

EVIDENCE OF A MAGMATIC FLUID AND METAL SOURCE FOR Fe-OXIDE Cu-Au MINERALISATION

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Abstract - Fe-oxide-Cu-Au deposits typically formed in continental arc and intracratonic tectonic settings, predominantly in the Proterozoic, but also during the Phanerozoic. The lack of reported evaporitic sequences in several major Fe-oxide-Cu-Au districts including the Gawler Craton and Stuart Shelf, Tennant Creek, Great Bear Magmatic Zone, and Carajás districts suggests that the presence of evaporites is not a prerequisite for the formation of these deposits.

Fluid inclusion studies of Fe-oxide-Cu-Au deposits typically indicate the presence of coexisting hypersaline and CO₂-rich fluid inclusions that may have originated by unmixing of an original H₂O-CO₂-salts fluid. At the Lightning Creek prospect in the Cloncurry district, these fluid types were generated during crystallisation of granitic sills that are associated with a major magnetite-rich vein system. Stable isotope data from Lightning Creek and a number of Cu-Au deposits in the Cloncurry district and elsewhere are compatible with formation of these deposits principally from magmatic-hydrothermal fluids. Syn- to post-mineralisation Na-Ca-rich fluids are present in many deposits, and may represent meteoric and/or connate fluids that mixed with the hypersaline magmatic fluids during or after mineralisation.

Fe-oxide-Cu-Au deposits form part of the spectrum of intrusion-related Cu-Au deposits that also encompasses porphyry Cu-Au deposits. The intrusive rocks associated with both types of mineralisation have several features in common, including a magnetite-series, high-K and mildly alkaline character and a range in composition from diorite to granite. In intracratonic environments, magmas are typically formed by high temperature partial melting of older igneous rocks triggered by intrusion of mantle-derived magmas into the crust. This promotes enrichment of the magmas in components such as U, F, Mo and REE, which may be enhanced by subsequent fractionation and ultimately transferred to the Fe-oxide-Cu-Au deposits that occur in these environments.

The incorporation of components derived from host rocks and/or non-magmatic fluids is a common feature of Fe-oxide-Cu-Au and porphyry Cu-Au deposits. Elements such as Fe, K, and Cu can be mobilised during sodic-calcic alteration caused by magmatic and non-magmatic fluids and may be contributed to the deposits. However, Fe-oxide-Cu-Au deposits, like porphyry Cu-Au deposits, are formed dominantly via magmatic-hydrothermal processes and contain an imprint of the nature of the parental intrusions and magmatic-hydrothermal fluids in their alteration and metal enrichment characteristics.

Introduction

The Fe-oxide-Cu-U-Au-REE class of ore deposits was recognised by Hitzman *et al.* (1992), who inferred that the deposits formed primarily in shallow crustal environments (<4-6 km) as expressions of deeper-seated, volatile-rich igneous-hydrothermal systems. The deposits were noted as being predominantly mid-Proterozoic in age, located in areas that were cratonic or continental margin environments, and in many cases linked to extensional tectonic regimes. The deposits are generally rich in Fe-oxides (magnetite or hematite), commonly with associated CO₃, Ba, P, or F minerals. Associated alteration tends to be sodic at deep

levels, potassic at intermediate to shallow levels, and sericitic/siliceous at very shallow levels (Hitzman *et al.*, 1992).

The Fe-oxide-Cu-U-Au-REE deposits have been proposed by Barton and Johnson (1996) to reflect the incorporation of ligands and metals into magmatic and/or non-magmatic fluids during interaction between fluids and evaporitic sequences. Within this model, the composition of the intrusive rocks exerts only a second order control on alteration and mineralisation, chiefly through the supply of heat necessary to drive hydrothermal convective systems. However, work on a variety of Fe-oxide-Cu-U-Au-REE

Table 1: Tonnage-grade and other data for selected Fe-oxide-Cu-Au deposits. + reserves only, does not include past production. * estimated.

Deposit	Tonnes (x 10 ⁶)	Cu (%)	Au (g/t)	Mineralisation styles	Associated metals	References
Chile						
Candelaria	366	1.08	0.26	Breccia, skarn	As, Mo, Pb, Zn	Ryan <i>et al.</i> , 1995
Mantos Blancos	100*	0.98		Breccia	Ag	Minorco Annual Report, 1997
Susana	>100	?		Diatreme breccia	Ag	Espinoza <i>et al.</i> , 1996
Manto Verde	110.8*	0.66		Breccia		Minorco Annual Report, 1997
Santos	19	1.7	0.4	Vein, breccia	Ag	Marschik and Fontboté, 1996
Minifta-Despreciada	3	16		Veins	Mo, U	Espinoza <i>et al.</i> , 1996
Europe						
Paithohavare	1.15	2.1	0.9	Breccia	Co	Lindblom <i>et al.</i> , 1996; Freitsch <i>et al.</i> , 1997
Bidjovagge	3	1.8	0.5	Vein, stockwork	REE, U, Te, Co, Ni	Bjørlykke <i>et al.</i> , 1987; Etner <i>et al.</i> , 1993
Aitik	300	0.4	0.2	Vein, breccia	Mo	Freitsch <i>et al.</i> , 1997
Australia						
Olympic Dam	2000	1.6	0.6	Diatreme breccia	Co, Ag, U, REE	Reeve <i>et al.</i> , 1990
Ernest Henry	166	1.1	0.54	Breccia	Co, Mo, REE	Ryan, 1998
Mount Elliott	2.47	3.7	2.1	Skarn, breccia	Co, Ni	Fortowski and McCracken, 1998
Starra	7.4	1.88	3.8	Ironstone-hosted	Co	Rotherham <i>et al.</i> , 1998
Osborne	11.2	3.51	1.49	Breccia, ironstone-hosted	Ag, Co, Mo, Bi, Te, Se, Hg, Sn	Adshead <i>et al.</i> , 1998
Greenmount	3.6	1.5	0.78	Vein, stockwork	Co	Krcmarov and Stewart, 1988
Eloise	3.1	5.5	1.4	Vein, breccia, stockwork	Ag, Co, Ni, Zn	Gold Gazette, February, 1995; Baker, 1998
Warrego	5	2.6	2	Ironstone-hosted	Bi	Gouleitch, 1975
Brazil						
Salobo	789	0.96	0.52	Breccia	Ag, Co, Mo, Ni, REE, U	Lindenmayer and Teixeira, 1999
Alemão	170	1.5	0.82	Breccia, alteration	Mo, U	Barreira <i>et al.</i> , 1999
Igarapé Bahia	23.4		2.9	Breccia		Tazava <i>et al.</i> , 1998
Sossego	219	2.19	1.14		Co, Ni	Mining Journal, February 18th, 2000
Cristalino	200*	1.4	0.25	Stockwork	Co, Ni	Huhn <i>et al.</i> , 1999
Pojuca	58	0.9		Ironstone-hosted, veins	Au, Co, Ni, Mo, Zn	Winter, 1994

deposits has suggested that they are primarily products of magmatic-hydrothermal fluid systems (e.g. Ménard, 1995; Lindblom *et al.*, 1996; Rotherham *et al.*, 1998; Baker, 1998; Borrok *et al.*, 1998), without a requirement for involvement of evaporitic ligand sources.

Recent work in the Cloncurry district of northwest Queensland (Pollard *et al.*, 1998; Perring *et al.*, 2000) has indicated links between Fe-oxide-Cu-Au mineralisation and a group of mildly alkalic, K-rich, magnetite-series, metaluminous intrusive rocks that show evidence for the generation of fluids rich in Fe and Cu during crystallisation. These rocks are similar to intrusive rocks associated with Cu-Au mineralisation (e.g. porphyry Cu-Au) elsewhere, and suggest that Fe-oxide-Cu-Au deposits form part of a spectrum of granitoid related Cu-Au deposits that spans a range of crustal depths and tectonic settings. Within this context, the nature of the intrusive rocks linked to Fe-oxide-Cu-Au deposits merits much greater scrutiny, and could be viewed as a primary control on some of the characteristics of the deposits. If Fe-oxide-Cu-Au and porphyry Cu-Au deposits are both primarily products of magmatic-hydrothermal systems, then questions also arise as to the nature of the links between these two types of Cu-Au deposits.

This paper focuses on Fe-oxide-Cu-Au deposits, examining evidence for the nature of the hydrothermal fluids, the source of the fluids, the nature of the associated intrusive rocks, and comparisons with porphyry Cu-Au deposits. It is suggested that the development of these two styles of mineralisation is largely related to the composition and evolution of the granitoids and hydrothermal fluids that contributed to ore formation. In porphyry Cu-Au systems, the fluids are commonly hypersaline brines that evolved by boiling of magmatic-derived H₂O-salt fluids, while in Fe-oxide-Cu-Au systems, the fluids are commonly hypersaline brines that evolved by unmixing of magmatic-derived H₂O-CO₂-salt fluids. The variable CO₂ content of the parent magmas as evidenced by the nature of the hydrothermal fluids appears to be a key factor in the mechanical and physico-chemical evolution of the mineralising systems.

Characteristics of Fe-oxide-Cu-Au Deposits

The Fe-oxide-Cu-U-Au-REE class of deposits as defined by Hitzman *et al.* (1992) embraces a wide range of deposits linked essentially by their Fe-oxide-rich mineralogy (Table 1). For the purposes of this paper, deposits will be considered in two groups, massive Fe-oxide±apatite deposits that commonly contain only traces of Cu and Au mineralisation, and Cu-Au deposits (the focus of this paper) that mostly contain abundant Fe-oxides. The Cu-Au deposits commonly exhibit enrichment in a variety of other elements, including Co, Ni, As, Mo, W, U, LREE, and Te (e.g. Table 1).

Fe-oxide-Cu-Au mineralisation occurs in a variety of vein, stockwork, breccia, skarn and ironstone-hosted deposits (Table 1). Common sites for mineralisation at the regional

scale were second order structures oblique to major strike slip faults (e.g. Candelaria, Manto Verde, see Marschik and Fontboté, 1996; Vila *et al.*, 1996), with ore zones commonly localised within breccia zones formed by strain partitioning between more competent (e.g. ironstones, albitised rocks, volcanic and intrusive rocks) and less competent lithologies. Mineralisation also occurs within hydrothermal intrusive breccias and diatreme breccias (e.g. Olympic Dam (Australia), Susana and Buena Esperanza (Chile)), and may be present within breccia fragments and/or as a phase that overprints the breccia matrix.

Fe-oxide-Cu-Au deposits appear to form over a wide range of crustal depths, from near-surface environments such as at Olympic Dam (Reeve *et al.*, 1990), to depths around 10-15 km in the Cloncurry district (Pollard *et al.*, 1998; Perring *et al.*, 2000). In deeper-seated districts, there is commonly widespread development of sodic and/or sodic-calcic alteration characterised by the development of alteration minerals including albite, clinopyroxene, amphibole, scapolite, and titanite (Oliver *et al.*, 1993; De Jong and Williams, 1995; Freitsch *et al.*, 1997). The early sodic and sodic-calcic alteration is commonly overprinted by potassic alteration characterised by biotite and/or K-feldspar.

In many deposits, magnetite is an abundant phase that overprints early sodic and potassic alteration, consistent with magnetite formation under conditions of high temperature and low activities of reduced sulphur, similar to those in many porphyry Cu-Au deposits. Sulphide mineralisation overprints magnetite, and the main hypogene copper-bearing phases are generally chalcopyrite and bornite.

In shallow level districts, particularly where surface-derived fluids gained access to hydrothermal systems, alteration is dominantly sericitic, and the main Fe-oxide phase is typically hematite (hematite-sericite systems). Mineralisation occurs in hydrothermal intrusive breccias, diatreme breccias, veins and mantos (Reeve *et al.*, 1990; Espinoza *et al.*, 1996). The manto deposits typically occur in vesicular and volcanoclastic rocks, with sulphides dominated by hypogene chalcocite filling vesicles and other open spaces (Espinoza *et al.*, 1996). Copper-bearing phases in the shallow level systems commonly include early chalcopyrite and/or bornite, with later high-sulphidation state minerals such as digenite, covellite and chalcocite commonly in a zonal arrangement (Reeve *et al.*, 1990; Haynes *et al.*, 1995; Espinoza *et al.*, 1996). Barren or low-grade hematite-quartz or hematite may be present in the uppermost parts of these systems (Reeve *et al.*, 1990; Haynes *et al.*, 1995; Espinoza *et al.*, 1996).

Individual districts can encompass a range of depth environments characterised by different alteration and mineralisation styles. The Gawler Craton and Stuart Shelf include very shallow level deposits such as Olympic Dam, as well as deeper magnetite-rich systems such as Manxman. Northern Chile is another region where shallow level hydrothermal intrusive breccia hosted, hematite-rich systems (e.g. Susana (Espinoza *et al.*, 1996) and deeper, magnetite-rich systems (e.g. Candelaria; Ryan

et al., 1995) are present. Some deposits also contain evidence for different alteration/mineralisation styles in deeper and shallower parts. For example, Olympic Dam contains magnetite, pyrite and chalcopyrite mineralisation at deeper levels, and this also occurs as clasts in breccias that are overprinted by hematite and bornite-chalcocite mineralisation (Reeve *et al.*, 1990; Oreskes and Einaudi, 1990).

Detailed studies of individual deposits suggest several different mechanisms of sulphide and gold precipitation, and these can strongly influence metal ratios, grades and the potential size of deposits. Metal precipitation caused by fluid unmixing appears to be common (e.g. Bidjovagge (Ettner *et al.*, 1993), Pahtohavare (Lindblom *et al.*, 1996)), and the 2:1 Cu:Au ratio (Cu %:Au g/t) that is a feature of the larger deposits in the Cloncurry district (Table 1) may reflect fluid unmixing as the dominant metal precipitation process (Pollard *et al.*, 1997b).

In some deposits, there is evidence for the presence of early, magmatic-derived fluids and later, meteoric fluids (e.g. Olympic Dam (Oreskes and Einaudi, 1992), Emmie Bluff (Gow *et al.*, 1994)) and/or evidence of mixing of magmatic and other fluids during mineralisation (e.g. Tennant Creek deposits (Huston *et al.*, 1993), Candelaria (Ullrich and Clark, 1999)). Fluid reductants including magnetite ironstones (Huston *et al.*, 1993; Rotherham *et al.*, 1998) or graphitic metasediments (Ettner *et al.*, 1993) can be a critical ingredient that contributes to metal precipitation from highly oxidised fluids. This can lead to significant gold enrichment relative to other deposits, e.g. Starra (Rotherham *et al.*, 1998) and Tennant Creek deposits (Huston *et al.*, 1993). However, the deposits tend to be small because the fluid needs to continuously access previously unreacted rocks in order for the fluid reduction process to continue, and such active structural environments appear to be rare.

Some deposits show evidence for extensive chalcopyrite alteration of earlier magnetite as at Alemão (personal observation, 2000), or Fe-rich silicates (biotite, amphibole) as at Eloise (Baker, 1998). This can lead to significantly higher grade than if the sulphides had formed only as infill, and is similar to the sulphidation and grade enhancement that is common in magnetite skarns associated with porphyry Cu-Au systems.

Fluids and Alteration in Fe-oxide-Cu-Au Deposits

Fluid inclusion work on Fe-oxide-Cu-Au and Fe-oxide±apatite deposits consistently indicates the presence of coexisting, high-temperature, hypersaline and CO₂-rich fluid inclusions in pre- and syn-ore hydrothermal minerals (Table 2). This has been observed in deeper-seated Cu-Au deposits such as Osborne (Adshead *et al.*, 1998) and shallow level deposits such as Olympic Dam (Conan-Davies, 1987). Similar fluid inclusions are also reported from Fe-oxide±apatite deposits formed at deep levels, such as Lightning Creek (Perring *et al.*, 2000)

and shallow levels, such as Vergenoeg (Borrok *et al.*, 1998). The hypersaline and CO₂-rich fluids are commonly interpreted to have formed by unmixing of an original H₂O-CO₂-salts fluid (Ettner *et al.*, 1993; Oliver, 1995; Adshead *et al.*, 1998).

Stable isotope compositions inferred for the hydrothermal fluids in Fe-oxide-Cu-Au deposits (see below) are consistent with a magmatic source, and suggest that the original fluid was derived from a CO₂-bearing magma. This CO₂-bearing character of the hydrothermal fluids contrasts with the commonly very low abundances of CO₂ observed in fluid inclusions from porphyry copper systems (Beane and Bodnar, 1995). The low solubility of CO₂ in granitic magmas (Holloway, 1976) suggests that CO₂-bearing magmas will generate a fluid phase at higher temperature and pressure compared with CO₂-free magmas. This provides a simple explanation for the wide depth range for Fe-oxide-Cu-Au deposits compared to porphyry Cu-Au deposits.

The timing and mechanism of fluid saturation in the magmas and subsequent fluid unmixing has not been well-established in Fe-oxide-Cu-Au districts. Pressure decrease during upward intrusion of the magmas may be a major cause of CO₂ saturation, and would result in partitioning of water, chlorine and metals to the fluid phase. Since CO₂ promotes fluid saturation at an earlier stage than in CO₂-free magmas, the fluids generated from CO₂-bearing magmas may have a greater opportunity to extract copper from the magma prior to its incorporation in crystallising biotite.

In porphyry Cu-Au systems the fluids are commonly very low in CO₂ and early alteration is dominantly potassic due to increasing equilibrium Na/(Na+K) in the fluids with decreasing temperature, i.e. falling temperature promotes potassic alteration of the rocks (Orville, 1963). In Fe-oxide-Cu-Au systems the CO₂-bearing character of the fluids promotes a different evolution because the H₂O-CO₂-salts fluids will unmix due to decreases *in pressure* and/or temperature, resulting in partitioning of CO₂ to the vapour phase and salts to the liquid phase (Bowers and Helgeson, 1983). Ettner *et al.* (1993) described unmixing of CO₂-H₂O-salt fluids by decompression, prior to albitisation of the wall rocks, to form CO₂ and H₂O-salt fluids in the Bidjovagge Cu-Au deposit. Pollard (2000) proposed that albitisation results from unmixing because the CO₂-bearing fluids are likely to have a higher Na/(Na+K) equilibrium ratio than similar CO₂-free fluids as indicated experimentally by Iiyama (1965). Following removal of CO₂ by unmixing, the hypersaline fluid will have Na/(Na+K) greater than the equilibrium value for the conditions and will cause albitisation of feldspars. Albitisation due to unmixing will give way at lower temperatures to potassic alteration due to increasing equilibrium Na/(Na+K) in the fluid phase with decreasing temperature in Cl-bearing fluids (Orville 1963). If cooling is rapid (e.g. at shallower levels), the high Na/(Na+K) in the original carbonic fluid may be counteracted by decreasing temperature, resulting in little or no albitisation. This model is consistent with albitisation being caused by

Table 2: Fluid inclusion data from iron-oxide-copper-gold deposits and districts. Hypersaline is used to refer to fluid inclusions containing multiple solid phases. Modified from Pollard (2000)

Deposit/District	Host minerals	Primary fluid inclusion types	Reference
Candelaria, Chile	Quartz	1. CO ₂ 2. Hypersaline	Ullrich and Clark, 1999
Salobo, Brazil	Quartz	1. CO ₂ ± CH ₄ 2. 39-52 wt.% eq. NaCl	Lindenmayer and Teixeira, 1999
Bidjovagge, Norway	Quartz	1. CO ₂ ± CH ₄ -N ₂ 2. CH ₄ 3. H ₂ O-NaCl-CaCl ₂ ±CO ₂ -CH ₄ (Cu-Au mineralisation - 25 wt.% NaCl+CaCl ₂ ; Au-Cu mineralisation - 30-45 wt.% eq. NaCl)	Ettner <i>et al.</i> , 1993; Ettner <i>et al.</i> , 1994
Pahtohavare, Sweden	Quartz	1. CO ₂ 2. Hypersaline 3. H ₂ O-NaCl-CaCl ₂	Lindblom <i>et al.</i> , 1996
Vergenoeg, South Africa	Fluorite	1. CO ₂ 2. Hypersaline	Borrok <i>et al.</i> , 1998
Olympic Dam, South Australia	Quartz	3. CO ₂ 4. Hypersaline	Conan-Davies, 1987
Mary Kathleen fold belt, Australia	Quartz	1. CO ₂ 2. CO ₂ -H ₂ O-CaCl ₂ (35 wt.% eq. CaCl ₂) 3. NaCl-H ₂ O-CaCl ₂ -KCl (>30 wt.% eq. NaCl)	Oliver, 1995
Cloncurry deposits			
Osborne	Quartz	1. CO ₂ 2. Hypersaline 3. 20-37 wt.% eq. NaCl	Adshead <i>et al.</i> , 1998
Starra (ironstone)	Quartz	1. CO ₂ 2. 34-52wt.% eq. NaCl	Rotherham <i>et al.</i> , 1998
Lightning Creek	Quartz	1. CO ₂ 2. Hypersaline	Perring <i>et al.</i> , 1999
Eloise	Quartz	1. CO ₂ +H ₂ O 2. Hypersaline 3. 30-47wt.% eq. NaCl	Baker, 1998

fluids that were derived from potassic intrusive rocks and evolving on a down temperature path. Thus, the common occurrence of early albitisation overprinted by potassic alteration in Fe-oxide-Cu-Au deposits is a reflection of the evolution of the original CO₂-bearing magmatic fluids, without any necessity for the involvement of components derived from evaporitic rocks (Pollard, 2000).

Sources of Components in Fe-oxide-Cu-Au Deposits

Barton and Johnson (1996) proposed that Fe-oxide-Cu-Au deposits derived components from evaporitic rocks via circulation of magmatic and/or non-magmatic fluids. However, in their study of carbonate-evaporite rocks in the Mary Kathleen fold belt (Australia), Oliver *et al.* (1992) concluded that the preservation of large volatile activity gradients at outcrop scales requires that individual layers did not reach equilibrium with fluid produced by other layers to any significant degree, and that the rocks were

not infiltrated by any significant volume of externally derived fluid (Oliver *et al.* 1992). This is in marked contrast to sodic(-calcic)-altered rocks in the same region, where oxygen and carbon isotope data provide evidence for circulation of large volumes of isotopically homogeneous fluids that were probably released from crystallising magmas (Oliver *et al.* 1993). In the adjacent Cloncurry district, Mark and Foster (2000) have documented the development of albite-actinolite-apatite-rich rocks associated with crystallisation of an aplite-pegmatite complex, while Perring *et al.* (2000) described sodic-calcic alteration of intrusive rocks that was considered to be autometamorphic in origin. Oxygen and hydrogen isotope data from these sodic-calcic mineral assemblages are compatible with precipitation from magmatic fluids (Mark and Foster, 2000; Perring *et al.*, 2000), while data for sodic-calcic minerals from veins and breccias within metasediments suggest variable degrees of interaction of magmatic fluids with the host metasediments (Pollard *et al.*, 1997a).

Oxygen and hydrogen isotope analyses of pre-ore and syn-ore hydrothermal minerals have been reported from a number of Fe-oxide-Cu-Au deposits (and Fe-oxide-apatite deposits). These are consistent with a dominantly magmatic source for the hydrothermal fluids, commonly with indications of meteoric or connate fluids in the later stages (e.g. Olympic Dam (Oreskes and Einaudi, 1992), Tennant Creek (Huston *et al.*, 1993), Emmie Bluff (Gow *et al.*, 1994), Eloise (Baker, 1996), Great Australia (Cannell and Davidson, 1998), Starra (Rotherham *et al.*, 1998), Vergenoeg (Borrok *et al.*, 1998), Lightning Creek (Perring *et al.*, 2000). Similarly, sulphur isotope data for sulphides and sulphates from Fe-oxide-Cu-Au deposits are also generally interpreted to reflect a magmatic source for the sulphur (e.g. Starra (Rotherham *et al.*, 1998), Eloise (Baker, 1996), Aitik (Freitsch *et al.*, 1997), Tennant Creek (Huston *et al.*, 1993), Candelaria (Ullrich and Clark, 1999). A role for sulphur from non-magmatic sources has also been proposed for Olympic Dam (Haynes *et al.*, 1995), some Cloncurry deposits (Pollard *et al.*, 1997a) and late stage fluids at Candelaria (Ullrich and Clark, 1999).

Perring *et al.* (2000) found that H₂O-CO₂-salts fluids were exsolved from monzogranite magma during crystallisation of granitic sills at the Lightning Creek prospect in the Cloncurry district. The fluid unmixed to form hypersaline and CO₂-rich fluids that formed a major quartz-magnetite ± clinopyroxene ± albite ± apatite ± titanite vein system containing very minor, overprinting pyrite and chalcocopyrite (Perring *et al.*, 2000). PIXE analysis indicates that primary, hypersaline fluid inclusions hosted by quartz in one of the sills contain approximately 1 wt.% Cu and 10 wt.% Fe in addition to abundant Na, K, Ca and Cl (Perring *et al.*, 2000). This provides direct evidence that magmatic hydrothermal fluids generated during crystallisation of monzogranite sills at Lightning Creek were strongly enriched in Cu, Fe and other components necessary to form the Fe-oxide-Cu-Au deposits elsewhere in the district.

At the Olympic Dam deposit, Johnson and McCulloch (1995) used Sm-Nd isotope data to infer that a proportion of the REE and Cu were sourced from mafic or ultramafic rocks or magmas similar to those intruded before, during and after formation of the mineralisation. Sm-Nd data from Tennant Creek also imply a contribution of REE and by implication, ore metals from a primitive source (Skirrow, 1999).

In Fe-oxide-Cu-Au districts, there is now a large, and growing body of evidence to indicate that fluids derived from contemporaneous magmas played a major role in the formation sodic-calcic alteration and Cu-Au mineralisation. This suggests that Fe-oxide-Cu-Au deposits can be viewed as part of a spectrum of intrusion-related Cu-Au deposits that also includes porphyry Cu-Au deposits.

Intrusive Rocks Associated with Fe-oxide and Porphyry Cu-Au Deposits

The majority of large porphyry Cu-Au deposits occur in continental and island arc terrains, and range in age from Ordovician to Pleistocene (Sillitoe, 1997), while the majority of Fe-oxide-Cu-Au deposits are Proterozoic in age (Table 1) and typically formed in intracontinental tectonic settings. However, Fe-oxide-Cu-Au deposits are also known from Phanerozoic and Proterozoic continental arc settings (Hildebrand, 1986; Hitzman *et al.*, 1992). The overlap in the two types of deposits in terms of age and tectonic setting is best represented in the coastal batholith of northern Chile, which contains both types of deposits.

The intrusive rocks linked to mineralisation in both porphyry Cu-Au and Fe-oxide-Cu-Au deposits, span a broad compositional range encompassing diorite, monzodiorite, monzonite and monzogranite (Sillitoe, 1997; Pollard *et al.*, 1998; Perring *et al.*, 2001). The intrusives linked to porphyry Cu-Au mineralisation are I-type, magnetite-series rocks that include calc-alkaline, high-K calc-alkaline

Table 3: Compositions of intrusive and extrusive rocks in iron-oxide-copper-gold-uranium-gold-REE districts.

District	Age	Mineralisation	Associated igneous rocks	References
Durango, Mexico	Tertiary	Fe	Rhyolite	Lyons, 1988
Southeast Missouri, U.S.A.	Proterozoic	Fe	Granite, rhyolite	Emery, 1968
Bushveld Complex, South Africa	Proterozoic	Fe	Alkali feldspar granite	Borrok <i>et al.</i> , 1998; Pollard <i>et al.</i> , 1991
Iron Springs, U.S.A.	Miocene	Fe	Quartz monzonite	Barker, 1995
Great Bear Magmatic Zone, Canada	Proterozoic	Fe, Fe-Cu-Au	High-K diorite to quartz monzonite	Hildebrand, 1986
Gawler Craton/Stuart Shelf, Australia	Proterozoic	Fe, Fe-Cu-Au	High-K quartz monzodiorite, granite, mafic, ultramafic	Creaser, 1996; Reeve <i>et al.</i> , 1990; Johnson and McCulloch, 1995
Cloncurry, Australia	Proterozoic	Fe, Fe-Cu-Au	High-K diorite to syenogranite	Pollard <i>et al.</i> , 1998; Perring <i>et al.</i> , 2000
Norbotten, Sweden	Proterozoic	Fe, Fe-Cu-Au	Alkali syenite, rhyolite porphyry	Cliff <i>et al.</i> , 1990
Coastal Batholith, Chile	Cretaceous	Fe, Fe-Cu-Au	Gabbro to granite	Espinoza <i>et al.</i> , 1996; Ménard, 1995

and shoshonitic suites Müller and Groves, 1993; Sillitoe, 1997; Blevin, 1998). These magmas may have originated by partial melting of subducted oceanic crust and/or the overlying mantle wedge, with variable contributions from continental crust. This type of environment tends to produce magmas with high S and low F and CO₂/H₂O (see Harris, 1982). Fe-oxide-Cu-Au deposits are typically related to I-type, magnetite-series granitoids formed by partial melting of older igneous material in the middle to lower crust with a variable mantle input (Ramo and Haapala, 1995; Creaser, 1996; Pollard *et al.*, 1998). This tends to produce magmas with low S and high F and CO₂/H₂O. In the Cloncurry district, the intrusive rocks associated with Cu-Au mineralisation range from alkaline to subalkaline (as defined by Irvine and Barragar, 1971), and are calc-alkaline, high-K to shoshonitic in character (Pollard *et al.*, 1998).

In reduced (ilmenite-series) magmas, sulphide droplets can form and strip elements which favour sulphide melts from the silicate melt (e.g. Cu, Pb, Zn, and Au) (e.g. Blevin and Chappell, 1992). These droplets may eventually crystallise as pyrrhotite. In the more oxidised (magnetite-series) magmas associated with copper-gold deposits, SO₂/H₂S is higher, and the higher solubility of sulphur allows chalcophile elements to remain within the melt during magma evolution. Thus, copper concentrations can increase in oxidised magmas that evolve via fractionation of plagioclase, olivine, pyroxene, hornblende and magnetite because the bulk distribution coefficient will be in favour of the melt. However, copper partitions strongly into biotite and the appearance of biotite as a liquidus phase could cause copper depletion during fractionation (Stanton, 1994). The generation of a magmatic fluid phase results in partitioning of metals and other components between melt and fluid. Partitioning behavior depends on temperature, pressure, *f*O₂ and fluid composition, but for most metals is strongly in favour of a chloride-rich aqueous fluid phase. The partitioning of copper is proportional to the chloride concentration, and copper extraction is most efficient when the volatiles are evolved early in the crystallisation of the melt (Candela and Holland, 1986), before copper is incorporated in crystalline phases such as biotite.

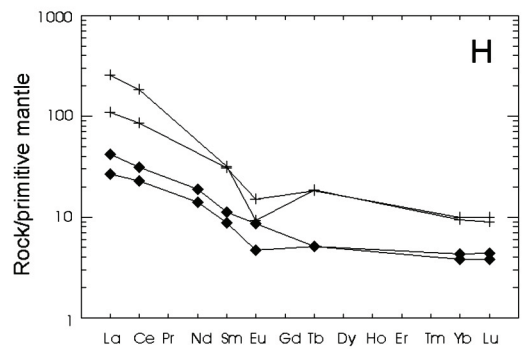
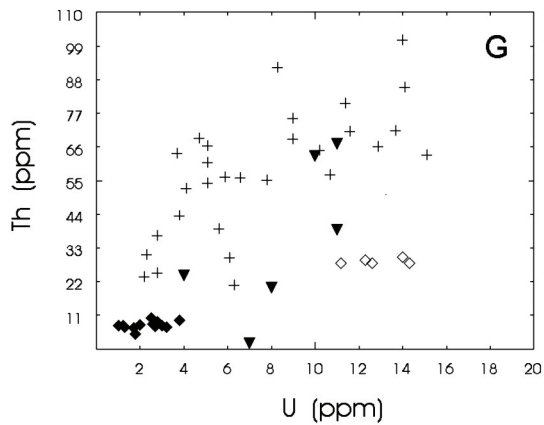
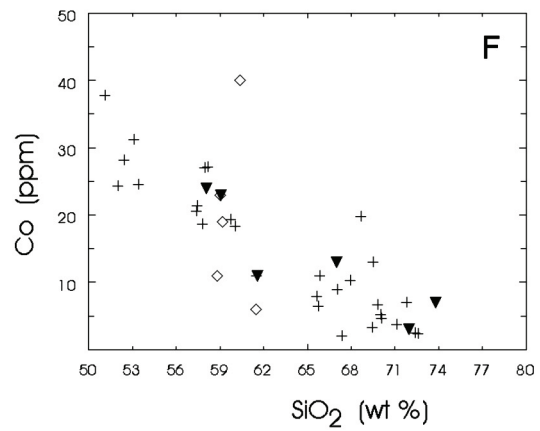
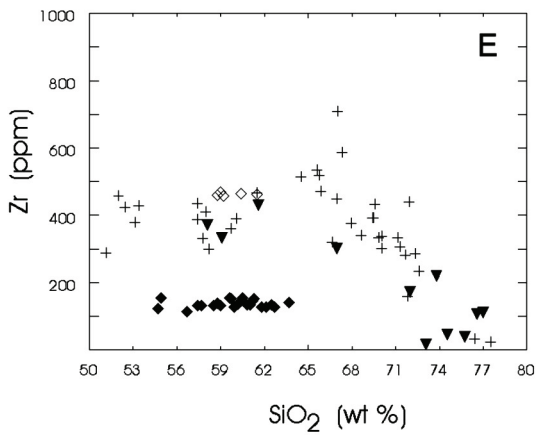
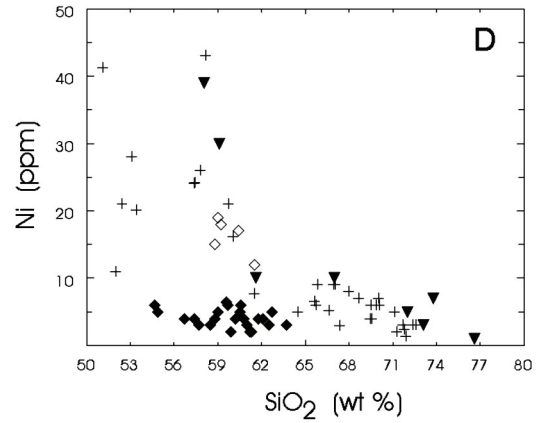
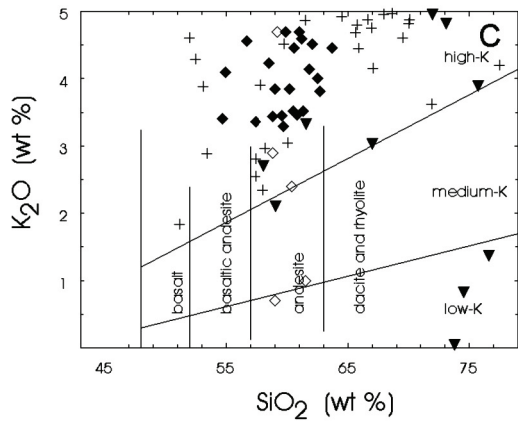
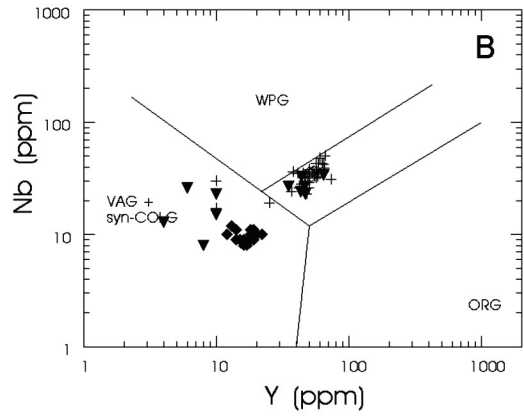
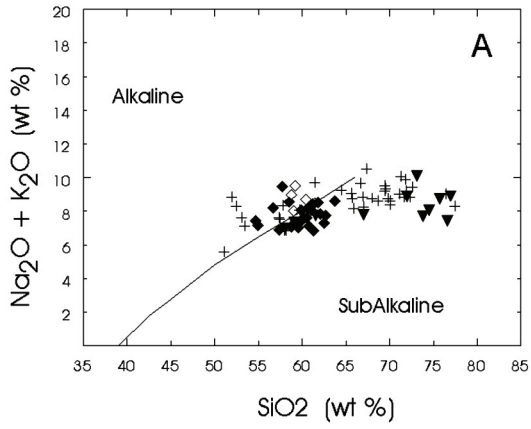
Wyborn and Sun (1994) related the alkali-rich character of magmas to higher intrinsic Fe³⁺:Fe²⁺ ratios and high sulphur solubility, and suggested that these characteristics were critical to generation and evolution of sulphur-undersaturated magmas that have the ability to concentrate copper and gold for release to hydrothermal fluids in the upper crust. When judged by these compositional parameters, the intrusive rocks associated with Fe-oxide-copper-gold deposits are the same as those associated with porphyry-copper-gold deposits (Fig. 1). Nevertheless, the environment of magma generation and the nature of the source material controls the composition of the magma, and magmas with different trace element characteristics are formed in different tectonic environments (Pearce *et al.*, 1984; Fig. 1). The trace element geochemistry of intrusive rocks linked to copper-gold deposits will therefore reflect their tectonic setting and the nature of the source materials, while their copper-gold mineralising potential is more closely related to oxidation state, magma evolution and the timing of magmatic fluid generation.

There are several distinctive geochemical features of the granitoids linked to Fe-oxide-Cu-Au deposits, especially those formed in intracratonic settings, that may help to explain some of the features of the deposits. The older, metaigneous rocks that are the principal source of many granitoids linked to Fe-oxide-copper-gold deposits (Creaser, 1996; Pollard *et al.*, 1998; Ramo and Haapala, 1995) typically require high temperatures to promote partial melting via biotite and amphibole breakdown. Melting of these minerals contributes water and fluorine to the magma (Creaser *et al.*, 1991). The high temperatures of partial melting also promote higher solubilities of refractory minerals such as Fe-Ti phases and zircon, leading to enrichment of the magmas in components concentrated in these minerals, including zirconium, titanium, uranium and rare earth elements (e.g. Keppler, 1993; Fig. 1). Enrichment in Fe (high Fe/Mg) is also a common feature (Ramo and Haapala, 1995).

Uranium and rare earth elements partition strongly into fluorine-rich fluids (Keppler and Wyllie, 1991) and may account for the enrichment of many deposits in these components (Table 1). Many deposits are also enriched in Mo and/or W (Table 1), which may reflect generation of parental magmas from older metaigneous rocks enriched during their prior magmatic history, as well as fractionation of the parent magmas.

Nickel and/or cobalt enrichment is a feature of some Fe-oxide copper-gold deposits (Table 1), and may partly reflect the composition of the source, where more felsic sources generate magmas with lower vanadium, chromium, cobalt and nickel compared to those generated from more mafic sources (Creaser *et al.*, 1991). In the Cloncurry district, deposits such as Mt Elliott and Eloise are significantly enriched in nickel and cobalt (typically thousands of ppm) compared to Ernest Henry which, in contrast, is enriched in fluorine, REE and molybdenum. At Mt Elliott there is evidence for intrusion of intermediate dykes during alteration and mineralisation (Wang and Williams, 2001; Drabsch, 1998) and nickel and cobalt enrichment could reflect derivation of the hydrothermal fluids from these intermediate magmas (Fig. 1), and/or leaching of nearby, older basic rocks. Other deposits in the district lacking strong nickel and cobalt enrichment may have formed from fluids derived from more evolved members of the same granitoid suite (e.g. Lightning Creek).

The above discussion suggests that some of the features of Fe-oxide-Cu-Au deposits reflect element enrichments that are due to the nature of the source rocks, conditions of partial melting, degree of fractionation and complexing of components by magmatic fluids. For example, F, U and REE enrichment, reflecting source and high temperature partial melting, is mainly a feature of deposits in intracratonic settings, while enrichment in Mo (source and fractionation) occurs in deposits from intracratonic and continental arc settings. Many of the Fe-oxide-Cu-Au deposits are probably linked to magmas that did not undergo significant biotite fractionation. In contrast, many of the large Fe-oxide±apatite deposits are closely associated with felsic igneous rocks (e.g. Borrok *et al.*, 1998; Table 3), and the low copper contents of these



+ Cloncurry Supersuite (Pollard *et al.*, 1998)
 ▼ Lightning Creek prospect (Perring *et al.*, 2001)

◇ Mount Elliott trachytes (Drabsch, 1998)
 ◆ Ertzberg District, Indonesia (McMahon, 1994)

deposits may reflect biotite fractionation in the parental magmas prior to fluid saturation, a lack of reduced sulphur, and/or high temperatures of Fe-oxide precipitation. Some Chilean magnetite±apatite deposits are associated with more basic rocks (Brookstrom, 1977; Ménard, 1995), and many of these contain a minor, overprinting sulphide component.

In continental arc settings, it can be anticipated that the magmas will exhibit a range of trace element characteristics reflecting mixtures of the potential sources (downgoing slab, overlying mantle wedge and/or continental crust, including older meta-igneous rocks), and that these may be passed through to the associated Cu-Au deposits. Mantle-derived mafic magmas are also associated with granitoids in continental arc and intracratonic environments (e.g. Arancibia and Clark, 1996; Pollard *et al.*, 1998), and these may also provide components to the Cu-Au deposits.

Links between Fe-oxide-Cu-Au and Porphyry Cu-Au Deposits

Fe-oxide-Cu-Au deposits and porphyry Cu-Au deposits represent parts of a broad spectrum of intrusion related magmatic-hydrothermal systems. Both types of deposits are so broadly defined that there is considerable scope for ambiguity in the classification of some deposits.

In porphyry Cu-Au systems, the fluids are commonly hypersaline brines which evolved by boiling of magmatic-derived H₂O-salt fluids. Although carbon dioxide-bearing inclusions have been reported (e.g. Graney and Kesler, 1995), their occurrence and distribution are poorly known (Beane and Bodnar, 1995). In Fe-oxide-Cu-Au systems, the fluids are commonly hypersaline brines which evolved by unmixing of magmatic-derived H₂O-CO₂-salts fluids. The variable CO₂ content of the parent magmas as evidenced

by the nature of the hydrothermal fluids appears to be a key factor in determining differences in the mechanical and physico-chemical evolution of the mineralising systems.

Fluids that are evolved at deeper levels by first boiling (Fe-oxide-Cu-Au systems) generate considerably less mechanical energy than fluids evolved at shallower levels by second boiling (porphyry systems)(see Burnham and Ohmoto, 1980). The repeated fracturing (stockwork development) due to fluid evolution at shallow levels that is proposed for porphyry systems (Burnham, 1979) is therefore unlikely to occur in Fe-oxide-Cu-Au systems. Instead, magmas were commonly emplaced at deep levels into hot terrains still cooling from peak metamorphism (Cloncurry, Gawler Craton, and Fennoscandia), where there was greater opportunity for fluid migration and interaction with the host rocks. Pre-existing structures were commonly reactivated, and new fracture systems tended to exploit competency contrasts and areas where strain partitioning created zones of brecciation in competent rocks.

At shallow levels, hydrothermal intrusive breccia and diatreme systems are common in both porphyry and Fe-oxide-Cu-Au systems. In porphyry systems, these may reflect release of a magmatic vapour phase from boiling within an underlying batholith or intrusion, while in Fe-oxide-Cu-Au systems they may reflect unmixing and generation of a CO₂ phase.

The CO₂-bearing character of hydrothermal fluids in Fe-oxide-Cu-Au systems promotes fluid separation from the magmas at higher pressure compared to the H₂O-rich fluids of typical porphyry Cu-Au systems. Albitisation occurs mainly in deeper level systems (Hitzman *et al.*, 1992) and reflects unmixing of the CO₂-bearing hydrothermal fluids (Pollard, 2000). Sodic and sodic-calcic assemblages are also reported from a number of porphyry Cu systems (Carten,

Figure 1: (Facing page) Chemical variation diagrams for intrusive rocks from the Cloncurry district, Australia (iron-oxide-copper-gold mineralisation) and the Ertsberg district, Indonesia porphyry copper-gold mineralisation.

- A. Silica – alkalis diagram (Irvine and Barragar, 1971) showing the alkaline to sub-alkaline character of the intrusive suites.
- B. Nb-Y diagram (Pearce *et al.*, 1984). Ertsberg district rocks plot in the volcanic arc field, while Cloncurry rocks, apart from strongly fractionated samples, plot in the within plate granite field.
- C. Silica-potassium diagram showing the high-K character of intrusive rocks from both districts, except for albitised samples from Mt Elliott and Lightning Creek.
- D. Silica-nickel variation diagram showing enrichment of less evolved Cloncurry rocks in Ni.
- E. Silica-zirconium diagram showing strong enrichment of Cloncurry rocks in Zr relative to rocks from the Ertsberg district.
- F. Silica-cobalt variation diagram for Cloncurry rocks showing compatible behaviour of Co.
- G. Uranium-thorium variation diagram showing enrichment of Cloncurry rocks in both elements relative to Ertsberg district rocks.
- H. Primitive mantle normalised rare-earth element diagram showing enrichment of Cloncurry samples in LREE

1986; Arancibia and Clark, 1996; Gustafson and Quiroga, 1995). Following the early stage sodic-calcic alteration, the evolution of many Fe-oxide-Cu-Au and porphyry Cu-Au systems is broadly similar, and both are commonly characterised by development of potassic alteration (biotite, K-feldspar), abundant magnetite and actinolite, and late sulphides. The major exceptions are the Fe-oxide-Cu-Au deposits, such as those in Scandinavia, where mineralisation is linked to albitisation, scapolitisation and carbonate alteration (Freitsch *et al.*, 1997).

There is a widespread perception that the Fe-oxide-Cu-Au deposits are “low-sulphur” deposits because they commonly contain abundant Fe-oxides and less pyrite than many porphyry-related deposits. The Fe-oxide rich character should be treated separately to the low pyrite character because in both types of systems, the sulphides typically overprint earlier Fe-oxides and the two are not directly linked. Thus, abundant Fe-oxide does not necessarily imply low sulphur in the fluids, because unusually high activities of reduced sulphur are required to stabilise pyrite relative to magnetite in most high-temperature (600°C) hydrothermal solutions (Borrok *et al.*, 1998). Similarly, in a survey of porphyry Cu-Au deposits in the circum-Pacific region, Sillitoe (1997) noted that 9 of the 11 major deposits contain 5% or more hydrothermal magnetite in the ore. Magnetite is also a major component of skarns linked to porphyry Cu-Au deposits (e.g. Ertsberg district, Rubin and Kyle, 1998). Clearly, magnetite enrichment is a feature common to Cu-Au deposits of both porphyry and Fe-oxide affiliation.

The perceived low pyrite content as a reflection of a low-sulphur character of the Fe-oxide-Cu-Au deposits relative to porphyry systems also requires careful consideration. Some of the more oxidised deposits contain abundant sulphate minerals such as barite and anhydrite (e.g. Olympic Dam), while many of the more reduced deposits, or parts of deposits contain abundant pyrrhotite (e.g. Osborne, Eloise, some Tennant Creek deposits), i.e. sulphur is tied up in phases apart from pyrite. Similarly, detailed examination of the paragenesis of the Grasberg Cu-Au deposit (Pollard *et al.*, 2000) indicates that the sulphides are dominated by chalcopyrite and bornite, and that pyrite is predominantly associated with an overprinting high-sulphidation Cu-Au system. Grasberg cannot be considered as a low-sulphur system because huge amounts of sulphur are present in anhydrite that predates chalcopyrite-bornite (Pollard *et al.*, 2000).

Discussion and Conclusions

Hitzman *et al.* (1992) described Fe-oxide-Cu-Au deposits as expressions of deeper-seated, volatile-rich igneous-hydrothermal systems. The accumulation of extensive data from a number of deposits and districts since that time strongly reinforces this conclusion. Numerous stable isotope studies have confirmed a dominantly magmatic source for the hydrothermal fluids and sulphur. In some cases, a role for additional fluids of meteoric and connate origin has been identified (e.g. Olympic Dam, Tennant

Creek), and some sulphur isotope data suggest incorporation of evaporite-derived sulphur in the hydrothermal system (e.g. Candelaria).

The lack of reported evaporites in several Fe-oxide-Cu-Au districts (e.g. Kautokeino greenstone belt (Ettner *et al.*, 1993), Gawler Craton and Stuart Shelf, Tennant Creek, Great Bear Magmatic Zone, Carajás district) suggests that they are not a prerequisite for the formation of these deposits.

In many Fe-oxide-Cu-Au deposits, magnetite formed before sulphide mineralisation. This reflects the high temperature and low activity of reduced sulphur in pre-ore hydrothermal fluids. In many cases, the Fe-oxides do not appear to play any crucial role in Cu-Au mineralisation. However, in some deposits, hematite formed synchronous with sulphides (and sulphates) through oxidation of earlier magnetite (Huston *et al.*, 1993; Rotherham *et al.*, 1998), indicating a critical role for the early magnetite as a fluid reductant.

The Fe-oxide-Cu-Au deposits share several features in common with porphyry Cu-Au deposits, including an association with a similar range of intrusive rocks, domination of high-salinity, high-temperature, magmatic fluids in the early stages of alteration/mineralisation, and similar parageneses concerning potassic alteration, magnetite and sulphide stages, especially in the magnetite-rich systems.

Features of Fe-oxide-Cu-Au systems that contribute to differences with porphyry Cu-Au systems include their common association with granitoids evolved from older crustal protoliths in cratonic environments, emplacement of the magmas into upper crustal environments that were in some cases still cooling following peak metamorphism, abundance of carbonates, barite and fluorite, and the involvement of H₂O-CO₂-salts fluids in alteration and mineralisation. The character of the magmas associated with Fe-oxide-Cu-Au deposits may promote enrichment in components such as U, F, Mo and REE, which may be enhanced by subsequent fractionation. Enrichments in components such as Co and Ni may reflect the degrees of fractionation in some of the parent magmas. The CO₂-bearing character of the magmatic fluids implies deeper level fluid saturation and early albitisation during unmixing. Fluids may have migrated large distances from source plutons and unmixed well below mineralised zones, such that albitisation is absent (Olympic Dam) or only observed in clasts that may have been transported upwards in intrusive breccia/diatreme systems (see Espinoza *et al.*, 1996).

The incorporation of components derived from host rocks and/or non-magmatic fluids is a common feature of Fe-oxide-Cu-Au systems because the deeper level of fluid generation allows greater opportunity for interaction between magmatic fluids, host rocks and/or external fluids. Detailed studies have shown that elements such as Fe, K, and Cu can be mobilised during sodic-calcic alteration (Aslund *et al.*, 1995; Mark, 1998), and may subsequently contribute to alteration and mineralisation. Externally derived fluids heated by igneous intrusions are capable of such alteration (Dilles and Einaudi, 1992) and may introduce components to the Cu-Au deposits. However, Fe-oxide-Cu-Au deposits,

like porphyry Cu-Au deposits, are formed dominantly via magmatic-hydrothermal processes and contain an imprint of the nature of the parental intrusions and hydrothermal fluids in their alteration and metal enrichment characteristics.

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