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ARTICLE

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An intrusion-related origin for Cu–Au mineralization in iron oxide–copper–gold (IOCG) provinces

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Abstract Major Cu–Au deposits of iron oxide–copper–gold (IOCG) style are temporally associated with oxidized, potassic granitoids similar to those linked to major porphyry Cu–Au deposits. Stable and radiogenic isotope evidence indicates fluids and ore components were likely sourced from the intrusions. IOCG deposits form over a range of crustal levels because CO_2-rich fluids separate from the magmas at higher pressures than in CO_2-poor systems, thereby, promoting partitioning of H_2O, Cl and metals to the fluid phase. At deep levels, the magma–fluid system cannot generate sufficient mechanical energy to fracture the host rocks as in porphyry systems and the IOCG deposits therefore form in a variety of fault-related structural traps where the magmatic fluids may mix with other fluids to promote ore formation. At shallow levels, the IOCG deposits form breccia and fracture-hosted mineralization styles similar to the hydrothermal intrusive breccias and sulphide vein systems that characterize many porphyry Cu–Au deposits. The fluids associated with IOCG deposits are typically H_2O–CO_2–salt fluids that evolve by unmixing of the carbonic phase and by mixing with fluids from other sources. In contrast, fluids in porphyry systems typically evolve by boiling of moderate salinity fluid to produce high salinity brine and a vapor phase commonly with input of externally derived fluids. These different fluid compositions and mechanisms of evolution lead to different alteration types and parageneses in porphyry and IOCG deposits. Porphyry Cu–Au deposits typically evolve through potassic, sericitic and (intermediate and/or advanced) argillic stages, while IOCG deposits typically evolve through sodic(–calcic), potassic and carbonate-rich stages, and at deeper levels, generally lack sericitic and argillic alteration. The common association of porphyry and IOCG Cu–Au deposits with potassic, oxidized intermediate to felsic granitoids, together with their contrasting fluid compositions, alteration styles and parageneses suggest that they should be considered as part of the broad family of intrusion-related systems but that they are typically not directly related to each other.

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Introduction

Iron oxide–copper–gold (IOCG) deposits have received considerable exploration attention due to the attractive size and grade of the larger examples. The deposits typically show a close temporal and spatial association with batholithic granitoids, but there is seldom an intimate association with particular intrusions as commonly is the case for skarn and porphyry copper deposits. An exception is the shallow-level Olympic Dam deposit that is hosted within granite and closely associated with emplacement of small volumes of felsic, mafic and ultramafic magmas (Haynes et al. 1995; Campbell et al. 1998).

Barton and Johnson (1996) proposed that IOCG deposits are formed from intrusion-driven hydrothermal systems which source components from evaporitic and other rocks in the host sequence. They also noted an apparently diverse character and tectonic setting of intrusive rocks in IOCG provinces and suggested that this militates against them playing an important role in mineralization other than as a potential source of heat. Pollard (2000) showed that intrusive rocks linked to IOCG deposits in the Cloncurry district (Australia) have similar geochemical features to intrusive rocks linked to porphyry Cu–Au deposits and this, together with isotopic studies favouring magmatic–hydrothermal fluids in deposit formation, was used to suggest a key role for intrusive rocks and magmatic-derived hydrothermal fluids in the genesis of IOCG deposits.

Studies of granitoid rocks linked to deposits of different metal associations indicate that they have specific mineralogical and chemical features especially with respect to oxidation state and degree of fractionation (e.g. Ishihara 1981; Lehmann 1990; Blevin and Chappell 1992, 1995).

This paper examines the nature of the intrusive rocks linked to major copper–gold deposits of IOCG style in several provinces worldwide using published information whose significance has been enhanced by recent geochronological and isotopic studies that indicate the importance of magmatic contributions to these major deposits. Comparison with intrusions associated with porphyry copper–gold deposits indicates close similarities and is consistent with a key role for intrusions as a source of components for the IOCG deposits.

Links between granitoids and IOCG deposits

Major copper–gold deposits of IOCG style (Tables 1 and 2) range in age from Archean to Mesozoic and are currently known in the Eastern Gawler Craton, Australia (Olympic Dam, Prominent Hill), the Cloncurry district, Australia (Ernest Henry), the Carajás district, Brazil (Salobo, Cristalino, Sossego, Alemão) and the Coastal Batholith of northern Chile (La Candelaria, Manto Verde). These deposits all contain greater than 100 million tonnes of ore each with copper and gold grades that exceed those in most porphyry copper–gold deposits (Williams et al. 2005). In addition to a close temporal association between copper–gold deposits and granitoids (see below), the metallogenic provinces that host these major deposits have a number of features in common. In each case, there is an association with major fault systems that probably acted as brittle–ductile shear systems of transpressional to transtensional character at the time of granitoid intrusion and mineralization (e.g. Dallmeyer et al. 1996; Holdsworth and Pinheiro 2000; McLean and Betts 2003). The tectonic settings of major Cu–Au deposits of IOCG style include a continental margin arc setting for northern Chile and possibly Carajás and an interpreted intracontinental arc setting distal to contemporaneous subduction zones for the Gawler Craton and Cloncurry (Creaser 1996; Dardenne et al. 1988; Betts et al. 2002; Ferris et al. 2002; Sillitoe 2003). There is a common temporal association of the granitoids with basaltic and/or ultramafic magmas, some of which have associated Ni–Cu mineralization. These mantle-derived magmas may have played a role in the generation of the granitoid magmas by providing heat for partial melting in the lower crust (Creaser 1996; Pollard et al. 1998). Sodic–calcic alteration is a feature of all major IOCG provinces, and although the origin of this alteration has been ascribed to the presence of evaporites in the host sequence (Barton and Johnson 1996), none are reported from the Carajás district or the Eastern Gawler Craton.

In the Eastern Gawler Craton, there is a close association of IOCG mineralization and granitoids of the Hiltaba Suite, with the Olympic Dam deposit (~1,590 Ma; Johnson and Cross 1995) being hosted within a Hiltaba Suite batholith (1,588±4 Ma; Creaser and Cooper 1993). In the Cloncurry district, there is a close association between IOCG

Table 1 Characteristics of IOCG provinces containing major Cu–Au deposits

	Carajás	Eastern Gawler Craton	Cloncurry	Northern Chile
Age Cu–Au mineralization	Archean	Proterozoic	Proterozoic	Mesozoic
Tectonic setting	Continental margin arc?	Intracontinental arc	Intracontinental arc	Continental margin arc
Major transcurrent fault system	Carajás fault	WNW faults at Olympic Dam	Mt Dore fault	Atacama fault
Intrusive rocks possibly linked to mineralization	Estrela and Old Salobo granites	Hiltaba Suite (Roxby Downs subsuite)	Eureka Supersuite	Coastal Batholith
Other intrusive types	Mafic and ultramafic	Mafic and ultramafic	Mafic	Mafic
Regional alteration	Sodic–calcic restricted	Sodic–calcic restricted	Sodic–calcic widespread	Sodic–calcic widespread
Evaporites	Not reported	Not reported	Mary Kathleen Group (metamorphosed)	Chañarcillo Group
Other mineralization styles	Ni–Cu and platinoids in mafic/ultramafic rocks	Au, Pb–Zn–Ag	Broken Hill type Pb–Zn–Ag, Co(–Cu) and Au-only deposits, Ni–Cu in mafic rocks	Magnetite–apatite, Porphyry Cu–Au, epithermal Au, Manto-type Cu–Ag
References	Holdsworth and Pinheiro (2000) Dardenne et al. (1988) Tallarico et al. (2005)	Ferris et al. (2002) Budd et al. (1998) Reeve et al. (1990) McLean and Betts (2003)	Williams and Pollard (2003) Pollard et al. (1998) Betts et al. (2002) P. J. Pollard (unpublished data)	Dallmeyer et al. (1996) Sillitoe (2003)

Table 2 Characteristics of granitoids and age of granitoids and Cu–Au mineralization in major IOCG provinces

Province	Carajás	Eastern Gawler Craton	Cloncurry	Northern Chile
Name	Estrela granite Old Salobo granite	Hiltaba Suite–Roxby Downs subsuite	Eureka Supersuite	Copiapó pluconic complex Sierra Dieciocho plutonic complex
Composition range	Tonalite to monzongranite (Estrela granite) Monzogranite (Old Salobo granite)	Quartz monzodiorite to granite	Diorite to monzogranite	Diorite to quartz monite and aplite
Oxidation state	Magnetite series (Old Salobo granite) Magnetite series (Estrela granite)	Magnetite series	Magnetite series	Magnetite series
Alkali–silica relationships	Subalkaline (Estrela granite)	Alkaline to subalkaline	Alkaline to subalkaline	Alkaline to subalkaline
Depth of emplacement	~15 km (Estrela granite)	6–8 km	10–15 km	2–3 km
Age	2,573±2 Ma (Old Salobo granite) 2,763±7 Ma (Estrela granite)	1,588±4 Ma (Roxby Downs Granite)	1,500–1,530 Ma	Copiapó plutonic complex—97–119 Ma Sierra Dieciocho plutonic complex—~120–127 Ma
Major deposits	Salobo, Sossego, Alemão, Cristalino	Olympic Dam, Prominent Hill	Ernest Henry	La Candelaria, Manto Verde
Age of major deposits	Salobo—2,576±8 Ma Re–Os molybdenite Sossego—>2.2–2.3 Ga Ar–Ar amphibole Alemão—2,575±12 Ma, Pb–Pb monazite Cristalino—2,719±36 Ma, Pb–Pb sulphides	Olympic Dam—~1,590 Ma U/Pb zircon	Ernest Henry—1,514±24 and 1,529±11 U/Pb titanite ages	Candelaria—114.9±1.0 Ma Ar–Ar biotite, 114.2±0.6 and 115.2±0.6 Ma Re–Os molybdenite Manto Verde—117±3 and 121±3 Ma K–Ar sericite
References	Lindenmayer et al. (1994) Machado et al. (1991) Barros et al. (1997, 2001) Requia et al. (2003) Marschik et al. (2003c) Tallarico et al. (2005) Soares et al. (2001)	Creaser (1996) Creaser and Cooper (1993) Johnson and Cross (1995) Haynes et al. (2005)	Pollard et al. (1998) Page and Sun (1998) Mark et al. (2006)	Marschik et al. (1997, 2003a,b) Mathur et al. (2002) Vila et al. (1996) Sillitoe (2003)

mineralization and granitoids of the Williams and Naraku batholiths that were termed the Eureka Supersuite by Pollard et al. (1998). The granitoids range in age from 1,530 to around 1,500 Ma (Page and Sun 1998) which is similar to the age of most of the Cu–Au deposits (Perkins and Wyborn 1998; Baker et al. 2001; Wang and Williams 2001; Mark et al. 2006). An exception is the Osborne deposit which has a Re–Os molybdenite age of 1,595 Ma (Gauthier et al. 2001), similar to the age of Olympic Dam. In the Carajás district, the Old Salobo Granite (2,573±2 Ma; Machado et al. 1991) has a similar age to the nearby Salobo Cu–Au deposit (2,576±8 Ma; Requia et al. 2003). Also in the Carajás district, the Estrela granite (2,763±7 Ma; Barros et al. 2001) is closely associated spatially with Cu–Au mineralization and is similar in age to sulphides from Cristalino (Pb–Pb age of 2,719±36 Ma; Soares et al. 2001). In northern Chile the Candelaria and Manto Verde deposits both occur in close proximity to granitoids of similar age to the IOCG mineralization, the ~115-Ma Candelaria deposit is associated with granitoids of the Copiapó plutonic complex (97–119 Ma, Table 2), while the Manto Verde deposit (117±3 and 121±3 Ma; Vila et al. 1996) is associated with the Sierra Dieciocho plutonic complex (~120–127 Ma; see Sillitoe 2003).

In addition to a temporal association between magmatism and mineralization, there are abundant isotopic data from IOCG deposits that are consistent with magmatic fluids being a major contributor to ore formation. For example, for the Candelaria deposit this includes oxygen and sulphur isotope (Marschik and Fontboté 2001), Re–Os isotope (Mathur et al. 2002) and lead isotope data (Marschik et al. 2003a). In the Cloncurry district, several stable isotope studies (oxygen, hydrogen and sulphur) have indicated a major role for magmatic fluids in mineralization (Rotherham et al. 1998; Mark et al. 2000; Baker et al. 2001; Williams and Pollard 2003) and there is also evidence for the generation of very Cu-rich fluids during crystallization of Eureka Supersuite magmas and the formation of a large magmatic–hydrothermal magnetite deposit at Lightning Creek (Perring et al. 2000). Stable and radiogenic isotope studies have indicated that magmatic-derived fluids were an important component in mineralization at Olympic Dam and have also indicated a role for mafic/ultramafic magmas in mineralization (Oreskes and Einaudi 1992; Johnson and McCulloch 1995; Campbell et al. 1998). In many IOCG deposits, there is isotopic and fluid inclusion evidence for

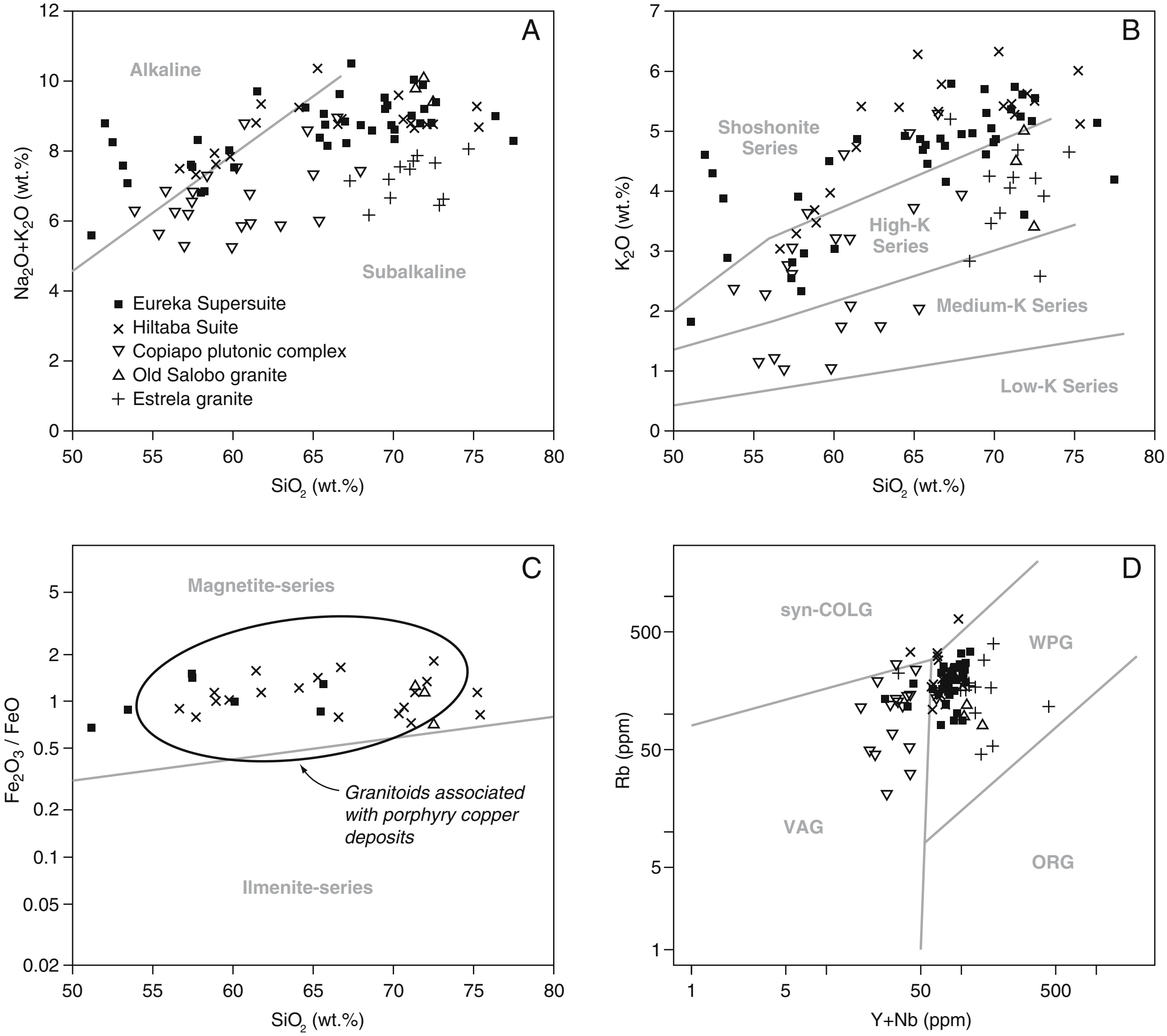

Fig. 1 **a** SiO_2–K_2O + Na_2O variation diagram for granitoids associated with Cu–Au deposits in IOCG provinces showing fields for alkaline and subalkaline compositions (Irvine and Barragar 1971). Data from Barros et al. (1997), Creaser (1996), Lindenmayer et al. (1994), Marschik et al. (2003b) and Pollard et al. (1998). **b** SiO_2–K_2O variation diagram for granitoids associated with Cu–Au deposits in IOCG provinces showing fields of Peccerillo and Taylor (1976). **c** SiO_2–Fe_2O_3/FeO variation diagram for granitoids associated with Cu–Au deposits in IOCG provinces showing fields for magnetite series and ilmenite series granites and intrusive rocks associated with porphyry copper deposits (from Lehmann 1990). **d** Y + Nb–Rb variation diagram for granitoids associated with Cu–Au deposits in IOCG provinces showing fields for different granite types from Pearce et al. (1984). *syn-COLG* Syn-collisional granite, *WPG* within plate granite, *VAG* volcanic arc granite, *ORG* orogenic granite

the presence of non-magmatic fluids during mineralization and fluid mixing has been proposed as a mechanism of ore formation in some deposits (Haynes et al. 1995; Williams et al. 2001; Oliver et al. 2004).

Composition of intrusive rocks in IOCG provinces

The intrusive rocks temporally associated with major copper–gold deposits in IOCG provinces range from diorite to syenogranite in composition (Table 2). The Eureka Supersuite has the broadest compositional range, with diorite to syenogranite represented and shows abundant evidence for mixing and mingling with basic magma (Pollard et al. 1998). The mafic members of some granitoid suites (Eureka Supersuite, Hiltaba Suite, Copiapó plutonic complex) fall in the alkaline field on the Na_2O + K_2O–silica diagram (Fig. 1a), while the exposed rocks of the Estrela granite are restricted to more felsic, sub-alkaline compositions. All the granitoids have a high-K to shoshonitic character except for some samples from the Copiapó plutonic complex (Fig. 1b). The intrusive rocks are all magnetite-series granitoids (Table 1, Fig. 1c), and with the exception of the Old Salobo granite are metaluminous to weakly peraluminous. The few available analyses of the Old Salobo Granite indicate a peralkaline composition, but the granite is described as being composed of feldspars, quartz, augite, hornblende and magnetite (Lindenmayer et al. 1994), i.e. it appears to lack peralkaline minerals.

Granitoids of the Copiapó plutonic complex were derived from a predominantly mantle source (Marschik et al. 2003b), while the granitoids from the other provinces considered here are all mainly products of partial melting of older crustal material possibly due to intrusion of mantle-derived magmas into the lower crust (Creaser 1996; Barros et al. 1997; Pollard et al. 1998). These different source regions are reflected in trace element compositions where the Copiapó granitoids plot in the volcanic arc granite field on tectonic discrimination diagrams while the other granitoids plot mainly in the within-plate granite field (Fig. 1d).

Intrusive rocks and copper–gold mineralization

Intrusive rocks linked to major copper–gold porphyry systems are magnetite series and range from diorite to monzogranite in composition (Sillitoe 1997). The mineralized porphyry stocks include calc-alkaline, high-K calc-alkaline and shoshonitic rocks (Sillitoe 1997). Most deposits situated in continental margin arcs are associated with high - K to shoshonitic intrusions while most deposits from island arc settings are associated with calc-alkaline intrusions (see Sillitoe 1997).

The potential of granitoid magmas to produce mineralization appears to be mainly a function of oxidation state and degree of fractionation (Lehmann 1990; Blevin and Chappell 1992, 1995). In more reduced magmas where pyrrhotite can form early, copper may be removed from the melt together with other components such as Au, Pb, Zn, Mo, Co and Ni (Blevin and Chappell 1992). Copper behaves as a compatible element in magmas over a wide range of conditions and production of copper-rich fluids is favoured by fluid saturation before significant crystallization (Candela 1989). This may help to explain why copper-associated magmas tend to be less fractionated than Mo-associated magmas and why copper deposits are commonly not associated with ilmenite-series (reduced) granites (Candela 1989; Lehmann 1990). Similarly, in more oxidized magmas the SO_2/H_2S ratio is higher and this results in greater partitioning of sulphur into the aqueous phase due to the lower solubility of SO_2 compared to H_2S in hydrous magmas (Burnham and Ohmoto 1980).

IOCG-associated intrusions fall in the same field as granitoids associated with porphyry copper deposits on the SiO_2–Fe_2O_3/FeO diagram (Fig. 1c) indicating that they share the same oxidation state and degree of fractionation. On this basis, the IOCG-associated intrusions would be considered as a potential source of mineralizing components in the same way as the porphyry copper-associated intrusions are considered to be a source of components for the ore deposits. Intrusions which are less oxidized and/or more or less fractionated are less likely to be associated with Cu–Au mineralization. For example, in the Gawler Craton regional scale variation in the geochemistry of the Hiltaba Suite is reflected in changes in the nature of the associated mineralization (Budd et al. 1998). The more fractionated and oxidized Roxby Downs subsuite is associated with IOCG deposits such as Olympic Dam, while the less fractionated and less oxidized Kokatha subsuite is associated with Au(±Sn±Ag) mineralization (Budd et al. 1998).

Candela (1989) considered a model where granitoids generated by partial melting of older crustal protoliths have lower Cl/H_2O compared to magmas generated by partial melting of subducted oceanic crust and/or the overlying mantle wedge. The crustal melts were modeled as being less likely to generate copper mineralization and more likely to generate molybdenum(–tungsten) mineralization due to lower initial Cu/Mo and relatively large degree of crystallization before vapor evolution (Candela 1989). However, fluid inclusion studies in IOCG systems show that carbon dioxide is a key component of the fluids (Pollard 2000; Perring et al. 2000) and CO_2 in magmas promotes fluid separation at much higher pressure compared with H_2O-only systems (Lowenstern 2001), suggesting that large degrees of crystallization are not required as vapor saturation will result from intrusion of the magmas to lower pressures. Formation of an immiscible fluid phase will also promote partitioning of components such as H_2O, Cl and Cu to the fluid phase suggesting that granitoids derived from partial melting of lower crustal protoliths also have the capacity to form Cu–Au deposits.

The generation of many of the intrusions associated with IOCG deposits from older metaigneous rocks may help to explain the enrichment of many of the copper–gold deposits in elements such as REE, U, F, Mo and W

(Pollard 2000). Partial melting of such sources requires high temperatures to promote the breakdown of biotite and amphibole and leads to an enrichment of F in the magmas (Creaser et al. 1991). These high temperatures also promote melting of Fe–Ti oxides and zircon, leading to enrichment of Zr, Ti, U and REE in the magmas (Keppler 1993). Mo and W enrichment may reflect generation of parental magmas from older metaigneous rocks enriched during their magmatic history. U, REE, Mo and W, together with Cu and Au ultimately partition to exsolved magmatic fluids which are enriched in H_2O, Cl, CO_2 and possibly F. The Candelaria deposit contains relatively low U and REE contents compared with Olympic Dam (Marschik and Fontboté 2001, Oreskes and Einaudi 1990), consistent with the lower REE and U contents of the mantle-derived granitoids which are a likely source of ore fluids at Candelaria (Marschik et al. 2003b) compared to the Hiltaba Suite granitoids which are a likely source of components for Olympic Dam (see Creaser 1996).

Discussion and conclusions

The formation of copper–gold deposits in IOCG provinces is linked to structural and physicochemical features that go far beyond magma composition alone. However, in terms of the characteristics of magmas that are important to copper–gold mineralization potential, the intrusive rocks linked to major Cu–Au deposits of IOCG style are the same as those linked to major porphyry copper–gold deposits. Taken together with the isotopic evidence for magmatic fluids being implicated in mineralization and the similar isotopic characteristics of intrusions and mineralization, this indicates a key role for intrusions as a source of fluids and metals in the genesis of major Cu–Au deposits of IOCG style. Sulphur isotope studies also commonly indicate a dominantly magmatic source for sulphur in IOCG deposits (e.g. Marschik and Fontboté 2001; Oliver et al. 2004) although it appears that in some cases, sulphur and metals may have been transported in different fluids, and in some cases, sulphur was possibly derived from nearby intrusive and/or volcanic rocks by separation from magma (mafic?) into a fluid phase and/or by hydrothermal leaching of crystalline rocks (Haynes et al. 1995; Williams et al. 2001; Oliver et al. 2004). An evolution by mixing of magmatic and evaporite-derived sulphur has been proposed for the main ore-forming event at Candelaria by Ullrich and Clark (1999), but Marschik and Fontboté (2001) found no evidence of evaporitic sulphur at Candelaria. In some IOCG provinces, there is a spatial and temporal association between Cu–Au deposits of IOCG style and magnetite ± apatite deposits (e.g. northern Chile) and the two may be related in a zonal pattern with massive magnetite deeper than, or peripheral to Cu–Au-bearing parts of the system (Sillitoe 2003). In some, cases the lack of copper mineralization may reflect a lack of available reduced sulphur rather than a lack of available copper (Perring et al. 2000).

Barton and Johnson (1996) ascribed sodic(–calcic) alteration to saline fluids derived from evaporitic sequences as documented for the Humboldt mafic complex in Nevada (Johnson and Barton 2000). Similar alteration is present in many provinces that lack any but minor amounts of Cu–Au mineralization (see Barton and Johnson 1996), and these also generally lack intrusive rocks similar to those described here from Cu–Au provinces. Stable isotope data for sodic(–calcic) alteration associated with mineralization in the Cu–Au provinces commonly indicate a predominantly magmatic fluid source (Perring et al. 2000; Mark et al. 2004; Oliver et al. 2004). Pollard (2001) proposed that sodic(–calcic) alteration in IOCG systems could be formed by unmixing of magmatic-derived H_2O–CO_2–salts fluids similar to those observed in the Cu–Au deposits and a similar type of model based on the evolution of H_2O–CO_2–salts fluids has also been used to account for feldspathic alteration in carbonatite and alkaline igneous systems by Rubie and Gunter (1983).

The intrusions linked to IOCG mineralization were emplaced at depths ranging from ~2–15 km (Table 2, Fig. 2), and many IOCG deposits appear to have formed at depths considerably greater than those of typical porphyry copper deposits. At these greater depths, the mechanical energy released during crystallization of the intrusions is likely to be insufficient to fracture the host rocks in the same way as is proposed for porphyry-related intrusions at epizonal levels (Burnham and Ohmoto 1980). Instead, the fluids would be channeled out of the intrusions along preexisting fractures which may include those controlling emplacement of the magma. IOCG deposits form distal to the generative intrusion in these circumstances because of the common lack of proximal zones of high fracture intensity. Regardless of depth, Cu–Au deposits of IOCG style are strongly localized by structures (Fig. 2) and commonly occur at intersections of structures or structures and lithological boundaries (e.g. Candelaria), in dilational jogs within transcurrent faults (e.g. Salobo), or along linking structures between major strands of transcurrent faults (e.g. Manto Verde). In situations where deposits form at shallow levels, the mineralization occurs in hydrothermal breccias and veins (e.g. Olympic Dam, Alemão, Fig. 2) similar to mineralization styles in some porphyry systems, but generally lacking quartz stockwork veins.

A fundamental difference between IOCG deposits and many porphyry deposits appears to be the mechanism of fluid evolution. Magmatic fluids in porphyry copper deposits are commonly saline H_2O-rich fluids that boil to produce hypersaline brine and a vapor phase (Ulrich et al. 2001). In contrast, fluid inclusion data from IOCG deposits and associated granitoids indicate the presence of hypersaline brine and coexisting CO_2-rich fluid which are interpreted to have evolved by unmixing (Pollard 2000; Perring et al. 2000). These differences in fluid composition and mechanism of evolution apparently lead to the different alteration styles observed in porphyry and IOCG Cu–Au systems. In porphyry systems, silicate alteration is dominated successively by biotite ± K-feldspar assemblages (potassic alteration), muscovite ± chlorite (sericitic

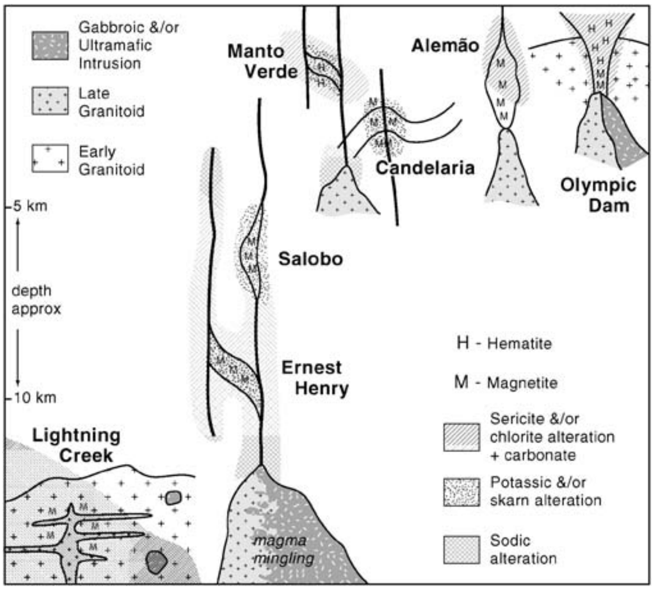

Fig. 2 Schematic model showing different styles of IOCG deposits discussed in the text, together with the major alteration styles and predominant iron oxide minerals. Lightning Creek is a major magnetite-rich system where crystallization of granite sills generated Cu-rich hydrothermal fluids which potentially formed mineralization elsewhere (see Perring et al. 2000)

alteration) and clay-bearing assemblages (intermediate and advanced argillic alteration) and indicates progressively greater acidity before eventual neutralization (Seedorff et al. 2005). In contrast, IOCG systems at deeper levels are commonly characterized by successive silicate alteration stages that include albite ± pyroxene (sodic or sodic–calcic alteration) and biotite ± K-feldspar (potassic alteration) in some cases followed by an amphibole and/or epidote-rich stage (e.g. Candelaria) and non-silicate stages commonly including iron oxides (dominantly magnetite), sulphides and carbonates (see Williams et al. 2005). Some deposits, including Salobo and Candelaria also have skarn and/or calc-potassic alteration (e.g. Marschik and Fontboté 2001; Requia et al. 2003) that is probably broadly equivalent to potassic alteration in other deposits. Alteration in shallower level IOCG systems is typically characterized by K-feldspar (potassic alteration; e.g. Manto Verde), muscovite ± chlorite ± carbonate (sericitic alteration) and iron oxides (dominantly hematite) and sulphides (Fig. 2). Alteration in deeper IOCG systems is similar to that associated with alkaline–ultramafic and carbonatite complexes (e.g. Rubie and Gunter 1983) and alkalic porphyry systems (Lang et al. 1995) in being dominated by feldspathic alteration (albite and/or K-feldspar), Fe–Mg–Ca silicates (pyroxene, amphibole, mica) and carbonates, but typically lacking the major quartz stockworks and sericitic and argillic alteration that are so common in calc-alkaline porphyry systems. This indicates that although porphyry and IOCG Cu–Au deposits share a common association with oxidized, potassic intrusive rocks, the two deposit styles are not directly related.

In addition to features such as sodic alteration and abundant iron oxides, exploration for Cu–Au deposits of IOCG style needs to take account of the nature of the intrusive rocks present within any region being explored. Sodic alteration and iron oxide development are a feature of many provinces that lack significant Cu–Au mineralization, while the types of intrusive rocks described here are a ubiquitous feature of IOCG provinces that host major Cu–Au deposits.

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