (Loosveld, 1989; Laing, 1998). The thicknesses of both the lower and upper sequences are not known with certainty but are assumed to be several kilometers. Though carbonaceous rocks are present, these sequences are generally relatively oxidized. In contrast, the western portion of the Mount Isa inlier contains abundant carbonaceous rocks producing a much more reduced overall sequence.

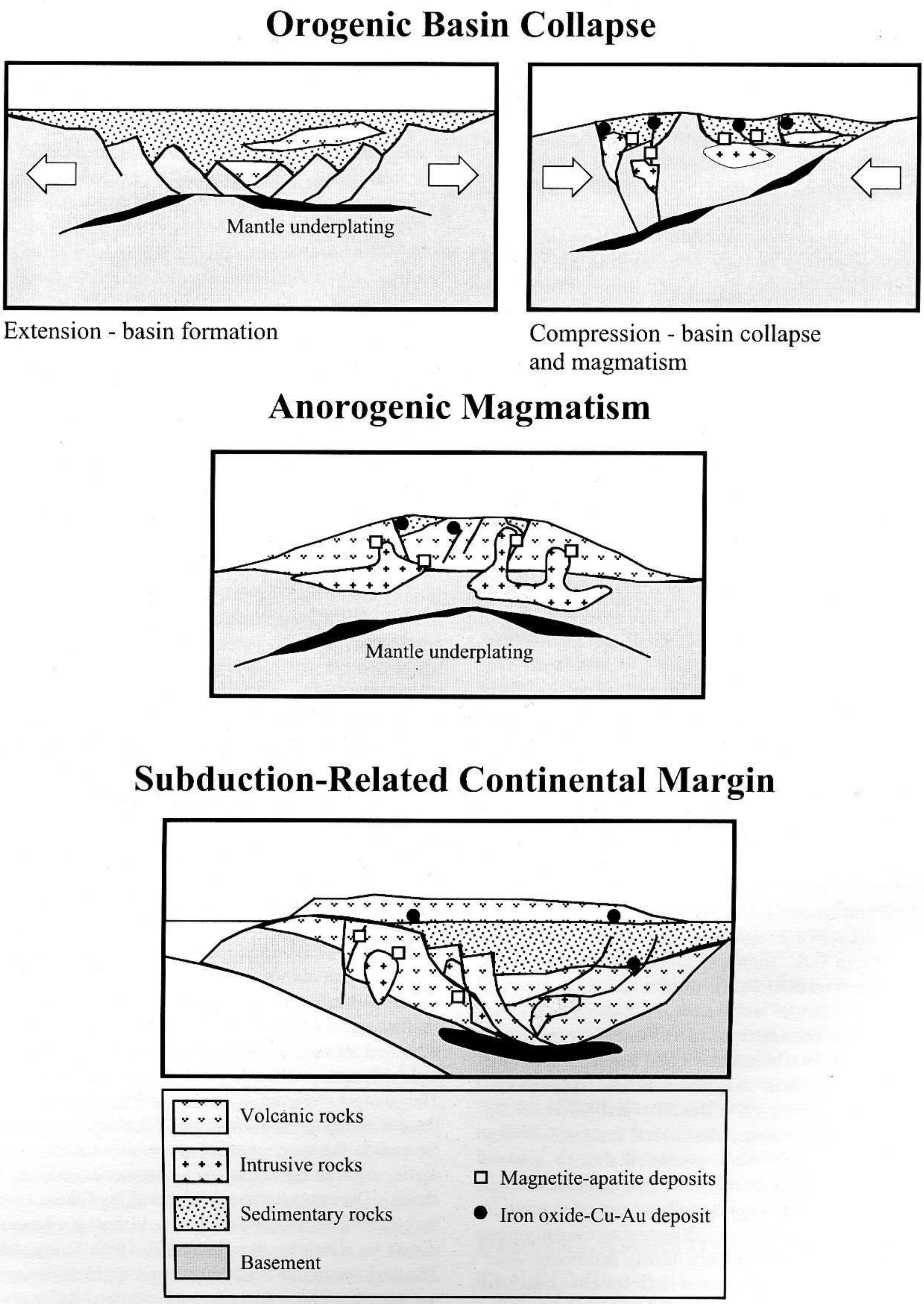

Figure 2. Tectonic setting of iron oxide-Cu-Au deposits

The area underwent deformation and at least some metamorphism during the Damantinan orogeny around 1590 Ma after deposition of the younger sedimentary sequence. However, the major period of orogenic collapse was during the Isan orogeny (1550-1500 Ma) (O'Dea et al., 1997). This event resulted in middle greenschist to upper amphibolite facies regional metamorphism (Williams, 1998). Interpretation of a deep seismic transect across the Mount Isa inlier, together with interpretation of surface geology (MacCready et al., 1998), suggests that the Cloncurry district underwent significant east-west shortening during an early phase of basin inversion and that this shortening occurred above a regional decollement which is associated with a high velocity layer taken to represent significant mafic intrusions derived from crustal underplating. A second stage of deformation affected the entire Mount Isa inlier and resulted in the formation of network of basement-cutting reverse and strike-slip faults that displaced the decollement (MacCready et al., 1998).

The Isan orogeny was accompanied by significant igneous activity. Trondhjemite and granodiorite plutons were emplaced early (around 1550 Ma) and were followed by voluminous magnetite-series mafic to felsic granitoids (Williams-Naraku batholiths) from about 1540 to 1500 Ma (Page and Sun, 1998; Pollard et al., 1998; Wyborn, 1998). Intrusion of the Williams-Naraku batholiths appears to have been accompanied, or immediately followed, by regionally extensive sodic and sodic-calcic alteration (Williams, 1994; de Jong & Williams, 1995; Pollard et al., 1998) and the formation of at least some magnetite-rich ("Kiruna-type") zones (e.g., Lightning Creek prospect; Perring et al., 2000) though the exact age of this alteration and mineralization is poorly known. The sodic and sodic-calcic alteration zones occur over large areas but are largely structurally controlled (Williams, 1994), commonly along major faults that may be splays off the regional decollement.

The iron oxide-Cu-Au systems post-date the regional sodic and sodic-calcic alteration. The iron oxide-Cu-Au deposits and prospects may either directly overprint zones of earlier sodic or sodic-calcic alteration (e.g. Starra; Rotherham, 1997) or show no particular spatial relationship to the earlier alteration event (e.g., Ernest Henry; Twyerould, 1997; Craske, 1995; Webb & Rowston, 1995). The iron oxide-Cu-Au systems are all associated with minor to extreme potassic alteration and in some cases hydrolytic alteration (sericite-carbonate); in general those with well-developed potassic alteration contain magnetite while those with hydrolytic alteration (Osborne, Starra) contain magnetite and hematite. The age of potassic alteration at the iron oxide-Cu-Au deposits ranges from 1540 Ma at Osborne to 1502 ± 3 Ma at Starra (Perkins & Wyborn, 1998) with most of the available ages clustering around 1510 Ma (e.g., 1510-1500 Ma at Ernest Henry, Twyerould, 1997). The available evidence suggests there may be a 10 to 20 Ma difference between the age of sodic or sodic-calcic alteration and the age of Cu-Au mineralization and potassic alteration. The iron oxide-Cu-Au deposits of the Cloncurry are remarkable for their diversity in terms of morphology. Most appear to be related to high-angle structures, perhaps formed during the later stages of the Isan orogeny.

Grenville Province, Canada and USA

The Grenville Province includes a group of highly metamorphosed sedimentary (1300 to 1000 Ma) and igneous rocks (1250 to 900 Ma) in southeastern Canada and the northeast United States. The tectonic setting of the area is poorly known and tectonic models for the area suggest the sediments were deposited in a back-arc basin, continental margin prism, or intracratonic rift. The Grenville orogeny includes two periods of intense deformation, the Elzevirian (1300 to 1200 Ma) and Ottawan (1200 to 1000 Ma) (Davidson, 1998) which are separated by a major igneous event. While the Grenville Province consists of a number of different tectonic zones, iron oxide deposits are restricted to the southeast terrane (Central Metasedimentary Belt of southeast Canada, Adirondack Lowlands metasedimentary belt of New York, and the metasedimentary belt exposed as outliers in southern New York and New Jersey). These areas contain complexly folded sequences of marbles, calcsilicate rocks, quartzites, tourmalinites, meta-evaporites, garnetiferous, commonly scapolite-bearing, biotite-quartz-feldspar gneisses, garnetiferous leucogneisses, and amphibolite. Amphibolites are particularly common in the New York-New Jersey area. Many of the granitoid and amphibolite layers were undoubtedly igneous, but extreme deformation and metamorphic recrystallization make it difficult to determine whether they were extrusive or intrusive. Overall, the sequence in this portion of the Grenville appears to represent a series of shallow-marine to lacustrine sediments deposited in a rift or sag basin which underwent orogenic collapse.

The metasedimentary rocks are intruded by an igneous suite composed of anorthosite, mangerite, charnokite, and granite which was metamorphosed during the second deformational event. The Adirondack Highlands anorthosites have Sm-Nd values indicating they were derived from a depleted mantle source (Ashwal & Wooden, 1983; Basu & Pettingill, 1983). Morse (1982) and Emslie (1985) suggest that the parental magma was an iron-rich, high-alumina gabbro or olivine tholeiite which underplated the crust. Fractionation to an anorthositic composition, together with melting of sialic crustal material, resulted in reduced magma density and crustal weakening and allowed the magmas to ascend through the crust. The low $\delta^{18}O$ values of the anorthosite (Valley & O'Neill, 1982) indicate interaction of the magmas with meteoric fluids though the mineralogy of the rocks indicates crystallization at depths of approximately 8 km (Ollila et al., 1984). This suggests that meteoric waters infiltrated to great depths during the igneous/metamorphic event.

The Adirondack and New York-New Jersey areas contain abundant low titanium, phosphorus-rich magnetite ("Kiruna-type") deposits (Hotz, 1953; Sims, 1953; Leonard & Buddington, 1964; Buddington, 1966; Baker & Buddington, 1970; Foose & McLelland, 1995). These deposits form irregular massive bodies to stockwork zones of magnetite veins in amphibolite and quartz-potassium feldspar gneisses. While some of the deposits contain minor amounts of chalcopyrite, no iron oxide-Cu-Au deposits are yet known though modern exploration in the area has been minimal.

Lufilian Orogen, Southern Africa

The Lufilan fold belt ("arc") of southern Africa consists of an intracratonic rift basin formed between 880 and 820 Ma (Hanson et al., 1994; Cahen et al., 1984) which underwent orogenic collapse during Pan-African orogenesis (Grunow et al., 1996). The Lufilian arc contains the major copperbelts of Zambia and Congo. The arc also contains a number of minor magnetite deposits associated with sodic and sodic-calcic alteration, Cu and U deposits associated with sodic alteration, and poorly known iron oxide-Cu-Au systems.

The Lufilian arc forms one segment of the transcontinental Damara-Lufilian-Zambezi orogenic system. The 200-300 km wide Lufilian fold belt spans a distance of approximately 700 km from Angola through the Democratic Republic of Congo and into Zambia. The fold belt is flanked to the south by the Mwembeshi dislocation, a major ductile-brittle shear zone with possible transcurrent movement (Coward & Daly, 1984; Hanson et al., 1993, 1994) which separates the Lufilian fold belt from the Zambezi belt (Wilson et al., 1997). The Katangan sequence is at least 8 km thick (Anderson & Unrug, 1984; Unrug, 1989). Within the Lufilian arc the Katangan sequence consists of a basal series of continental red beds which are conformably overlain by shallow-marine rocks. These grade upwards into a dominantly carbonate sequence with argillaceous and rare siliciclastic intervals. The sequence does contain several relatively thick intervals of reduced, argillaceous shales. Unlike the sequences in the Mount Isa and Grenville areas, the Katangan sequence is not known to contain significant volcanic intervals, although these have been hypothesized to be present based on the amount of copper present in the Congo and Zambian Copperbelts (Hitzman, 2000).

The Lufilian fold belt may be subdivided into two major zones: a northern zone of thin-skinned thrust sheets and a southern zone of more deeply rooted thrust faults (Unrug, 1988, 1989). The northern zone, which contains the Congo Copperbelt, consists of tightly folded, thin-skinned thrust sheets of weakly to non-metamorphosed Katangan strata. The thrust plates are commonly soled by thick breccia intervals which may represent deformed evaporite lenses. The southern or inner zone of the Lufilian arc, occupying northern and central Zambia, consists of thick-skinned thrust sheets which are interpreted to contain slices of pre-Katangan basement (Coward & Daly, 1984). Rocks within this southern zone, which contain the Zambian Copperbelt, are weakly to highly metamorphosed. To the west and southwest of the Zambian Copperbelt, metamorphic grade appears to increase in successive thrust sheets to the south reaching high-pressure amphibolite facies (Cosi et al., 1992). Metamorphism throughout the inner zone of the Lufilian arc is characterized by the growth of scapolite suggesting relatively saline metamorphic fluids. The age of the deformation and metamorphism in the Zambian portion of the Lufilian arc has been determined by K-Ar and Rb-Sr dating of metamorphic minerals (Cosi et al., 1992), by U-Pb dating of the syn- to post-tectonic Hook granitic batholith (Hanson et al., 1993), and by Re-Os and U-Pb dating of post-tectonic veins (Torrealday et al., 2000). These studies indicate that metamorphism may have begun as early as 710 Ma and continued to approximately 530 Ma.

Magmatic activity appears to be restricted to the southern or inner portions of the arc where significant amounts of intermediate to felsic magmas (Hook granite suite) were intruded at the end of the metamorphic event. Magnetite-apatite and iron oxide-Cu-Au systems are spatially associated with these intrusives although alteration and mineralization appear to post-date the intrusions themselves. Many systems appear to be located on splays off the Mwembeshi dislocation fault system. Massive magnetite bodies ("Kiruna-type") are associated with sodic and sodic-calcic alteration. These systems have been identified from the Hook granite area north to the Congo border. Many of the systems in the north are spatially associated with intermediate to mafic intrusive ("diorites") stocks or sills which have undergone extreme sodic alteration which has resulted in the formation of albite-actinolite-scapolite assemblages. This area also contains the poorly described, high-grade Kalengwa copper deposit which is spatially associated with a dioritic intrusion, and the Kansanshi copper deposit (Torrealday et al., 2000) which consists of veins of chalcopyrite with minor iron sulfides, molybdenite, monazite, and brannerite within an intense sodic alteration halo. Although these deposits lack significant iron oxides, the intense sodic alteration at both deposits is somewhat similar to that observed in many magnetite-apatite systems.

Iron oxide-Cu-Au systems have thus far only been recognized around the Hook granite and are extremely poorly explored. These are characterized by vertically oriented, structurally-controlled hematite-rich breccia zones up to several kilometers in length with late pyrite and chalcopyrite. Intrusive and volcanic rocks within these systems have undergone pre-mineralization potassic alteration characterized by the formation of potassium feldspar. Potassically altered rocks are then cut by magnetite which is in turn replaced by hematite during a hydrolytic (sericite-chlorite) alteration event. Sulfidation is the final event resulting in the precipitation of pyrite and then chalcopyrite.

Deposits Associated with Anorogenic Magmatism

The Middle and Late Proterozoic was characterized by large areas of apparently anorogenic magmatism within continental interiors. In some cases, these areas appear to be related to incipient rifting whereas in other areas the magmatism does not appear to be associated with significant downwarping. These areas contain voluminous felsic intrusive and extrusive rocks with lesser mafic igneous rocks. While such provinces become rarer in the Phanerozoic, apparently similar provinces have formed into the Tertiary (e.g., San Juan volcanic field, Colorado, USA).

The igneous rocks in these districts are comprised of both extrusive and intrusive rocks. Compositions of the rocks are variable ranging from rhyolites and granites to basalts and gabbros. The volcanic rocks are typically subaerial. Rhyolitic, welded, ash-flow tuffs are particularly common. In many districts it appears that the felsic extrusive rocks formed from voluminous caldera eruptions. The igneous rocks in these provinces may be calc-alkaline or alkalic in nature. Many of these areas are characterized by "syenites" and/or "red granites". The "syenites" are commonly intermediate to felsic igneous rocks which have undergone either weak potassic or sodic alteration while the "red granites" are intermediate to felsic rocks in which igneous feldspar has been weakly, but pervasively, replaced by small amounts of hydrothermal hematite. This pervasive hydrothermal alteration has obscured original igneous compositions over vast areas. Sedimentary rocks are typically present within the dominantly volcanic sequences and comprise coarse volcaniclastic and lacustrine sedimentary rocks; there is little evidence of evaporites.

These volcanic provinces are probably the result of crustal melting associated with crustal underplating of mantle-derived magmas. Such underplating may be the result of incipient or aborted rifting, mantle hot spots moving under a continental mass, or extremely low-angle subduction. Many of these anorogenic provinces have magnetite-apatite deposits ("Kiruna-type") as one of their hallmarks. Such districts include the well-known southeast Missouri district of the USA, the Great Bear Lake district of Canada, the Kiruna district of Sweden, and the Gawler province of Australia. Lesser known examples are the late Proterozoic Arabian shield in southern Saudi Arabia and the western desert of Egypt.

While the magnetite-apatite deposits in these districts have been known for years, iron oxide-Cu-Au systems appear to be rare, though the Gawler province hosts Olympic Dam, the single largest known iron oxide-Cu-Au deposit. Available data suggest that the Olympic Dam deposit formed either significantly later than the nearby magnetite-apatite deposits (Oreskes & Einaudi, 1990, 1992) or through the interaction of fluids responsible for the magnetite deposits with saline, metal- and oxidized sulfur-rich meteoric or connate fluids (Haynes et al., 1995).

Gawler Province

The Gawler volcanic province occupies at least 90,000 km^2 in South Australia on the Stuart Shelf and areas to the south and west. It consists of Early Proterozoic deformed granitic and metasedimentary rocks of the Hutchinson Group and Lincoln Complex (Parker, 1990). These basement rocks are intruded by the Hiltaba granite suite (Fanning et al., 1988; Parker, 1990) which consists of quartz monzodiorite to granite plutons emplaced between 1585 Ma and 1600 Ma (Mortimer et al., 1988; Creaser & Cooper, 1993; Johnson & Cross, 1991). The plutons also intrude a pile of consanguineous volcanic rocks termed the Gawler Range Volcanics (Giles, 1988; Creaser & Cooper, 1993) which are dominated by felsic volcanic rocks but include basaltic flows (equivalent to the Roopena Volcanics in the southern and central portions of the Stuart Shelf (Giles & Teal, 1979)). The sequence contains relatively minor sedimentary layers.

The Gawler province contains a number of magnetite-(apatite) ("Kiruna-type") systems such as the Acropolis and Wirrda Well prospects (Cross et al., 1993). These prospects contain massive magnetite bodies and vein magnetite stockworks in both intrusive and volcanic rocks associated with sodic and sodic-calcic alteration. Many of these prospects contain minor chalcopyrite and pyrite. The Olympic Dam iron oxide-Cu-Au deposit occurs in proximity to these magnetite-rich systems. However, mineralization at Olympic Dam is restricted to a large, hematite-rich breccia complex which occurs entirely within granite (Oreskes & Einaudi, 1990; Reeve et al., 1990). The breccia complex is interpreted to be a volcanic maar (Reeve et al., 1990) which formed during Gawler Range volcanism (Johnson & Cross, 1991). The deposit contains an early magnetite-chlorite-sericite-siderite assemblage with minor pyrite and chalcopyrite which is overprinted and replaced by a hematite-sericite-copper-iron sulfide-pitchblende-barite-fluorite-chlorite assemblage (Oreskes & Einaudi, 1990; Haynes et al., 1995). The age of mineralization appears to be roughly equivalent to the age of volcanism based on both geological observations (mineralized clasts within the maar breccias) and geochronology (Johnson & Cross, 1991).

Theoretical modeling studies (Haynes et al., 1995) suggest that the Olympic Dam deposit formed by fluid mixing of a deep, relatively oxidized, iron-rich hydrothermal fluid capable of generating the Kiruna-type magnetite deposits with a cooler, highly oxidized meteoric or connate fluid containing Cu, U, Au, Ag, and sulfate derived from interaction of extremely saline lacustrine water with mafic volcanic rocks.

Southeast Missouri

The St. Francois terrane in southeast Missouri contains a series of 1400 - 1500 Ma (Bickford & Mose, 1975) felsic intrusions with lesser rhyolitic volcanic rocks and very minor mafic volcanic and intrusive rocks (Kivarsanyi, 1980). The terrane has a surface exposure of approximately 900 km^2, though geophysics and scattered drill intercepts suggests it covers an area of at least 90,000 km^2 in southeastern Missouri and that similar age rocks extend west into northeastern Oklahoma. The intrusive rocks of the St. Francois terrane comprise a dominantly felsic suite derived from partial melting of crustal material (Cullers et al., 1981). The plutons intruded consanguineous volcanic rocks (predominantly rhyolite ash-flows) which have a maximum known thickness of approximately 1500 m. Virtually no sedimentary rocks are recognized in the St. Francois terrane.

The St. Francois area contains more than 30 iron oxide-rich deposits (Sims et al., 1987). Six major magnetite-apatite ("Kiruna-type") deposits are known: Pea Ridge

(Emery, 1968; Marikos et al., 1989), Iron Mountain (Murphy & Ohle, 1986), Pilot Knob (Wracher, 1976; Panno & Hood, 1983), Bourbon (Kisvarsanyi & Proctor, 1967; Snyder, 1969), Kratz Spring, and Camels Hump. These deposits occur primarily in sodic and/or sodic-calcic alteration zones. Several deposits contain volumetrically insignificant zones of cross-cutting potassic or hydrolyitc alteration with elevated Cu-Au. The Pilot Knob deposit consists of an underground magnetite orebody and a surface deposit consisting of layered and brecciated hematite and hematitic volcaniclastic rocks which have been interpreted as forming in a shallow-water, lacustrine environment (Anderson, 1976). The Boss Bixby deposit (Kisvarsanyi & Smith, 1988) consists of stockwork magnetite with pyrite and chalcopyrite associated with weak potassic alteration.

Although Boss Bixby represents a significant copper resource, no economic iron oxide-Cu-Au deposits have yet been located in this terrane. It is noteworthy that the hematite deposit at Pilot Knob, which shares many textural features with portions of the hematitic sediments downdropped into the Olympic Dam breccia complex, does not contain significant copper or gold. It may be that though the hydrothermal system breached the surface, no saline, sulfate-rich surface and groundwater was available for mixing as at Olympic Dam. The absence of significant mafic rocks in the St. Francois area, combined with an apparent lack of evaporites in the section even in lacustrine sequences, perhaps due to temperate climatic conditions, may account for the absence of large iron oxide-Cu-Au deposits.

Deposits Associated with Extensional Environments along a Subduction-Related Continental Margin

Iron oxide-Cu-Au deposits also occur within dominantly volcanic sequences along continental margins which are the site of subduction. In a number of cases, such as the Mesozoic of northern Chile and southern Peru and the Mesozoic of western North America, the volcanic arc was undergoing extension and was characterized by low topographic relief. Extension may have been due to a low angle of subduction, the formation of strike-slip fault systems as the result of oblique subduction, or hiatuses in subduction. These arcs are characterized by thick sequences of subaerial volcanic rocks and commonly include extensional sag or rift basins filled with shallow-marine to subaerial sedimentary rocks. The sedimentary sequences typically contain halite facies evaporites. Deep back-arc basins, such as the present-day Sea of Japan, filled with deep-water turbidites, appear to be poor analogues for these ancient basins. A better analogy may be the present-day Salton Sea trough (McKibben and Hardie, 1997) developed in a major pull-apart basin along the San Andreas strike slip fault system which links two subduction zones. However, the occurrence of Pliocene-age iron oxide deposits in the high Andes of Chile and Argentina illustrates that low topographic relief is not a prerequisite for deposit formation. It is probable that deposits like El Laco in Chile and Rio Grande-Arizaro in Argentina are simply not often preserved in the geological record due to erosion.

Mesozoic of Northern Chile

The Mesozoic and Cenozoic of northern Chile provide perhaps the best view of the interplay between tectonics, magmatism, and the formation of both magnetite-apatite ("Kiruna-type) and iron oxide-Cu-Au systems. Northern Chile contains hundreds of magnetite-apatite deposits in the Chilean Iron Belt (CIB) which runs parallel to the coast from 31°S northward to 25°S, a distance of approximately 600 km. Overlapping this belt, and extending beyond it to the north (22°S) and south (33°S) over a distance of 1100 km are a group of copper sulfide deposits, termed "manto-type" copper deposits (Sato, 1984) or volcanic redbed copper deposits (Kirkham, 1996). Iron oxide-Cu-Au deposits are also known in the area. Prospects and deposits of this type are currently recognized from just south of Vallenar (almost 29°S) to just south of Chanaral (26°S), a distance of approximately 250 km. These mineralized belts parallel, and are roughly coincident with, the Atacama fault zone which is known to extend on land from La Serena (30°S) to Iquique (20°S).

The basement in the western margin of Chile consists of penetratively deformed, low-grade, late Paleozoic metasedimentary rocks (Bell, 1987). These rocks are unconformably overlain by Triassic continental sediments in the western coastal belt and continental to marine sediments to the east (Chong & von Hillebrandt, 1985). During the earliest Jurassic, extension resulted in the formation of a major basin to the east of the present-day Coast Range of Chile, which was infilled with carbonate and terrigenous sediments (Mpodozis & Ramos, 1989). Marine sediments and volcaniclastic rocks were deposited in the Coast Range area which underwent rapid downdrop.

In the Sinemurian (early Jurassic), intensive volcanism and plutonism was initiated from 18°S to 26°S along a volcanic arc located in what is now the Coast Range. The volcanic products of this volcanism, termed the La Negra Formation (Jurassic) and Cerros Florida and Bandurrias Formations (Cretaceous) are largely subaerial basalts and andesites with minor more felsic rocks. These Juro-Cretaceous basic lavas display high-K, calc-alkaline to shoshonitic affinity and reach an aggregate thickness of approximately 15 km (Vegara et al., 1995). Extension and subsidence during eruption of this thick sequence of volcanic rocks resulted in low-relief topography close to sea level. Plutonic complexes were emplaced within the volcanic arc during the Early Jurassic, Late Jurassic, and Early Cretaceous (Dallmeyer et al., 1996). The plutons consist of hornblende-biotite gabbro, diorite, tonalite/granodiorite, and minor granites and display textural evidence of emplacement at relatively shallow crustal levels. The Atacama fault zone is approximately coincident with the Jurassic - Early Cretaceous volcanic arc. During the Jurassic, movement appears to have been dominantly left-lateral while during the Cretaceous movement shifted to dip-slip and normal down to the east (Scheuber & Andriessen, 1990; Brown et al., 1993).

Approximately 100 km east of the volcanic arc, extension and transtension during the Jurassic resulted in the deposition of a mixed carbonate and siliciclastic marine succession up to 2 km in thickness in a back-arc basin. This sequence includes significant gypsum (now anhydrite) beds in both sabkha and deep-water (basinal) settings (Ardill et al., 1998). The basin interior contained numerous organic-rich, reduced mudstones. At the end of the Jurassic a major marine regression led to deposition of continental red beds in the Early Cretaceous (Chong, 1977) and the development of evaporitic horizons (Cisternas & Diaz, 1990). Contraction of the arc and back-arc system occurred after the Santonian and continued into the early Tertiary (Mpodozis & Ramos, 1990; Semper et al., 1997). During this time the active magmatic arc began to migrate eastward as shown by mid-Cretaceous volcanic and intrusive rocks, including the Oligocene porphyry copper belt, which overlie, or cut, Jurassic to Early Cretaceous back-arc sediments (Olson, 1989; Scheuber & Reutter, 1992).

The Jurassic-Early Cretaceous Coast Range volcanic arc appears to have had a high geothermal gradient which resulted in burial metamorphism of the volcanic rocks (Levi, 1970; Offler et al., 1980). The majority of the Jurassic and Early Cretaceous volcanic rocks display zeolite to prehnite-pumpellyite facies metamorphism while rocks immediately adjacent to the Atacama fault zone are at lower amphibolite to greenschist grade (Brown et al., 1993). Radiometric dating suggests the volcanic rocks were metamorphosed approximately 10 to 20 Ma after they were extruded (Åberg et al., 1984).

The earliest ore deposits in this area are the copper manto deposits. The Bueno Esperanza (Espinoza et al., 1996) and Mantos Blancos (Tassinari et al., 1993) deposits formed during the late Jurassic between 170 and 145 Ma. Mineralization of this style continued into the Cretaceous (Albian) at El Soldado (Wilson and Zentilli, 1999) and in deposits hosted in Cretaceous volcanic rocks such as at Centenario (Cupo, 2000). While some of these deposits appear to be spatially associated with local intrusions, the majority are structurally controlled zones of mineralization unrelated to distinctive intrusions. Most occur on splays of the Atacama fault zone, probably in areas of local extension. The intergrowth of metamorphic minerals with sulfides suggests that many of these deposits are the result of interaction of the burial metamorphic fluids with host rocks, with mineralization occurring because of local changes in oxidation state (Kirkham, 1996).

The ore deposits of the Cretaceous Iron Belt (CIB) are, in general, poorly dated. Geological considerations suggest early Cretaceous (Neocomian) ages (Bookstrom, 1977; Espinoza, 1990) for many of the deposits. In the Vallenar area, recent U-Pb dating of the Cachiyuyuito stock which is intimately associated with magnetite-apatite mineralization has yielded a Neocomian age of 129.8 ± 0.1Ma which provides a maximum age for magnetite mineralization (Fox, 2000). These intrusive rocks, and the associated magnetite-apatite deposits, occur along the Atacama fault zone or on subparallel fault splays to the east.

Several iron oxide-Cu-Au systems are currently recognized in this portion of Chile. These include the giant Candelaria deposit (Ryan et al., 1995; Martin et al., 1997), the nearby deposits of the Punta del Cobre district (Hopf, 1990; Marschik, 1996; Marschik & Fontboté, 1996), the Manto Verde deposit (Vila et al., 1996); and the Productura prospect (Fox, 2000). The age of these systems is dominantly Early Cretaceous (Barremian to Aptian) (Marschik & Fontboté, 1996; Vila et al., 1996; Ullrich & Clark, 1998) though alteration and mineralization at Productura may have extended into the late Cenomanian (Fox, 2000).

The available geological and geochronological evidence that suggests magnetite-apatite deposits were formed during a restricted time period in the early Cretaceous and were followed by the formation of the iron oxide-Cu-Au systems. The manto-type copper deposits formed prior to the magnetite-apatite deposits and continued to be formed through the entire period of iron oxide-rich deposit formation. The close overlap in deposit age and location, combined with similarities in metal contents and alteration assemblages, suggests these three deposit types are in some way related.

The manto-type copper deposits appear to have formed largely from fluids derived from metamorphism of the thick package of subaerial volcanic rocks. The chemistry of these fluids is very poorly known. However, the alteration and sulfide mineral assemblages indicate a relatively oxidized, possibly highly saline fluid of moderate temperature. The magnetite-apatite deposits are associated with intense sodic or sodic-calcic alteration zones that commonly contain abundant scapolite. Ore fluids are suggested to have been relatively high temperature, saline, oxidized, and contained low sulfur. The close spatial relationship of the magnetite-apatite deposits with specific dioritic intrusive rocks strongly suggests a relationship with magmatism. The iron oxide-Cu-Au systems are associated with sodic-calcic (Ullrich & Clark, 1998) and potassic (Marschik & Fontboté, 1996; Fox, 2000) alteration. The fluids responsible for these deposits appear to have been saline to hypersaline, oxidized fluids. Sulfur isotopic values for the chalcopyrite in these deposits (Marschik & Fontboté, Ullrich & Clark, 1998; 1996; Fox, 2000) range between -6.5 and +7.2 ‰ suggesting a magmatic contribution of sulfur; detailed work at Candelaria suggests that early fluids with a near-magmatic sulfur composition were replaced through time by a more oxidized, sedimentary-sulfate-related sulfur (Ullrich & Clark, 1998). The iron oxide-Cu-Au deposits formed during a period of extension and most appear to be associated with deep-rooted normal fault systems located to the east (downthrown side) of the Atacama fault system. These data suggest that a regional, burial metamorphic fluid containing copper and sulfur was available at least locally from the late Jurassic to at least the mid-Cretaceous and that this fluid was responsible for the formation of manto-type copper deposits, particularly in hydrothermal cells driven by intrusions. Mineralization took place along structural zones formed in response to local (early) or regional (later) extension. The emplacement of numerous copper-poor, magnetite-apatite deposits took place in the early Cretaceous at the onset of a period of major extension. Whether the fluids that formed these systems required halogens derived from evaporites in the adjacent extensional basins is unclear. The regional geological setting suggests that high salinity, basinal brines should have been available at this time. Zones of potassic alteration with associated iron oxide-Cu-Au mineralization were formed after the magnetite-apatite deposits during a period of increased regional extension. While some of these systems overprint magnetite-apatite systems (as at Productura), others are spatially distinct from these earlier systems (Candelaria area). The iron oxide-Cu-Au systems appear to display a spatial (and temporal) relationship with intermediate intrusions which probably provided the thermal energy for large-scale convection cells. These iron oxide-Cu-Au systems were locally overprinted by Cu-Au mineralization associated with sodic-calcic (Candelaria; Ullrich & Clark, 1998) or continued potassic (Productura; Fox, 2000) alteration. This Cu-Au mineralization appears to have formed in zones of fluid mixing involving influx of a highly saline fluid, perhaps a derivative of the burial metamorphic fluid or fluid derived from continued dewatering of adjacent evaporite-bearing basins. Thus, the formation of the iron oxide-Cu-Au systems may require the availability of several distinct fluids. At least one of these fluids (high salinity, copper-rich fluid) may not be directly related to magmatism.

Pliocene of the High Andes of Northern Chile - Northern Argentina

Northern Chile has remained in a dominantly compressional regime during most of the Tertiary (Jordan et al., 1997) though this did not result in major uplift of the area until the Oligocene (Gregory-Wodzicki, 2000). The magmatic arc reached the area of the current high Andes during the Miocene. This coincided with the formation of evaporites in enclosed saline lakes in the Puna (high plateau) area of northern Chile and Argentina (Vanderoort et al., 1995). The Puna experienced a burst of intensive ignimbritic magmatism between 12 and 5 Ma (Coira et al., 1982; Allmendinger et al., 1997). This was followed by eruption of minor mantle-derived basalts between 2 and 3 Ma. Kay & Kay (1993) suggest the these mafic volcanic rocks, together with the evidence for concurrent extension (Marrett et al., 1994), signal a period of delamination of the lower crust and associated underplating by mantle-derived melts.

The El Laco magnetite-apatite deposits (over 500 Mt of 98 percent magnetite) occur in Pliocene rocks at the western edge of the Puna (Park, 1961; Haggerty, 1970; Henríquez & Martin, 1978; Frutos, et al., 1990; Rhodes et al., 1999). The age of the volcanic rocks hosting the deposits is approximately 2 Ma (Maksaev et al., 1988). Across the border to the southeast in Argentina, the recently discovered Rio Grande and Arizaro iron oxide-Cu-Au prospects (Mansfield Minerals Inc., 2000) occur in rocks which are probably Pliocene to Pleistocene in age. The El Laco deposit is characterized by early sodic-potassic alteration which is overprinted by calcic (diopside-rich) alteration associated with magnetite mineralization (Rhodes et al., 1999). At Rio Grande and Arizaro, sodic-calcic alteration is associated with magnetite and weak copper mineralization. This event appears to be cut by potassic alteration with copper-gold.

As demonstrated by Rhodes et al. (1999), the El Laco deposits appear to have formed by metasomatic replacement of andesite as well as by possible precipitation of magnetite from surface hot springs. Isotopic results indicate that the hydrothermal fluids could have been heated, closed-basin waters or deep-seated (possibly magmatic) fluids which reacted with buried evaporite deposits which are present in the area (Stoertz & Eriksen, 1974; Alonso et al., 1991). The Rio Grande and Arizaro prospects occur within a volcanic edifice that protrudes through the nearly 1-km-thick, halite-dominated, evaporite-filled Salar de Arizaro (Vandervoort, 1997). The presence of copper and gold at the Rio Grande and Arizaro prospects may indicate that in these areas, large volumes of surficial waters were present during the formation of the hydrothermal cell in contrast to a "dryer" setting at El Laco. The fluids at Rio Grande and Arizaro were able to scavenge both copper and gold from adjacent wall rocks, which include nearby porphyry copper deposits (Mansfield Minerals Inc., 2000).

The Pliocene magnetite-apatite and iron oxide-Cu-Au systems of the Puna appear to be genetically related. The deposits clearly display a spatial link to magmatism. Igneous rocks in both the El Laco and Rio Grande areas appear to be andesites to dacites that, where unaltered, are indistinguishable from surrounding volcanic rocks. This suggests that magmatism's most important role is as a driver of hydrothermal circulation. While highly saline fluids, probably derived from lacustrine evaporites, appear to be necessary to form the magnetite deposits, an additional fluid, probably also saline and containing copper and sulfur, is required to form the iron oxide-Cu-Au deposits. Tectonically, the deposits are associated with regional extension.

Other Deposits Which May Be in the Iron Oxide-Cu-Au Family

While the vast majority of deposits classified as belonging to the iron oxide-Cu-Au family fall within one of the tectonic environments listed above, there are several intriguing deposits and districts which appear to be located in other types of environments or have other controls. These deposits include: the iron oxide-Cu-Au-U breccia pipes of the Wernecke Mountains, Yukon, Canada (Laznica and Edwards, 1979; Hitzman et al., 1992) ; the iron oxide-Cu-U breccia pipes of the Mount Painter area of Australia (Coats & Blisset, 1971; Lambert et al., 1982); the Vergenoeg iron oxide-fluorite deposit in South Africa (Crocker, 1985; Borrok et al., 1998); and possibly the Bayan Obo iron oxide-LREE deposit in China (Drew et al., 1990).

The Wernecke and Mount Painter deposits formed in thick sedimentary basins which lack significant volcanic or intrusive rocks. Both basins are currently deformed but the extent of deformation at the time of mineralization or the relationship of deformation to mineralization is presently unclear. In both districts it appears that the breccia bodies may be directly related to diapiric intrusion of salt as salt domes and salt walls. Though no significant igneous rocks are recognized with the Wernecke breccias, sulfur and carbon isotopic compositions suggest a magmatic component to the hydrothermal systems (Hitzman, 1992). Thus it is possible that these districts represent preserved high-level remnants of a weakly deformed orogenic basin collapse system.

The Vergenoeg deposit, which occurs in volcanic rocks which are co-magmatic with the underlying Bushveld Complex, appears to be directly related to magmatism. The ore fluids are highly saline and high temperature, indicating that hydrothermal fluids directly related to a magma can form magnetite-apatite-type deposits (Borrok et al, 1998). The genesis of the Bayan Obo magnetite-LREE deposit is unclear. Genetic models include syngenetic mineralization in the Middle Proterozoic (Zhongxin et al., 1992), metasomatic replacement during the Caledonian (Chao et al., 1992), and metasomatic replacement associated with carbonatite emplacement (Drew et al., 1990). Without additional studies it is difficult to establish whether this deposit should be included with other iron oxide-Cu-Au systems.

Discussion

The close spatial relationship of the magnetite-apatite ("Kiruna-type") deposits with iron oxide-Cu-Au deposits, combined with the presence of large amounts of replacive iron oxides and commonly similar alteration types in both deposit types, strongly suggests they are genetically linked. Geochronological evidence, however, indicates that they are not always temporally associated, even when there is spatial coincidence of the deposits. While nearly all the magnetite-apatite deposits throughout the world are generally similar in style of mineralization and alteration, the iron oxide-Cu-Au deposits display great variability. This suggests that there are fundamental differences between the two types of deposits.

The magnetite-apatite deposits are generally closely related in time and space to mafic to felsic intrusive rocks. Ore fluids in these deposits appear to have been relatively high temperature, oxidized, sulfide-poor, and saline. While such fluids could be magmatic (as evidenced by Vergenoeg), in many districts it appears that the ore fluids represent a mixture of magmatic with highly saline "basinal" fluids (Barton and Johnson, 1996). It is probable that the magnetite-apatite deposits form in a spectrum of environments from those with relatively small alteration zones directly related to dominantly dioritic intrusions (such as some of the Chilean iron-magnetite deposits) to larger-scale systems with large alteration envelopes derived from more regional fluid flow.

Because of the paucity of well studied iron oxide-Cu-Au deposits, the ore fluids for these deposits are more poorly characterized. Where good data exists, it appears that these deposits result from: 1) significant cooling of a fluid similar to that responsible for precipitation of magnetite-apatite and sodic or sodic-calcic alteration; 2) interaction of a fluid similar to that causing precipitation of magnetite-apatite with a cooler, copper-, gold-, and relatively sulfate-rich fluid of meteoric or "basinal" (metamorphic in the case of Chile?) derivation; or 3) a fluid unrelated to that responsible for the magnetite-apatite systems but which is also oxidized and saline, though probably cooler and sulfate-bearing. The variability of potential ore fluids, together with the diverse rock types in which these deposits are located, results in the wide variety of deposit styles and mineralogies.

Fluids for both magnetite-apatite and iron oxide-Cu-Au systems appear to be derived from large volumes of relatively oxidized rock. In order to form an iron oxide-Cu-Au system, the oxidized rock sequence undergoing regional alteration must contain source rocks (such as subaerial mafic volcanic rocks or red beds) capable of providing significant copper. Fluid flow in the majority of both the magnetite-apatite and iron oxide-Cu-Au systems is probably the result of large-scale hydrothermal systems initiated by major intrusive systems which are ultimately derived from crustal underplating by mantle-derived magmas. The depth of formation of both magnetite-apatite and iron oxide-Cu-Au systems appears to range from several kilometers (4-6 km) to the near surface. In some deep-seated systems, such as those in the Cloncurry district and the Lufilian arc, mineralization may have taken place concurrent with, or slightly after regional metamorphism. Fluid flow in such metamorphic regimes is problematic (Yardley, 1986). Though Etheridge et al. (1983) have proposed that convection may be possible in such systems, and detailed studies in some areas have demonstrated that significant mineralogical and chemical changes may occur over relatively large areas (Ferry, 1983; Graham et al., 1983), most workers believe these systems are single-pass. The concentration of regional sodic and sodic-calcic alteration around large scale, late deformation (extensional?) faults in the Cloncurry district suggests that such regional fluid flow may only be possible during the waning stages of metamorphism during a major extensional event which can provide increased, large-scale permeability. In the Mesozoic of Chile both magnetite-apatite and iron oxide-Cu-Au mineralization is concurrent with burial metamorphism but the deposits appear to have formed relatively shallowly, above the zone of maximum metamorphism.

It is clear that some porphyry copper systems contain alteration suites (sodic, calcic-sodic, and potassic) that mimic those of the magnetite-apatite and iron oxide-Cu-Au systems. Where well studied, it is apparent that these porphyry systems are hybrid magmatic-hydrothermal systems involving the influx of non-magmatic brines (Carten, 1986; Dilles & Einaudi, 1992; Barton et al., 2000). Thus, there is probably a spectrum of deposits stretching from classic porphyry copper deposits to examples of both the magnetite-apatite and iron oxide-Cu-Au systems. The critical factor for making an iron oxide-Cu-Au system is the influx of non-magmatic, oxidized, saline, and relatively copper-rich solutions.

Exploration Implications

Increased understanding of the genesis of these deposits can aid targeted geological exploration. Key exploration features for this family of deposits include:

1. Identification of basins, anorogenic magmatic provinces, or subduction-related continental margins containing a dominantly oxidized package of rocks including significant source rocks (subaerial mafic volcanic rocks and/or continental red beds) and, ideally, marine or lacustrine evaporites.
2. The presence of large volumes of magmatic rocks including evidence that magmatism was related to mantle-underplating.
3. The presence of magnetite-apatite systems (which are more common than iron oxide-Cu-Au systems) indicates the correct tectonic setting and is an extremely favorable indicator.
4. Iron oxide-Cu-Au systems will be stratigraphically higher, or temporally later, than the magnetite-apatite deposits.
5. Delineation of high-angle structures related to deep-seated faults. Splays off major faults or regionally subparallel fault zones in the hangingwalls of major faults appear to be the best target areas.
6. Identification of zones of sodic-potassic, potassic, or hydrolytic alteration which are associated with iron oxide-Cu-Au deposits.
7. In high-level systems, search for evidence of convection systems that involve alkaline, high-salinity lacustrine fluids.

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