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Economic Geology, v. 105, pp. 641–654

Iron Oxide Copper-Gold (IOCG) Deposits through Earth History: Implications for Origin, Lithospheric Setting, and Distinction from Other Epigenetic Iron Oxide Deposits

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Abstract

The iron oxide copper-gold (IOCG) group of deposits, initially defined following discovery of the giant Olympic Dam Cu-U-Au deposit, has progressively become too-embracing when associated deposits and potential end members or analogs are included. The broader group includes several low Ti iron oxide-associated deposits that include iron oxide (P-rich), iron oxide (F- and REE-rich), Fe or Cu-Au skarn, high-grade iron oxide-hosted Au ± Cu, carbonatite-hosted (Cu-, REE-, and F-rich), and IOCG sensu stricto deposits. Consideration of this broad group as a whole obscures the critical features of the IOCG sensu stricto deposits, such as their temporal distribution and tectonic environment, thus leading to difficulties in developing a robust exploration model.

The IOCG sensu stricto deposits are magmatic-hydrothermal deposits that contain economic Cu and Au grades, are structurally controlled, commonly contain significant volumes of breccia, are commonly associated with presulfide sodic or sodic-calcic alteration, have alteration and/or brecciation zones on a large, commonly regional, scale relative to economic mineralization, have abundant low Ti iron oxides and/or iron silicates intimately associated with, but generally paragenetically older than, Fe-Cu sulfides, have LREE enrichment and low S sulfides (lack of abundant pyrite), lack widespread quartz veins or silicification, and show a clear temporal, but not close spatial, relationship to major magmatic intrusions. These intrusions, where identified, are commonly alkaline to subalkaline, mixed mafic (even ultramafic) to felsic in composition, with evidence for mantle derivation of at least the mafic end members of the suite. The giant size of many of the deposits and surrounding alteration zones, the highly saline ore fluids, and the available stable and radiogenic isotope data indicate release of deep, volatile-rich magmatic fluids through devolatization of causative, mantle-derived magmas and variable degrees of mixing of these magmatic fluids with other crustal fluids along regional-scale fluid flow paths.

Precambrian deposits are the dominant members of the IOCG group in terms of both copper and gold resources. The 12 IOCG deposits with >100 tonnes (t) resources are located in intracratonic settings within about 100 km of the margins of Archean or Paleoproterozoic cratons or other lithospheric boundaries, and formed 100 to 200 m.y. after supercontinent assembly. Their tectonic setting at formation was most likely anorogenic, with magmatism and associated hydrothermal activity driven by mantle underplating and/or plumes. Limited amounts of partial melting of volatile-rich and possibly metal-enriched metasomatized early Precambrian subcontinental lithospheric mantle (SCLM), fertilized during earlier subduction, probably produced basic to ultrabasic magmas that melted overlying continental crust and mixed with resultant felsic melts, with devolatilization and some penecontemporaneous incorporation of other lower to middle crustal fluids to produce the IOCG deposits. Preservation of near-surface deposits, such as Olympic Dam, is probably due to their formation above buoyant and refractory SCLM, which resisted delamination and associated uplift.

Most Precambrian iron oxide (P-rich) or magnetite-apatite (Kiruna-type) deposits have a different temporal distribution, apparently forming in convergent margin settings prior to or following supercontinent assembly. It is only in the Phanerozoic that IOCG and magnetite-apatite deposits are roughly penecontemporaneous in convergent margin settings. The Phanerozoic IOCG deposits, such as Candelaria, Chile, occur in anomalous extensional to transtensional zones in the Coastal Cordillera, which are also the sites of mantle-derived mafic to felsic intrusions that are anomalous in an Andean context. This implies that special conditions, possibly detached slabs of metasomatized SCLM, may be required in convergent margin settings to generate world-class IOCG deposits.

It is likely that formation of giant IOCG deposits was mainly a Precambrian phenomenon related to the extensive mantle underplating that impacted on buoyant metasomatized SCLM. Generally smaller and rarer Phanerozoic IOCG deposits formed in tectonic settings where conditions similar to those in the Precambrian were replicated.

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0361-0128/10/3891/641-14

Submitted: November 11, 2008
Accepted: September 11, 2009

Introduction

The discovery in 1975 by Western Mining Corporation of the giant Olympic Dam breccia-hosted iron oxide Cu-Au-U-REE deposit in South Australia focused attention on a hitherto poorly known type of ore system (Roberts and Hudson, 1983). Following the classic studies of Oreskes and Einaudi (1990, 1992), the term iron oxide Cu-Au (or IOCG) deposit was introduced by Hitzman et al. (1992) and has been generally accepted (e.g., Porter, 2000, 2002) for an increasingly diverse group of deposits associated with iron oxides, many of which have only subeconomic to trace copper and gold contents or have controversial associations (Williams et al., 2005).

In the most recent major review of the IOCG deposit class, Williams et al. (2005) provide an empirical definition that deposits in the class have the following: (1) copper, with or without gold, as economic metals, (2) hydrothermal ore styles and strong structural controls, (3) abundant magnetite and/or hematite, (4) Fe oxides with Fe/Ti ratios greater than those in most igneous rocks and bulk crust, and (5) no clear spatial associations with igneous intrusions as, for example, displayed by porphyry and skarn ore deposits. In apparent contradiction to this classification, however, Williams et al. (2005) discuss numerous deposits with economically insignificant copper and gold contents, and one of the five examples described in detail, Raúl-Condestable in Peru, is spatially associated with a quartz-diorite porphyry complex and genetically related volcanic dome, with contemporaneous alteration and mineralization zoned around the intrusive complex; that is, it is a proximal magmatic-hydrothermal system. Williams et al. (2005) also make several references to porphyry skarn systems, and many of the districts or deposits discussed or listed in their table A1, which follows groupings by other authors, are described as having skarn alteration and are more generally accepted as skarns (e.g., Meinert et al., 2005).

The object of this review is to better define IOCG deposits, briefly explore relationships with other iron-rich hydrothermal deposits, and examine the temporal evolution of IOCG deposits. Insights are provided that allow this temporal framework to better explain associations of IOCG deposits with other iron oxide deposits and constrain their tectonic setting throughout Earth evolution.

Most other ore deposit types, as demonstrated by recent reviews in Hedenquist et al. (2005) and Groves et al. (2005a, c), have tectonic settings (e.g., Kerrich et al., 2005), regional to district-scale geologic environments, igneous or basinal associations, and sources of fluids and ore components that are distinctive and well defined. The fact that these features are so obscure or contentious in the case of IOCG deposits (Williams et al., 2005) strongly suggests that the presently accepted ore deposit model (Porter, 2000; 2002) is too diverse and that at least some deposits currently included in the group have been misclassified. As currently defined, IOCG deposits represent a rather wide range of loosely related deposits that share a number of common characteristics (Haynes, 2000; Sillitoe, 2003). The extreme range of inferred tectonic settings for IOCG deposits is of particular concern. In addition, the extremely wide range of alteration styles ascribed to IOCG deposits appears, at least in part, to be due to lack of clear distinction between regional- or district-scale and deposit-scale alteration, as alluded to by Williams et al. (2005).

In view of these constraints, this review proceeds in four stages. It provides the following: (1) a critical examination of the IOCG classification, (2) an examination of the essential, larger scale features of the deposits clearly designated as within the IOCG or supposedly related groups, (3) definition of their temporal distribution, and (4) a discussion of the tectonic implications.

IOCG Classification

Figures 1 and 2, taken from Williams et al. (2005: figs. 2, 3), show that, as currently defined, IOCG deposits and proposed associated deposits range in age from about 2600 Ma to the Cenozoic, and can range in copper grade over about three orders of magnitude (<0.1 to <10% Cu). If some of the Tennant Creek deposits from northern Australia are included in the group, gold grades also range over more than two orders of magnitude, from <0.5 to >10 g/t Au.

Importantly, however, if only the world-class to giant, sulfide-bearing examples are considered, including the Precambrian deposits from Carajas, Brazil, and Stuart Shelf and Cloncurry, Australia, and potential Phanerozoic analogs from Chile, they show remarkably consistent ore grades that cluster between about 0.7 and 1.5 percent Cu and between 0.1 and 0.6 g/t Au in hypogene ores (e.g., Williams et al., 2005; Grainger et al., 2008). These ranges are similar to, but generally slightly higher than, the ranges of copper and gold grades of most world-class to giant gold-rich porphyry Cu deposits (e.g., Seedorff et al., 2005). These data suggest a misclassification of many of the smaller deposits ascribed to the IOCG

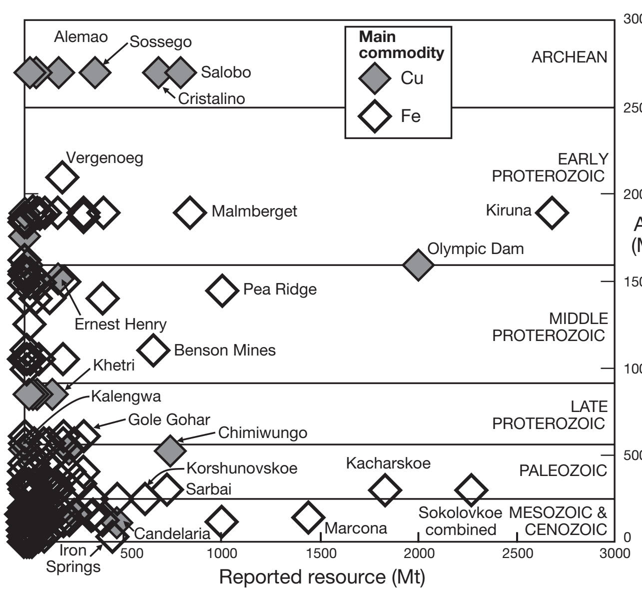

Fig. 1. Age versus size distribution of IOCG deposits (shaded diamonds) and iron oxide deposits (magnetite-apatite and skarn grouped together as unshaded diamonds) divided on the basis of main commodity recovered (Cu or Fe), after Williams et al. (2005: fig. 2), to show contrast between episodic distribution of Precambrian deposits versus much more continuous distribution of Phanerozoic ores. Note also the contrast between more regular distribution of larger deposits and more chaotic distribution of small deposits, which are abundant in the Phanerozoic.

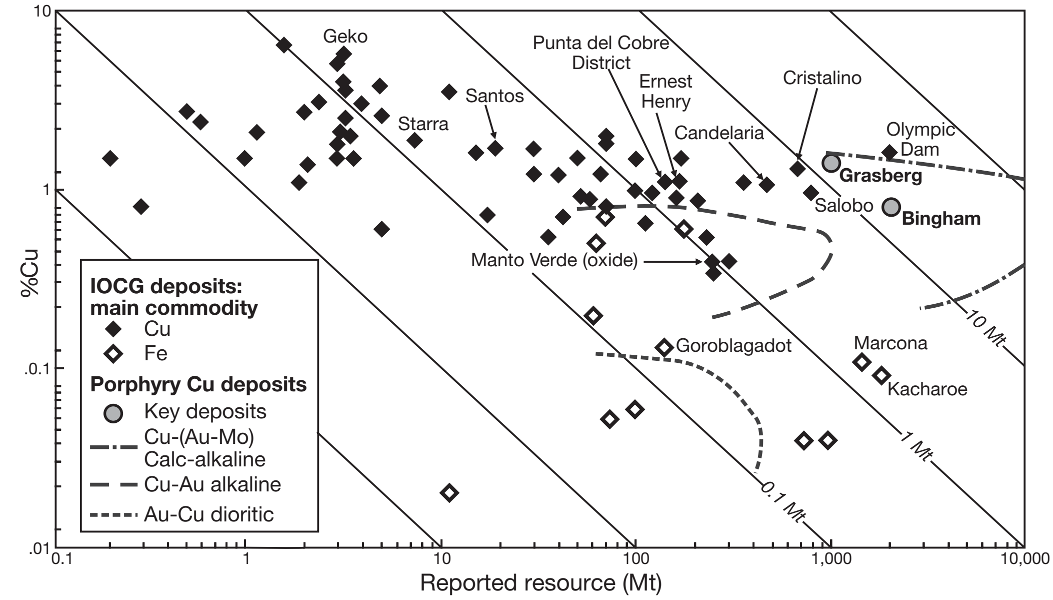

FIG. 2. Grade-tonnage data showing copper grades for selected IOCG deposits and other deposits (magnetite-apatite and skarn), after Williams et al. (2005: fig.3). Note the extreme range (three orders of magnitude) of copper grades when deposits are combined in this way and even one order of magnitude variation for the Cu-bearing IOCG deposits. Note also the generally higher copper (and gold, not shown) grades than those of most porphyries, at the same size.

deposit group in which copper and/or gold grades are much higher, typical of those of skarns (Meinert et al., 2005).

Another factor consistent with misclassification is the published age distribution of deposits ascribed to the IOCG deposit group in general, as summarized by Williams et al. (2005) and shown as Figure 1 here. It is noticeable that, although there is some scatter when smaller deposits are included, the Precambrian deposits either assigned to IOCG or phosphorus-rich iron oxide subgroups form in relatively consistent time periods with significant gaps lacking mineralization, which is consistent with the periodic distributions of other Precambrian deposit types (e.g., Groves et al., 2005a, c; Groves and Bierlein, 2007). This contrasts with the distribution of Phanerozoic deposits ascribed to the IOCG deposit group, in which the smaller examples show virtually continuous age ranges, with a peak concentration in the Mesozoic and Cenozoic, which is the same time when porphyry Cu-Au, skarn, and epithermal Au-Ag deposits are selectively preserved (e.g., Groves et al., 2005a), with many of the more tonalitic to dioritic magnetite-series end members having magnetite as an alteration product. In contrast, several of the larger, generally Fe-rich deposits cluster in relatively specific time periods, as is the case for the much larger Precambrian deposits. These temporal patterns, the lack of any potential confusion between IOCG deposits and porphyry-skarn-epithermal systems in the Precambrian due to the extreme rarity of the latter at that time, and the listing of skarns and porphyry systems within the context of the broader IOCG deposit group in Williams et al. (2005), make a clearer distinction between deposit types essential before definitive conclusions concerning their temporal distribution and tectonic setting can be considered. As an example, deposits from the Bergslagen district of central Sweden include the type locality for the definition of skarn (Törnebohm, 1895, as described by Meinert et al., 2005), but are included in the lists of deposits in the broad IOCG group in Williams et al. (2005). Yerington, Nevada, is also generally accepted as a classic porphyry-skarn system (Harris and Einaudi, 1982; Proffett and Dilles, 1984), not an IOCG, as implied by its listing in table A1 of Williams et al. (2005).

It is suggested here that deposits included in the broad category of the IOCG group in thematic issues (e.g., Porter, 2000; 2002) or reviews (e.g., Williams et al., 2005) would be better considered to be iron oxide-associated deposits and subdivided into five subgroups: (1) iron oxide Cu-Au deposits —these represent IOCG deposits sensu stricto, (2) P-rich iron oxide deposits, (3) carbonatite-iron oxide lithophile-element (F- and REE-rich) deposits, (4) Cu-Au porphyry and Fe skarn deposits, and (5) high-grade magnetite-replacement Au ± Cu magnetite deposits. Subgroups 2 and 3 do not generally have economic copper or gold grades. Skarns with abundant magnetite are distinguished from the other subgroups based on their definitive skarn mineralogy (summarized in Meinert et al., 2005) and proximal relationship to causative intrusions. The subgroups are shown in broad age order in Table 1, which demonstrates that unequivocal, potentially economic, IOCG deposits sensu stricto are actually quite rare. Given the discussion above, a more robust definition is that the IOCG sensu stricto deposit class has the following: (1) Cu + Au as economic metals, (2) hydrothermal characteristics and structural controls, commonly with breccias, 3) abundant low Ti Fe oxides (magnetite, hematite) and/or Fe silicates (grunerite, Fe actinolite, fayalite), (4) LREE enrichment and low S sulfides, including chalcopyrite-bornite-chalcocite and pyrrhotite (i.e., they are not pyrite deposits with Cu ± Au grades as for most other hydrothermal Cu-Au deposits), (5) lack of abundant synsulfide quartz veins and alteration that commonly includes a decreased SiO_2 content of

TABLE 1. Grouping of Iron-Oxide Associated Deposits from Table 1A of Williams et al. (2005) into Subgroups That Better Reflect Deposit Associations

Age	Subgroup 1 IOCG sensu stricto	Subgroup 2 Iron-oxide (P)	Subgroup 3 Alkaline Intrusion/ carbonatite/iron-oxide lithophile elements	Subgroup 4 Skarn	Subgroup 5 High-grade Au (Cu)
Cenozoic		El Laco		Iron Springs	
		Cerro de Mercado		Cortez, Yerington	
Mesozoic	Candelaria			*Hangkow*	
	Manto Verde	Chilean iron belt		Cornwall, Grace	
	Raul-Condestable	Peruvian iron belt		Korshunovsk, Tagar	
Paleozoic				Kachar, Sarbai, Sokolovsk	
				Teyskoe, Ampalyskoe	
				Tashtagol	
				Magnitogorsk	
				Goroblagodat, Peschansk	
				Chogart	
Neoproterozoic		*Kasempa*		*Jabal Isas*	
Mesoproterozoic	Olympic Dam				
	Ernest Henry				
	(Boss-Bixby 70mt)	Benson Mines			
	Singhbhum	Pea Ridge	*Bayan Obo*	(Dover 26mt)	Starra
	Mt. Elliot/SWAN	Acropolis	*O'OKIEP*	(*Osbourne* 11mt)	*Tick Hill*
Paleoproterozoic					Warrego
		Kiruna			Nobels Nob
		Malmberget	*Vergenoeg*		White Devil
		Svappavaara	PALABORA	Grangesberg	Peko
Neoarchean	Salobo				
	Cristallino				
	Sossego-Sequerinho				
	Alemao-Igarape Bahia				

Only large (>100 t) deposits shown except for high-grade subgroups; italics indicate uncertainty of association; capitals in subgroup 3 indicate potential magmatic end members

wall rocks, and (6) a temporal relationship with magmatism, yet no close spatial association with causative intrusions (cf. porphyry skarn Cu-Au, intrusion-related gold, and Sn-W systems).

The iron-rich groups are further subdivided on the basis of whether they are simply P-rich iron deposits or contain potentially economic grades of F or REE (Fig. 3). Given the genetic controversies concerning many of the smaller deposits, their relatively small contribution to resources on tonnage versus age plots, and their low economic ranking unless they have anomalously high Cu and/or Au grades, only those deposits with larger than 100 t resources are considered here, with the exception of group 5, the potential high-grade magnetite-replacement Cu-Au associates. Emphasis is placed on Precambrian examples because these for the most part fall unequivocally into the IOCG group. This approach effectively bypasses the controversy of whether smaller Phanerozoic deposits are skarns or IOCG deposits by eliminating them from the group of deposits being considered. In terms of their age distribution, both IOCG sensu stricto and P-rich iron oxide deposits are plotted as a test of genetic relationship. If they are end members of the same deposit class, as suggested by many authors (e.g., Meyer, 1988; Hitzman et al., 1992; Haynes, 2000; Porter, 2000), then they should share similar time ranges and tectonic settings within the supercontinent cycle.

Analysis of Crustal to Regional Scale Features

Before their temporal distribution and implications for tectonic setting are considered, it is important to define the essential features of the IOCG deposits, and potentially linked sulfide-poor iron oxide (± P, F, REE) deposits, at the appropriate scale. Williams et al. (2005) described the variations in ore grades, metal ratios, alteration assemblages, and isotopic and fluid inclusion characteristics that have led to inconclusive models at the deposit scale. As discussed above, this complex variability is considered to relate to misclassification of many deposits, lack of clear distinction between regional-, district-, and deposit-scale alteration, and the nondefinitive nature of ore fluid chemistry. The giant size of many of the IOCG deposits and the regional scale of their pre- to synformation alteration zones strongly indicate that they should be viewed at the crustal to regional (ultimately lithospheric) scale in order to determine their important genetic components.

An important parameter of the IOCG deposits sensu stricto is their range in depth of formation from the deep crust (>10 km; e.g., Ernest Henry, Salobo) to the paleosurface (e.g.,

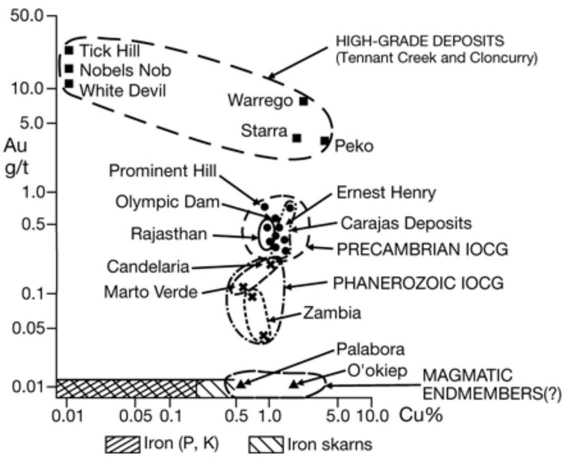

FIG. 3. Gold (glt) versus copper (%) grades for IOCG deposits sensu stricto versus fields for iron oxide (P, F, REE) deposits and skarn deposits, as grouped in this paper. Only deposits with greater than 100 t resources are plotted. Resource data are from Williams et al. (2005), except for the Carajas deposits (from Grainger et al., 2008), Palabora (Verwoerd, 1993) and O'okiep (Wilson, 1998). The high-grade Cu-Au or Au deposits from Tennant Creek and Cloncurry, Australia, commonly placed in the IOCG group, are also plotted using data from Williams et al. (2005). Note the lower copper and gold grades (closer to most porphyry-skarn Cu-Au deposits) of most of the Phanerozoic IOCG examples relative to the Precambrian examples and the low gold grades of Palabora and O'okiep. Also note that the upper limit in terms of gold for iron oxide-P-F deposits is poorly documented.

Olympic Dam). They thus contrast with porphyry skarn Cu-Au systems, which are normally restricted to the upper 5 km of the crust (e.g., Meinert et al., 2005; Seedorff et al., 2005). This implicates a deeper source of ore fluids, and at least some ore components, for IOCG deposits than those levels that characterize causative magmas emplaced at high crustal levels for porphyry-skarn systems. There is also consensus that geochemically complex brines, commonly with a carbonic component, were involved in ore genesis (e.g., Oreskes and Einaudi, 1992; Haynes et al., 1995; Williams and Pollard, 2003). Some authors (e.g., Barton and Johnson, 1996) have argued that evaporative or other nonmagmatic brines were involved in IOCG formation. However, the notion that such fluids were an essential component appears untenable for at least the world-class to giant Precambrian IOCG deposits, which formed in previously metamorphosed rocks (e.g., Baker et al., 2008), and is possible, but not essential (Sillitoe, 2003) for some Phanerozoic examples (Chiaradia et al., 2006). The most logical explanation is that deep and volatile-rich magmas, capable of producing wall-rock alteration and metal deposition at greater depths than normal porphyry Cu-Au causative dioritic to granodioritic magmas, were critical in ore formation, whereas evaporative or mixed magmatic and nonmagmatic brines are an unrelated fluid type, involved primarily in pre-ore, regional-scale alteration. The importance of lithospheric involvement is also consistent with the studies of Chiaradia et al. (2006), which conclude that for some world-class IOCG deposits low Cl/Br ratios (800-1500) and relatively high δ^{37}Cl (0.2–2.1‰) indicate a mantle-derived fluid, with greater mantle input than for fluids generating porphyry Cu-Au systems (δ^{37}Cl = 0‰). Initial Os isotope ratios also indicate mantle derivation (Marschik and Fontboté, 2001; Mathur et al., 2002), as do Sm/Nd isotope signatures of some IOCG deposits, as summarized by Kerrich et al. (2005). The occurrence of swarms of altered lamprophyre dikes containing chromites with Mg # similar to those of kimberlites (D.I. Groves, unpub. data) in the breccias pipe at Olympic Dam adds further support to this concept. The lamprophyres may have been derived from coeval mantle magmas that released volatiles into the giant hydrothermal system.

Although direct spatial associations between IOCG deposits and proximal causative intrusions are rare, the world-class to giant IOCG deposits are invariably located in provinces where there is evidence of synchronous intrusive activity (e.g., Campbell et al., 1998; Skirrow et al., 2007; Grainger et al., 2008): only deposits with low tonnage (e.g., Wernecke Mountains, Yukon, Canada: Goad et al., 2000) are situated in terranes lacking significant coeval magmatism. The petrogenetic association and source of intrusive magmas is highly debated, but there is both direct (e.g., Grainger et al., 2008) and indirect (e.g., Campbell et al., 1998) geochronological and/or isotopic evidence that primitive alkaline magmas were involved in formation of the Precambrian Carajas group of deposits and the Proterozoic Olympic Dam deposit, respectively. The carbonic component of the ore brines and the ubiquitous enrichment in LREE in the IOCG ores are also suggestive of an alkaline source. In terms of their gold content, the IOCG deposits are most similar to the alkaline group within the porphyry Cu-Au deposit class (e.g., Seedorff et al., 2005: fig. 3). Thus, a deep alkaline magmatic source is likely for at least the Precambrian examples of IOCG deposits sensu stricto, and a likely protolith is metasomatized SCLM (e.g., Groves and Vielreicher, 2001; Groves et al., 2005 c).

Other evidence for the involvement of deep volatile-rich alkaline magmas for Precambrian IOCG deposits includes the magnitude of brecciation in most IOCG systems and the broad similarity of the breccias pipes and maars at Olympic Dam (Fe-oxide Cu-Au-U-REE) and Vergenoeg (Fe-oxide F-REE) with the alkaline magmatic Argyle lamproitic diamond pipe in the Kimberley Block of Western Australia (e.g., Goff et al., 2004). There are no other mineral deposits, except for other IOCG deposits and some of the iron oxide (P) deposits, which show such features of comparable magnitude. Indeed, the huge extent of associated alteration and brecciation is a defining characteristic of true IOCG deposits.

The true IOCG systems, as well as the P-rich iron oxide deposits, are characterized by large volumes of early altered wall rocks, which reflects a hydrothermal event predating sulfide deposition. This early alteration is generally sodic (albite formation) or sodic-calcic (albite-amphibole), with temporally associated disseminated hematite (forming red-colored albite) and/or disseminated to veinlet magnetite. Early sodic or sodic-calcic alteration may form large, irregular zones surrounding the younger IOCG deposits (Olympic Dam and other deposits in the Gawler Province), be structurally localized along shear zones (Carajas), or display both relationships (Cloncurry). Sulfide mineralization in the true IOCG deposits may be temporally associated with either calcic (amphibole, epidote, and/or carbonate) and/or potassic (biotite, potassium feldspar, or white mica in high level, hydrolytic systems) later alteration. The majority of the P-rich iron oxide deposits lack these later alteration stages.

Iron-rich mineralizing systems can be formed through a number of different processes. Particular magma compositions, tectonic settings, or deposit types are not necessarily indicated by solely iron enrichment. Clearly, porphyry systems can produce Fe-rich deposits, such as skarns, and porphyry systems that interact with evaporite wall rocks (e.g., Yerington, Ajo) can produce sodic alteration with abundant magnetite that mimics some aspects of IOCG system alteration. However, IOCG systems are produced by deep-seated, crustal-scale processes that operate on a much larger scale than that of an individual porphyritic intrusion. Again, it should be emphasized that size of associated alteration is a defining characteristic of IOCG deposits. This is one of the reasons that Groves and Vielreicher (2001) suggested that the Palabora carbonatite Cu-Fe-P-REE system was best classified as an IOCG deposit. Unlike most individual carbonatite plugs, it is a small part of a 2 × 1 km pipe, within an approximately 8 × 3 km alkaline complex, and surrounded by satellite intrusions, alteration zones, and aeromagnetic anomalies that extend for tens of kilometers from Palabora itself. However, the association between Palabora and the IOCG class of deposits remains controversial, even with varying opinions among the authors of this paper.

Whereas most Precambrian IOCG deposits were formed in old, cold metamorphosed crust (Fig. 4), and in association with posttectonic (Carajas, Olympic Dam, Gawler Province, and Khetri, Rajasthan province) or very late tectonic (Cloncurry province) intrusions, the Candelaria and Manto Verde deposits, almost universally ascribed to the IOCG group of deposits (e.g., Marschik et al., 1997, 2003; Hitzman, 2000; Mathur et al., 2002; Sillitoe, 2003; Williams et al., 2005), formed in the Coastal Cordillera of northern Chile and southern Peru in a Jurassic-Early Cretaceous volcanic-plutonic arc. The Andean metallogenic belt is best known for its giant porphyry Cu-Au and epithermal Au-Ag systems, with the former developed in association with high-level calc-alkaline porphyries during hiatuses in volcanic activity in a compressional to transpressional regime (e.g., Cooke et al., 2005). In contrast, Candelaria appears to have formed during a major extensional or transtensional event (e.g., Oyarzun et al., 1999), which initiated an arc-parallel fault system in response to subduction rollback at the retreating convergent margin (e.g.,

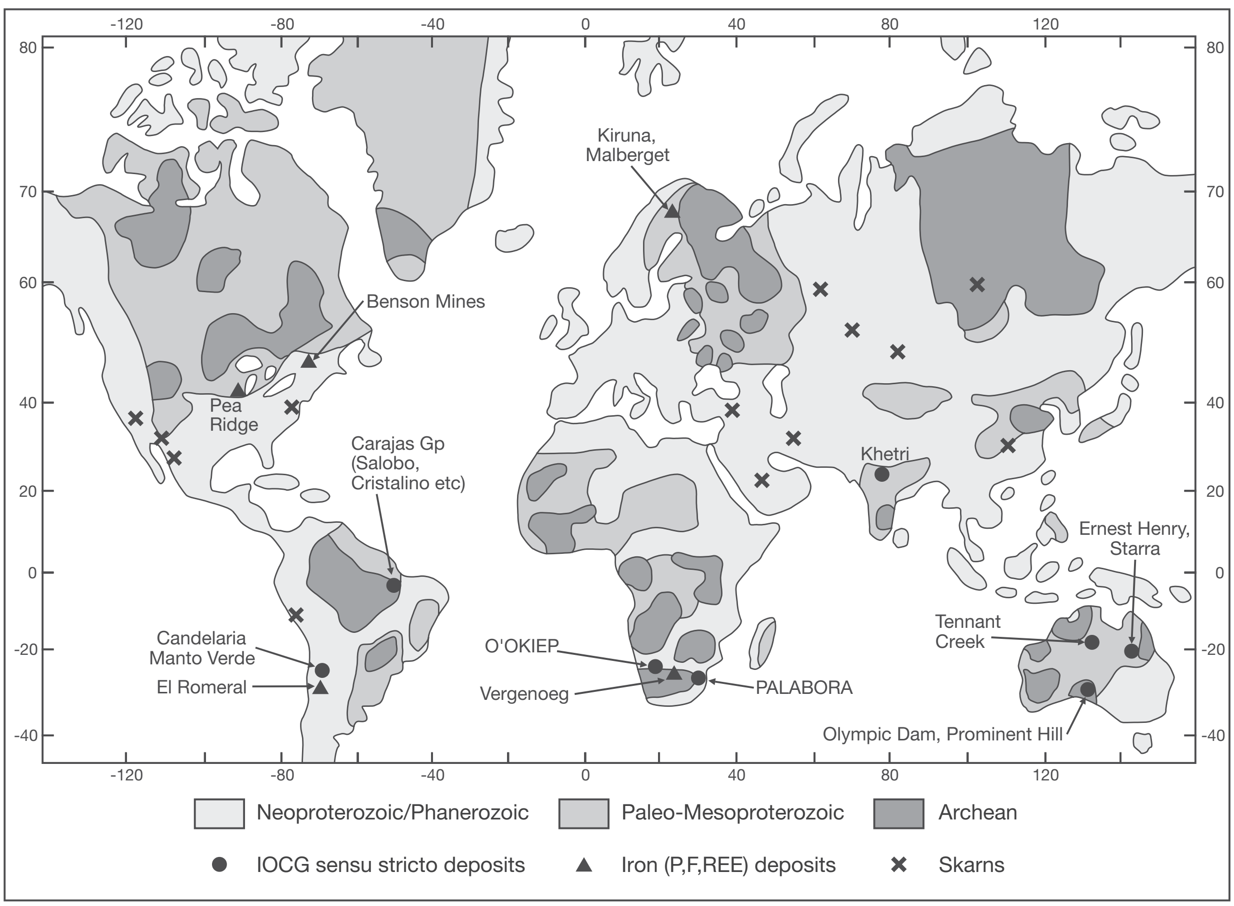

FIG. 4. Geographical distribution of deposits with greater than 100 t resources grouped as IOCG sensu stricto, iron oxide (P, F, REE) and skarn deposits in this paper. The distribution of the deposits is shown relative to the position of Archean and Paleo-Mesoproterozoic cratons as presented by Artemieva and Mooney (2001). Note that the extent of the Archean Siberian craton is generalized and that Archean rocks are mainly covered by Phanerozoic basins. Most IOCG deposits are located adjacent to the margins of Archean cratons, with the major exceptions of Candelaria and Manto Verde. Iron oxide (P, F, REE) deposits also are commonly close to the margins of Archean or Proterozoic cratons, with El Romeral as a major exception. In contrast, deposits designated as skarns in this paper show no such relationship as a group. Potential magmatic end members (not universally accepted) are shown in capital letters to distinguish them from more typical IOCG deposits.

Sillitoe, 2003). Associated magmatism produced a highly fractionated suite of mantle-derived intrusions ranging from gabbronorite to gabbro, diorite, tonalite, and granodiorite (e.g., Dallmeyer et al., 1996), with an alkaline to subalkaline affinity (Pollard, 2006). The Andean IOCG deposits are considered to have formed from a dominantly magmatic-hydrothermal fluid derived from these intrusions, with relatively minor involvement of nonmagmatic basinal fluid components (Sillitoe, 2003). The more strata-bound, mantolike form of the Candelaria orebody relative to the Precambrian deposits is probably due to the more permeable nature of the volcanic host rocks of the former relative to the metamorphic host rocks of the latter.

The marked contrast in the nature of the mantle-derived magmatism in the Copiapó region of the Coastal Cordillera to that elsewhere in the Andes suggests a distinct protolith, which is anomalously enriched in the incompatible elements. By analogy to the Precambrian deposits, it is speculated that this is a buoyant wedge of metasomatized SCLM beneath the extensional to transtensional zone hosting the IOCG deposits.

Magnetite-apatite (P-rich iron oxide) deposits, such as those of the Paleoproterozoic Kiruna and related districts of Sweden, have been considered to be end members of the IOCG group of deposits by several authors (e.g., Hitzman et al., 1992; Barton and Johnson, 1996). Both true IOCG deposits and P-rich iron oxide deposits are associated with large volumes of sodic- to sodic-calcic–altered and generally brecciated rocks, lack abundant quartz veins, and contain abundant low-Ti Fe-oxides. In contrast to IOCGs, P-rich iron oxide deposits lack economic copper and most contain background amounts of gold. Many of the iron oxide (P) deposits display spatial, temporal, and probably genetic relationships to intermediate (commonly dioritic) composition intrusions. The iron oxide (P) deposits are not directly associated with major structures or structural zones as are the true IOCG deposits.

Proton-induced X-ray emission (PIXE) data from fluid inclusions from the Lightning Creek P-rich iron oxide deposit in the Cloncurry district (Perring et al., 2000), magnetite-rich assemblages from the Gawler Province (Bastrakov et al., 2007), and from the Pea Ridge, southeastern Missouri, USA and El Romeral, Chile iron oxide (P) deposits (Hitzman, unpub. data, 2007) indicate that the hydrothermal fluids responsible for some of the iron oxide (P) deposits contained significant copper that did not precipitate, presumably due to the lack of available reduced sulfur. Unfortunately, comparable fluid inclusion data are not yet available from other P-rich iron oxide deposits, particularly those not associated with major true IOCGs, such as Kiruna. Such data may allow assessment of whether there is a spectrum from copper-rich, sulfide-poor hydrothermal fluids in true IOCG districts to copper- and sulfide-poor hydrothermal fluids in iron oxide (P) districts lacking true IOCG deposits.

While there are several districts, such as those of the Mesozoic of Chile and Peru, which contain both significant iron oxide (P) and IOCG deposits, most districts contain either IOCG with relatively minor magnetite-only deposits (Gawler, Cloncurry, Carajas) or iron oxide (P) deposits with relatively small, and temporally later, IOCG-type deposits/prospects (southeast Missouri and Kiruna). The question of a genetic relationship between IOCG and iron oxide (P) deposits remains open, although the temporal distribution of these two deposit types (discussed below) suggests that they represent either fundamentally different ore systems or somewhat similar hydrothermal systems developed in different tectonic environments.

The origin of the Kiruna deposits is highly contentious, as summarized by Smith et al. (2007), as is their magmatic association, with an alkaline association suggested by Meyer (1988), but questioned by Nyström and Henriquez (1994) and Bergman et al. (2001). Intrusive rocks within the age range of the Kiruna deposits (1880–1860 Ma: Billström et al., 2002) belong to the calc-alkaline to alkali-calcic monzonite suites, which were intruded during the Svecofennian orogeny (Skiöld, 1987). In the Andes, the magnetite-apatite deposits such as El Romeral have the same broad tectonic setting as the Candelaria and Manto Verde IOCG deposits. However, the iron oxide deposits in Chile and Peru have different intrusive associations and were formed prior to deposits classified as true IOCG bodies (Williams et al., 2005).

Temporal Distribution of IOCG Deposits and Proposed Associates

The temporal distribution of deposits considered to be IOCG sensu stricto, together with that of the iron oxide (P) and high-grade Cu-Au deposits at Tennant Creek, are plotted in Figure 5. As for many other Precambrian deposit groups (e.g., Kerrich et al., 2000; Goldfarb et al., 2001; Franklin et al., 2005; Groves et al., 2005c; Groves and Bierlein, 2007; Kerrich et al., 2008), the Precambrian IOCG deposits show a marked periodicity of about 500 to 700 m.y., consistent with the episodicity of the assembly and dispersal of the Precambrian supercontinents, Kenorland, Columbia, and Rodinia.

The major Carajas, Gawler, and Rajasthan IOCG provinces developed after supercontinent assembly in intracratonic settings or in far-field back-arc settings, dependent on which tectonic models are accepted. Skirrow (2008) provides a summary discussion of alternative anorogenic or intercontinental rift settings (e.g., Hitzman, 2000; Groves et al., 2005c) relative to back-arc settings (e.g., Betts et al., 2003; Wade et al., 2006) or foreland basin settings (e.g., Hand et al., 2007) for the Gawler craton IOCG deposits. Irrespective of a precise tectonic model, the preservation of the Precambrian IOCG deposits at variable but relatively shallow crustal levels, despite their antiquity, is consistent with their formation and subsequent preservation above buoyant Precambrian SCLM (Griffin et al., 2003). The formation of the deep magmatic Fe-rich deposits, such as Palabora and O'okiep (Table 1), outside the timeframe of supercontinent stability, despite their intracratonic setting and synchronicity with anorogenic magmatism, such as emplacement of the Bushveld Complex, could explain their exposure via deeper erosion of the less-stable lithosphere. This provides one argument against their inclusion in the IOCG deposit group.

The Tennant Creek group of high-grade, iron oxide-associated gold and/or copper deposits (e.g., Large, 1975; Wall and Valenta, 1990; Skirrow and Walshe, 2002) have been placed in the IOCG deposit group in several syntheses (see table A1 of Williams et al., 2005). However, their structural timing and position within the supercontinent cycle is quite different

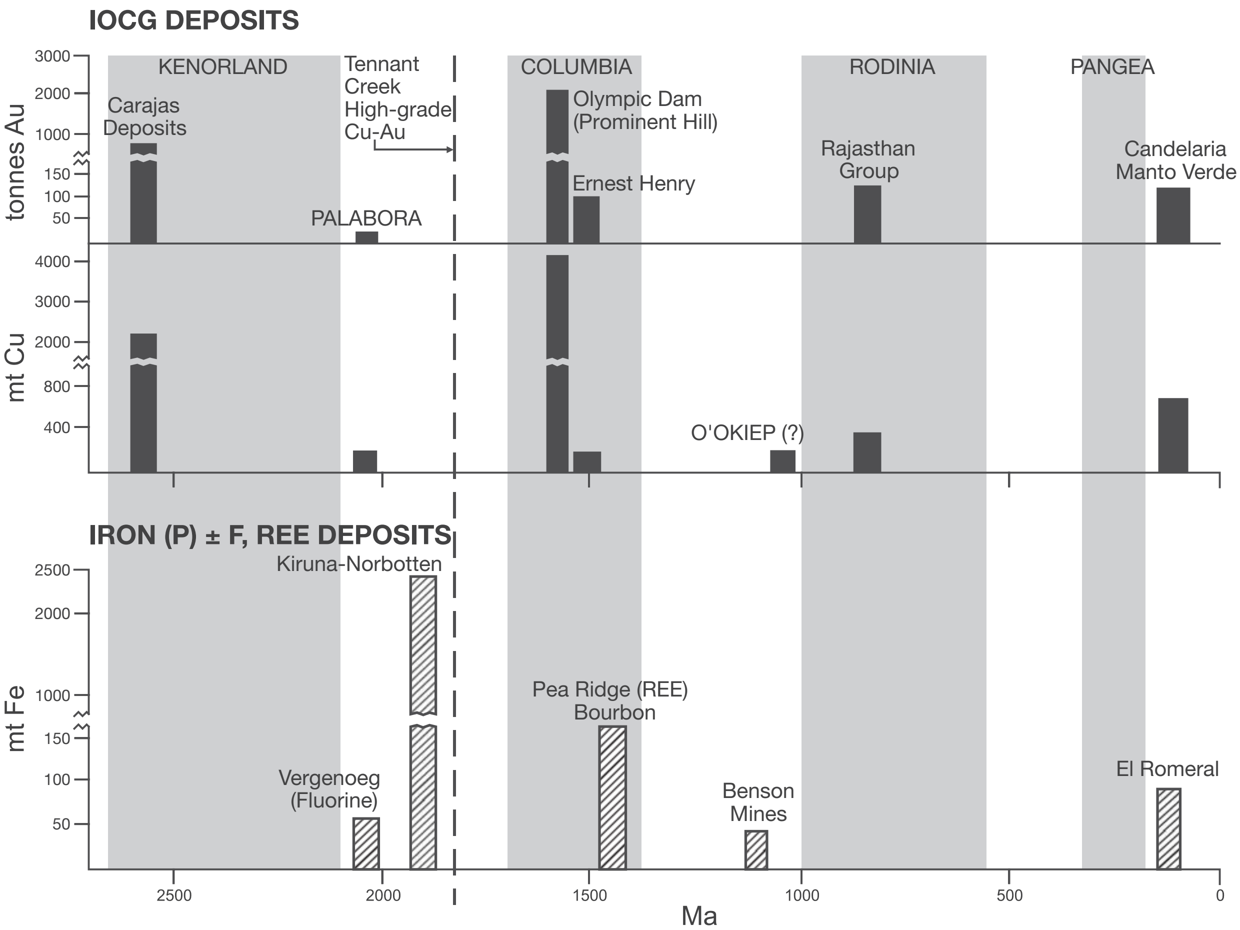

FIG. 5. Temporal distribution of large (>100 t resource) IOCG sensu stricto and iron oxide (P, F, REE) deposits in terms of the supercontinent cycle. Total copper and gold resources are plotted, with source of data in table A1 of Williams et al. (2005) or Table 1 of this paper. The most commonly accepted periods following supercontinent assembly and prior to break-up are shaded and the relevant supercontinents named following Rogers and Santosh (2004). It should be noted that events at convergent and divergent margins may be diachronous and that these boundaries are indicative, rather than definitive, for any particular terrane. Note clear temporal separation of the two types of deposit in the Precambrian versus occurrence in the same time periods and same belts in the Phanerozoic. Times of supercontinent formation and breakup are approximate.

from the well-accepted intracratonic Precambrian IOCG deposits (Fig. 5). Although the deposits occur near a probable lithospheric boundary between Archean basement and the Paleoproterozoic sedimentary rocks, they differ in a number of other respects from the classic IOCG deposits. As summarized by Solomon and Groves (2000), the hosting iron oxide bodies contain quartz, are broadly stratigraphically controlled, and may postdate Au-Cu mineralization by as much as 50 m.y., unlike the more temporally related iron oxides and sulfides in the IOCG deposits. The Cu-Au-Bi association also is anomalous, as well as the high gold and/or copper grades (Fig. 3). The Tennant Creek deposits thus have more features in common with orogenic or possibly intrusion-related gold deposits hosted in preexisting iron formations than they do with IOCG deposits, although they do not fit convincingly into any deposit category.

The Phanerozoic IOCG deposits, again, contrast markedly with their Precambrian analogs, forming during Mesozoic periods of supercontinent dispersal and reassembly in active arc environments. The periodicity between the latest Precambrian examples in Rajasthan and those in the Coastal Cordillera is greater than 700 m.y., if minor deposits in the Lufilian arc are excluded, but considerably greater than the periodicity of most other deposit groups (e.g., Goldfarb et al., 2001; Franklin et al., 2005; Groves et al., 2005c; Kerrich et al., 2005). This, together with the highly anomalous mafic composition of the mantle-derived intrusion suite associated with the IOCG deposits in the Coastal Cordillera of Chile and Peru, suggests that special tectonic conditions, for example, fragments of Precambrian SCLM below extensional segments of arcs, were required to form and preserve these deposits in convergent margins.

The iron oxide (P) or magnetite-apatite deposits show a similar episodicity (300–800 m.y.) to the IOCG deposits, but apparently formed predominantly during periods of convergent orogenesis. The Pea Ridge and Bourbon deposits of southeastern Missouri are an exception (Fig. 5), with Williams et al. (2005: table A1) suggesting an anorogenic setting. Interestingly, the southeastern Missouri district contains a significant IOCG sensu stricto deposit, Boss Bixby (Seeger, 2003). The marked contrast in timing of ore formation between the giant Precambrian IOCG deposits and most giant P-rich iron oxide deposits, as also recorded by Hitzman (2000), raises an interesting question relative to the relationship between these two deposit types. Even where small IOCG deposits or prospects occur in the same Precambrian districts as iron oxide (P) deposits, for example, the Rakkurijärvi Cu-Au prospect in the Norbotten district that hosts the giant Kiruna deposit, they are not coeval (Smith et al., 2007); in most cases, the massive barren magnetite mineralization is earlier (commonly by tens of millions of years). This is also true of Mesozoic Chile, where a large number of giant P-rich iron oxide (P) deposits predate by several tens of millions of years the much less common IOCG deposits. Phosphorus-rich iron oxide deposits appear to be the typical deposit style in convergent tectonic settings, adding further support to the concept that special conditions, such as underlying fragments of Precambrian SCLM, may be required to produce penecontemporaneous IOCG deposits in the same metallogenic corridor.

Tectonic Implications

Important constraints on tectonic controls of Precambrian IOCG deposits include the following.

1. Their first appearance at Carajas, coincident with the first significant development of Archean SCLM in the supercontinent Kenorland, and their maximum development following the assembly of the more extensive supercontinent, Columbia.
2. The occurrence of the Carajas and Gawler Province groups of giant IOCG deposits within crustal rocks above buoyant Archean SCLM (Griffin et al., 2003) and within about 100 km of craton margins (e.g., Grainger et al., 2008).
3. Despite the lack of unequivocal Archean lithosphere, the site of the Cloncurry district, above buoyant Paleoproterozoic (possibly Archean) lithosphere and 100 km west of a major lithospheric boundary between thick (50 km) crust to the west and more attenuated (30 km) crust to the east (e.g., Lilley et al., 2003; Kennett et al., 2004; Fishwick et al., 2008), which is coincident with a significant change in conductivity imaged in a coincident magnetotelluric survey (B.L.N. Kennett, writ. commun., 2008).
4. The essentially undeformed nature of the giant breccia-dominated deposits, their preservation at varying crustal levels, and existence of a maar at Olympic Dam (Fig. 4).
5. Their unusual geochemistry, with trace and minor element signatures typical of both basic (e.g., Co, Ni) and felsic (LREE, U, F) sources, and Cu and Au grades above those of most porphyry Cu-Au deposits, except those of alkaline affinity.
6. Their timing, consistent with an anorogenic setting or intracratonic setting affected by far-field stresses related to distant orogenesis.
7. Their broad synchronicity, but lack of clear spatial association, with atypical basic to felsic magmatism, commonly with an alkaline or subalkaline affinity.

Taken together, these features are consistent with a genetic relationship to deeply sourced, mantle-derived magmas from Archean or Paleoproterozoic SCLM near craton margins or other lithospheric boundaries (e.g., Sun and McDonough, 1989). A likely source of Cu, Au, incompatible elements, and volatile-enriched magmas is SCLM that was metasomatized during previous subduction on continental margins (e.g., Groves et al., 2005a, b). Haywood (2008) extends this model by suggesting that the sites of IOCG deposit formation were reactivated back-arc settings, in which domains of metasomatized SCLM below the back-arc, with anomalous volatile components (e.g., Bindeman and Bailey, 1999) and gold contents (e.g., Moss et al., 2001), were the source of the local partial melts ultimately responsible for IOCG mineralization. Haywood (2008) further suggests that mixing of these volatile-and metal-rich, alkaline, basic melts and oxidized silicic crustal melts produced sulfide-oxide immiscibility and volatile exsolution responsible for the IOCG hydrothermal systems. Similar models have been proposed by Clark and Kontak (2004) for the formation of Fe-Ti-P oxide melts at Antauta, Peru, closer to the margin of the Archean to Proterozoic basement of the Amazon shield.

Schematic models for the tectonic setting and generation of IOCG deposits based on these concepts are presented in Figures 6 and 7. Such models are very similar to those for the intrusion-related gold systems of the Tintina belt (e.g., Hart et al., 2004) and the Bingham Canyon continental porphyry Cu deposit (e.g., Maugham et al., 2002), and possibly the Carlin district gold deposits (e.g., Emsbo et al., 2006) above Archean SCLM, adjacent to the western margin of the North American craton (e.g., Groves et al., 2005b). These models could also explain the genesis of the Andean IOCG deposits if a wedge of old back-arc metasomatized SCLM was located below the extensional zone of the Coastal Cordillera, as suggested by the emplacement of the anomalous mafic to felsic intrusions more or less synchronously with the formation of the IOCG deposits.

Summary and Conclusions

As alluded to or implied in several reviews (e.g., Hitzman, 2000; Sillitoe, 2003; Williams et al., 2005), the IOCG deposit group is now too-embracing, constituting IOCG deposits sensu stricto and numerous associated or potentially analogous deposit types (e.g., Porter, 2000; 2002). These all-embracing groups tend to obscure the important features of temporal distribution and tectonic setting of the actual IOCG deposits, which are critical for successful future exploration. The term IOCG was introduced following discovery of the giant Olympic Dam Cu-U-Au deposit in South Australia. If only Cu-Au deposits with generally similar characteristics to Olympic Dam are considered to be IOCG deposits sensu stricto, the group of deposits commonly assembled under the broad IOCG deposit umbrella are better viewed as iron oxide-associated deposits. These potentially include five subgroups: (1) iron oxide copper-gold deposits, such as Olympic Dam, (2) P-rich iron oxide or magnetite-apatite deposits, such as Kiruna, (3) carbonatite or other alkaline intrusion-iron oxide (F, REE) deposits, such as Palabora (arguably a magmatic end member IOCG) and Vergenoeg, (4) porphyry Cu-Au or skarn Fe to Fe-Cu-Au deposits, such as Yerington and Magnitogorsk, and (5) high-grade magnetite-replacement Au-Cu deposits such as those at Tennant Creek.

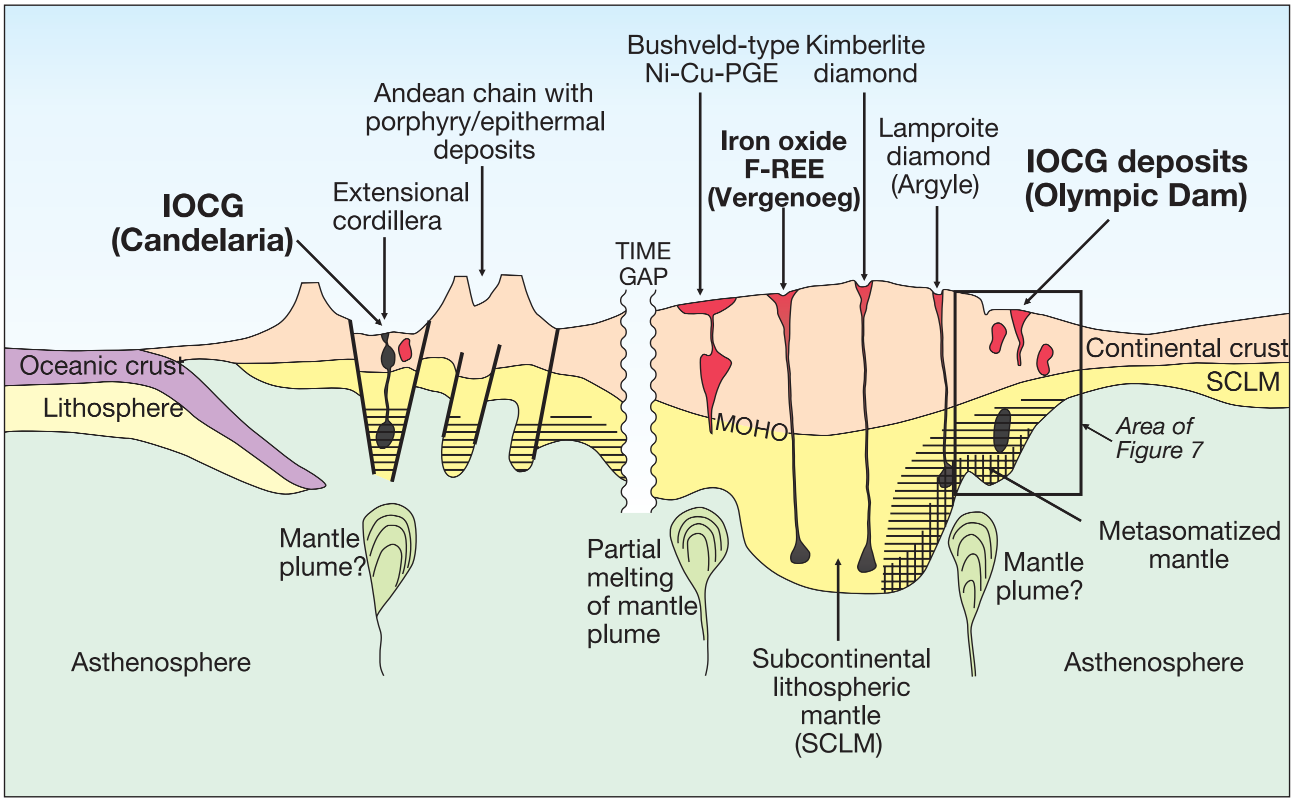

FIG. 6. Schematic diagram showing tectonic and lithospheric setting of IOCG deposits, both in Precambrian cratons and extensional parts of Cordilleran arcs. Note that IOCG deposits form in continental crust inboard of craton margins above metasomatized mantle lithosphere, normally Archean in age. Thickness of crust exaggerated relative to lithosphere to accommodate detail. Figure adapted from Groves et al. (1987) and Groves and Bierlein (2007).

When viewed in this manner, and particularly when misclassified deposits that do not contain economic concentrations of copper and/or gold are removed from the group, a tighter, more robust definition of IOCG deposits can be applied. The essential criteria are that IOCG deposits are formed by magmatic-hydrothermal processes, have Cu ± Au as economic metals, are structurally controlled—commonly with breccias, are surrounded by alteration and/or brecciation zones normally more regional in scale relative to economic mineralization, have depleted SiO_2 content of altered wall rocks, have abundant low Ti iron oxides or iron silicates, and have a close temporal, but not apparent spatial, relationship to causative intrusions. This definition distinguishes IOCG deposits from most other hydrothermal Cu-Au deposits that are commonly dominated by pyrite with accessory copper sulfides and gold (e.g., most porphyries, VHMS deposits) and/or have quartz veins or silicification together with iron oxides (e.g., diorite porphyries, high-grade Cu-Au-Bi deposits at Tennant Creek, ironstone-hosted orogenic gold deposits). If only those world-class deposits (>100 t) that could be considered economic or potentially economic hypogene orebodies are considered, then there are less than 20 deposits worldwide that fulfill the above criteria (Table 2). They are a coherent group with a very limited range of Cu and Au grades and Cu/Au ratios (Fig. 3), somewhat similar, particularly in terms of Au, to alkaline porphyry Cu-Au deposits.

The IOCG deposits also differ from most other hydrothermal deposit groups in the nature of temporally associated magmatism. Although there are felsic intrusions, commonly A-type granites with alkaline to subalkaline affinity, in the IOCG districts or provinces, there is abundant direct petrological and geochemical or indirect isotopic evidence for the involvement of ultrabasic to basic mantle-derived magmas, at least some with alkaline affinity, in the regional magmatic event. The petrologic and isotopic evidence for associated mantle-derived magmatism, the extreme LREE and volatile enrichment, the giant size of both hosting breccia bodies and the footprint of intense, commonly SiO_2-destructive, alteration halos point to devolatilization of deep, volatile-rich, mantle-derived magmas as the primary energy- and fluid-driving force for the IOCG ore systems.

All IOCG deposits contain enrichments of Fe, Cu, Au, and LREE. Individual deposits may contain trace to potentially economic levels of other metals (e.g., U and Ag at Olympic Dam, Zn at Candelaria). The diverse suite of trace metals in IOCG deposits is probably related both to the variable direct involvement of both ultrabasic to basic mantle-derived magmas (elements such as Ni and Co) and leaching of metals from large volumes of crustal material (elements such as U and Zn; e.g., Hitzman and Valenta, 2005).

The site of the Precambrian IOCG deposits, inboard of lithospheric boundaries, most commonly craton margins (Fig. 4), suggests that metasomatized SCLM, fertilized with

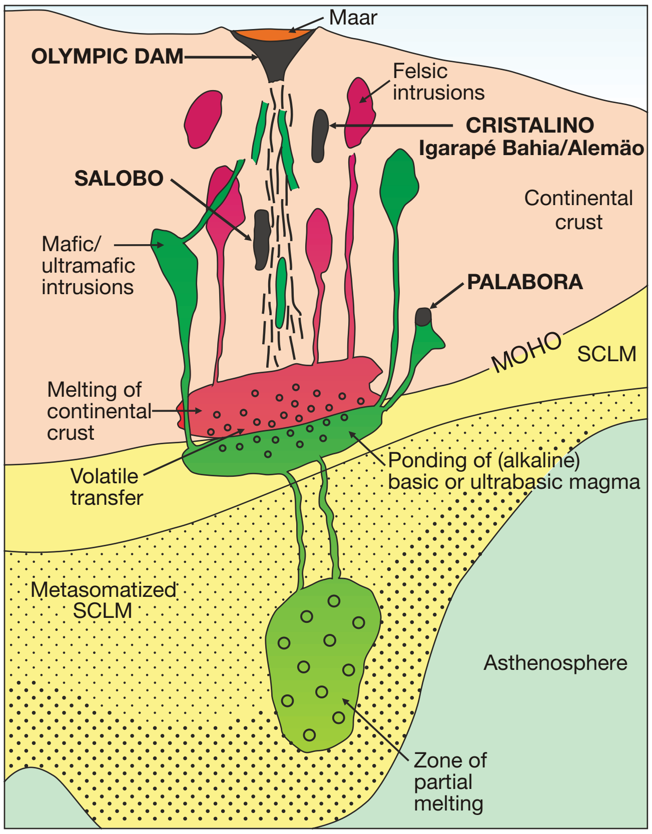

FIG. 7. Schematic diagram showing model for genesis of IOCG deposits. Small degrees of partial melting of metasomatized SCLM produces basic and ultrabasic melts, probably of alkaline affinity and enriched in volatiles, Cu, and Au. This melt ponds at the crust-lithosphere boundary and causes partial melting of the continental crust to produce felsic melts. Volatiles and metals transfer across the melt boundary. Felsic magmas ascend to produce felsic plutons, allowing higher density basic or ultrabasic magmas to follow to produce mafic-ultramafic intrusions in same district. Deep volatile exsolution produces giant breccia pipes with silicate rocks replaced by iron oxides, followed by Cu, Au, U, and other enriched elements. Model adapted from Hart et al. (2004).

volatiles, incompatible elements, and ore elements during prior subduction events, most probably in back-arc environments (Haywood, 2008), was the ultimate source of the causative volatile-rich magmas. Kerrich et al. (2005, 2008) explain this inboard location of IOCG ore systems through the conjunction of focusing of lithospheric extension and accompanying melting of metasomatized SCLM at necked transitions between thick Archean and thinner Proterozoic SCLM that guided mantle underplating. Such mechanisms are less clear for the Phanerozoic IOCG deposits, such as Candelaria, which are located in extensional or transtensional zones of arcs.

The temporal distribution of IOCG deposits (Fig. 5) is particularly informative. For the Precambrian, it shows giant IOCG provinces formed about 100 to 200 m.y. after supercontinent assembly. Importantly, IOCG deposits are not known prior to the first supercontinent, Kenorland, and the largest known deposit is located in the first extensive supercontinent, Columbia. This timing is entirely consistent with an intracratonic setting for mineralization, most probably related to mantle underplating, although some recent models, particularly for Australian provinces, suggest the involvement of far-field stress in the generation of IOCG ore systems (e.g., Hand et al., 2007).

Importantly, the Precambrian IOCG deposits appear to have formed at distinctly different times in the supercontinent cycle relative to the giant Precambrian P-rich iron oxide or magnetite-apatite deposits. While IOCG deposits formed in anorogenic domains, the P-rich iron oxide deposits formed late, during convergent orogenesis. Although the two deposit types share many features, most notably the association with crustal-scale alteration, the IOCG deposits and associated regional-scale alteration have a more complex history, indicating the involvement of multiple hydrothermal fluids over long time periods (e.g., Duncan et al., 2009) and perhaps suggesting a more direct involvement of mantle-derived fluids in IOCG formation.

Phanerozoic iron oxide (P) deposits formed during equivalent periods within the supercontinent cycle as their Precambrian

TABLE 2. Tonnage, Grade and Age Characteristics of Deposits Considered to be Within the IOCG Sensu Stricto Subgroup and Having Reserves > 100 t

Province	Deposit	Size (t)	Cu (%)	Au (glt)	Age
Coastal Cordillera	Candelaria	470	1.07	0.22	ca. 115 Ma[1]
	Manto Verde	230	0.55	0.11	ca. 115 Ma[1]
Rajasthan	Khetri	140	1.1	0.5	ca. 850 Ma[3]
	Others	140	1.3	0.4	ca. 850 Ma[3]
Cloncurry	Ernest Henry	167	1.1	0.54	ca. 1530 Ma[2]
Gawler craton	Olympic Dam	3810	1.0	0.5	ca. 1590 Ma[5]
	Prominent Hill	283	0.89	0.81	ca. 1590 Ma[5]
Carajas	Salobo	789	0.96	0.52	ca. 2570 Ma[7]
	Cristalino	500	1.0	0.3	ca. 2570 Ma[7]
	Sossego	355	1.1	0.28	ca. 2570 Ma[7]
	Igarapé Bahia-Alemão	219	1.4	0.86	ca. 2570 Ma[7]
	Cento et Dezoito	170	1.0	0.3	ca. 2570 Ma[7]

Notes: Potential magmatic end members in capital letters; ages from: [1] Mathur et al. (2002), [2] Williams et al. (2005) and references therein, [3] Knight et al. (2000), [5] Campbell et al. (1998), [7] Grainger et al. (2008) and references therein counterparts, and are broadly penecontemporaneous with Phanerozoic IOCG deposits in convergent margin settings. The consistent temporal pattern for both Precambrian and Phanerozoic iron oxide (P) deposits, but inconsistent pattern for Precambrian and Phanerozoic IOCG deposits, raises the possibility that the Phanerozoic IOCG deposits, such as Candelaria, formed in iron oxide (P) provinces due to special tectonic or lithospheric conditions at the time. Thus, it is possible that Precambrian IOCG deposits will be found in the future in convergent margin settings with similar special lithospheric conditions to those known from the Phanerozoic.

The formation of world-class to giant IOCG deposits is mainly a Precambrian phenomenon related to preservation above buoyant and refractory Archean to Paleoproterozoic continental crust after formation via devolatilization of deeply sourced, low-degree partial melts possibly derived from fertile metasomatized SCLM generated through the impingement of mantle underplating near craton margins or near other lithospheric boundaries. The complexity of associated magmatism, with mafic (ultramafic) to felsic plutons, can be explained by mixing of parent mantle-derived magmas with felsic magmas derived from underplating of the parent magmas below continental crust (cf. Hart et al., 2004). The formation of Phanerozoic IOCG deposits was potentially restricted to anomalous extensional tectonic settings where generation of highly anomalous, volatile-rich, mantle-derived magmas beneath continental crust led to penecontemporaneous intrusions of mafic and felsic intrusions (e.g., Kerrich et al., 2005). With the exception of Candelaria, the Phanerozoic IOCG deposits have lower copper and gold grades than Precambrian analogs.

The characteristics and origin of IOCG deposits can best be understood by focusing on Cu-Au deposits that are demonstrably similar. These deposits have a common tectonic setting and an essential genetic association with ultrabasic to basic mantle-derived magmas, at least some with alkaline affinity. In particular, the largest deposits appear to be associated with metasomatized SCLM that was fertilized with volatiles, incompatible elements, and ore elements during prior subduction events, and was the ultimate source of the causative volatile-rich magmas. The buoyant SCLM also allowed preservation of even those IOCG deposits formed at or near the surface in the Proterozoic, contrasting markedly with the rapid erosion of most porphyry, epithermal, and other shallowly formed ore deposits in Phanerozoic arcs underlain by negatively buoyant SCLM.

Acknowledgments

We are grateful to Dwight Bradley, Rich Goldfarb, and David Leach for the invitation to prepare this paper, and to Rich Goldfarb for handling the reviewing process. We acknowledge the deposit and data synthesis of Pat Williams and co-authors without which this overview would have been impossible. We also acknowledge the stimulation provided by a presentation by Nick Haywood at AESC in Perth in 2008, which reinforced many concepts previously published by us and our associates and stimulated additional thoughts on IOCG deposits. We are grateful to Col Steel and Sue Groves for technical assistance. An insightful review was provided by Rob Kerrich. His knowledge of plume-related phenomena significantly improved the final paper.

REFERENCES

Artemieva, I.M., and Mooney, W.D., 2001, Thermal thickness and evolution of Precambrian lithosphere: A global study: Journal of Geophysical Research, v. 106, p. 16,387–16,414.

Baker, T., Mustard, R., Fu, B., Williams, P.J., Dong, G., Fisher, L., Mark, G., and Ryan, C.G., 2008, Mixed messages in iron-oxide-copper-gold systems of the Cloncurry district, Australia: insights from PIXE analysis of halogens and copper in fluid inclusions: Mineralium Deposita, v. 43, p. 599–608.

Barton, M.D., and Johnson, D.A., 1996, Evaporitic source model for igneous-related Fe oxide-(REE-Cu-Au-Au) mineralization: Geology, v. 24, p. 259–262.

Bastrakov, E.N., Skirrow, R.G., and Davidson, G.J., 2007, Fluid evolution and origins of iron oxide Cu-Au prospects in the Olympic Dam district, Gawler craton, South Australia: ECONOMIC GEOLOGY, v. 102, p. 1415–1440.

Bergman, S., Kübler, L., and Martinsson, O., 2001, Description of regional maps of northern Norrbotten country (east of the Caledonian orogen): Sveriges Geologiska Undersökning BA 56, 100 p.

Betts, P.G., Giles, D., and Lister, G.S., 2003, The Hitaba Event—an example of hotspot related flat subduction?: Geological Society of Australia, Abstracts, v. 27, p. 67.

Billström, K., Wasström, A., Bergström, U. and Stigh, J. 2002, Age, geochemistry and crustal contamination of the Hemberget mafic-ultramafic layered intrusion in the Knaften area, northern Sweden, *in* Bergman, S., ed., Radiometric dating results 5, SGU C834, p. 18–30.

Bindeman, I.N., and Bailey J.C., 1999, Trace elements in anorthite megacrysts from the Kurile Island Arc: A window to across-arc geochemical variations in magma compositions: Earth and Planetary Science Letters, v. 169, p. 209–226.

Campbell, J.H., Compston, D.M., Richards, J.P., Johnson, J.P., and Kent, A.R.J., 1998, Review of the application of isotopic studies to the genesis of Cu-Au mineralisation at Olympic Dam and Au mineralisation at Porgera, the Tennant Creek district, and Yilgarn craton: Australian Journal of Earth Sciences, v. 45, p. 201–218.

Chiaradia, M., Banks, D. Cliff, R., Marschik, R., and de Haller, A., 2006, Origin of fluids in iron oxide-copper-gold deposits: Constraints from δ^{37}Cl, ^{87}Sr/^{86}Sr, and Cl/Br: Mineralium Deposita, v. 41, p. 565–573.

Clark, A.H., and Kontak, D.J., 2004, Fe-Ti-P oxide melts generated through magma mixing in the Antauta subvolcanic center, Peru: Implications for the origin of nelsonite and iron oxide-dominated hydrothermal deposits: ECONOMIC GEOLOGY, v. 99, p. 377–395.

Cooke, D.R., Hollings, P., and Walshe, J.L., 2005, Giant porphyry deposits: Characteristics, distribution and tectonic controls: ECONOMIC GEOLOGY, v. 100, p. 801–818.

Dallmeyer, R.D., Brown, M., Grocott, J., Taylor, G.K., and Treloar, P.J., 1996, Mesozoic magmatic and tectonic events within the Andean plate boundary zone, 26°–27° 30'S, north Chile: Constraints from ^{40}Ar/^{39}Ar mineral ages: Journal of Geology, v. 104, p. 19–40.

Duncan, R., Hitzman, M., Nelson, E., Stein, H., Zimmerman, A., and Kirwin, D., 2009, Re-Os molybdenite ages for the southern Cloncurry IOCG district, Queensland, Australia: Protracted mineralization over 210 myr, *in* Williams, P.J., ed., Smart Science for Exploration and Mining: Economic Geology Research Unit, James Cook University, Proceedings of the 10th Biennial Meeting of SGA, p. 626–628.

Emsbo, P., Groves, D.I., Hofstra, A.H., and Bierlein, F.P., 2006, The giant Carlin gold province; A protracted interplay of orogenic, basinal, and hydrothermal processes above a lithospheric boundary: Mineralium Deposita, v. 41, p. 517–525.

Fishwick, S., Heintz, M., Kennett, B.L.N., Reading, A.M., and Yoshikawa, K., 2008, Steps in lithospheric thickness within eastern Australia, evidence from surface wave tomography: Tectonics, v. 27(4), TC0049, doi 10.129/2007TC002116.

Franklin, J.M., Gibson, H.L., Jonasson, I.R., and Galley, A.G., 2005, Volcanogenic massive sulfide deposits: ECONOMIC GEOLOGY 100TH ANNIVERSARY VOLUME, p. 523–560.

Goad, R.E., Mumin, A.H., Duke, N.A., Neale, K.L., and Mulligan, D.L., 2000, Geology of the Proterozoic iron oxide-hosted, NICO cobalt-gold-bismuth, and Sue Dianne copper-silver deposits, southern Great Bear magmatic zone, Northwest Territories, Canada, *in* Porter, T.M., ed., Hydrothermal iron oxide copper-gold and related deposits a global perspective: Adelaide, Australian Mineral Foundation, p. 249–268.

Goff, B.H., Weinberg, R., Groves, D.I., Vielreicher, N.M., and Fourie, P.J., 2004, The giant Vergenoeg fluorite deposit in a magnetite-fluorite-fayalite-REE pipe: A hydrothermally altered carbonatite-related pegmatoid?: Mineralogy and Petrology, v. 80, p. 173–199.

Goldfarb, R.J., Groves, D.I., and Gardoll, S., 2001, Orogenic gold and geological time: A global synthesis: Ore Geology Reviews, v. 18, p. 1–75.
Grainger, C.J., Groves, D.I., Tallarico, F.H.B., and Fletcher, I.R., 2008, Metallogenesis of the Carajás mineral province, southern Amazon craton, Brazil: Varying styles of Archean through Paleoproterozoic to Neoproterozoic base-and precious-metal mineralisation: Ore Geology Reviews, v. 33 p. 451–489.
Griffin, W.L., O'Reilly, S.Y., Abe, N., Aulbach, S., Davies, R.M., Pearson, N.J., Doyle, B.J., and Kivi, K., 2003, The origin and evolution of Archean lithospheric mantle: Precambrian Research, v. 127, p. 19–41.
Groves, D.I., and Bierlein, F.P., 2007, Geodynamic settings of mineral deposit systems: Journal of the Geological Society, London, v. 164, p. 19–30.
Groves, D.I., and Vielreicher, N.M., 2001, The Phalabowra (Palabora) carbonatite-hosted magnetite-copper sulfide deposit, South Africa: An end-member of the iron oxide-copper-gold-rare earth element deposit group?: Mineralium Deposita, v. 36, p. 189–194.
Groves, D.I., Ho, S.E., Rock, N.M.S., Barley, M.E., and Muggeridge, M.Y., 1987, Archean cratons, diamond and platinum: Evidence for coupled long-lived crust-mantle systems: Geology, v. 15, p. 801–805.
Groves, D.I., Condie, K.C., Goldfarb, R.J., Hronsky, J.M.A., and Vielreicher, R.M., 2005a, Secular changes in global tectonic processes and their influence on the temporal distribution of gold-bearing mineral deposits: ECONOMIC GEOLOGY, v. 100, p. 203–224.
Groves, D.I., Mair, J.L., Vielreicher, R.M., and Hart, C.J.R., 2005b, The lithospheric settings of Carlin-type deposits: An important clue to their genetic associations and deposit associates: Geological Society of Nevada Symposium 2005, Window on the World, Reno, Nevada, Proceedings, p. 1–11.
Groves, D.I., Vielreicher, R.M., Goldfarb, R.J. and Condie, K.C., 2005c, Controls on the heterogeneous distribution of mineral deposits through time, *in* Mc Donald, I. et al., eds., Mineral deposits and earth evolution: Geological Society, London, Special Publication, v. 248, p. 71–101.
Hand, M., Reid, A., and Jagodzinski, L., 2007, Tectonic framework and evolution of the Gawler Craton, southern Australia: ECONOMIC GEOLOGY, v. 102, p. 1377–1395.
Harris, N.B., and Einaudi, M.T., 1982, Skarn deposits in the Yerington district, Nevada: Metasomatic skarn evolution near Ludwig: ECONOMIC GEOLOGY, v. 77, p. 877–898.
Hart, C.J.R., Mair, J.L., Goldfarb, R.J., and Groves, D.I., 2004, Source and redox controls on metallogenic variations in ore systems, Tombstone-Tungsten Belt, Yukon, Canada: Transactions, Royal Society Edinburgh: Earth Sciences, v. 95, p. 339–356.
Haynes, D.W., 2000, Iron oxide copper(-gold) deposits: Their position in the ore deposit spectrum and modes of origin, *in* Porter, T.M., ed., Hydrothermal iron oxide copper-gold and related deposits a global perspective, 1: Adelaide, Australian Mineral Foundation, v. 1, p. 71–90.
Haynes, D.W., Cross, K.C., Bills, R.T., and Reed, M.H., 1995, Olympic Dam ore genesis: A fluid mixing model: ECONOMIC GEOLOGY, v. 90, p. 281–307.
Haywood, N., 2008, The geodynamic setting and magmatic controls on genesis of world-class IOCG ore deposits: Geological Society of Australia, Abstracts, v. 89, p. 130.
Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., and Richards, J.P., eds., 2005, ECONOMIC GEOLOGY 100TH ANNIVERSARY VOLUME, 1136 p.
Hitzman, M.W., 2000, Iron oxide-Cu-Au deposit: What, where, when, and why, *in* Porter, T.M., ed., Hydrothermal iron oxide copper-gold and related deposits a global perspective: Adelaide, Australian Mineral Foundation, p. 9–26.
Hitzman, M.W., and Valenta, R.K., 2005, Uranium in iron oxide-copper-gold (IOCG) systems: ECONOMIC GEOLOGY, v. 100, p. 1657–1661.
Hitzman, M.W., Oreskes, N., and Einaudi, M.T., 1992, Geological characteristics and tectonic setting of Proterozoic iron oxide (Cu-U-Au-REE) deposits: Precambrian Research, v. 58, p. 241–287.
Kennett, B.L.N., Fishwick, S., Reading, A.M., and Rawlinson, N., 2004, Contrasts in mantle structure below Australia: Relation to Tasman Lines?: Australian Journal of Earth Science, v. 51, p. 563–569.
Kerrich, R., Goldfarb, R.J., Groves, D.I., and Garwin, S., 2000, The geodynamics of world-class gold deposits: Characteristics, space-time distribution, and origins: Reviews in Economic Geology, v. 13, p. 501–552.
Kerrich, R., Goldfarb, R.J., and Richards, J.P., 2005, Metallogenic provinces in an evolving dynamic framework: ECONOMIC GEOLOGY 100TH ANNIVERSARY VOLUME, p. 1097–1136.
Kerrich, R., Goldfarb, R.J., Cline, J., and Leach, D., 2008, Metallogenic provinces of North America in a superplume-supercontinent framework: Arizona Geological Society Digest, v. 22, p. 1–18.
Knight, J., Lowe, J., Joy, S., Cameron, J., Merrillees, J., Nag, S., Shah, N., Dua, G., and Jhala, K., 2002, The Khetri copper belt, Rajasthan: Iron oxide copper-gold terrane in the Proterozoic of the NW India, *in* Porter, T.M., ed., Hydrothermal iron oxide copper-gold and related deposits a global perspective, 2: Adelaide, Australian Mineral Foundation, p. 321–341.
Large, R.R., 1975, Zonation of hydrothermal minerals at the Juno Mine, Tennant Creek goldfield, central Australia: ECONOMIC GEOLOGY, v. 70, p. 1387–1413.
Lilley, F.E.M., Wang, L.J., Chamalaun, F.H., and Ferguson, J.J., 2003, Carpentaria electrical conductivity anomaly, Queensland, as a major structure in the Australian Plate, *in* Hillis, R.R., and Muller, R.D. eds., Evolution and dynamics of the Australian Plate: Geological Society of Australia Special Publication 22 and Geological Society of America Special Paper 372, p. 141–156.
Marschik, R., and Fontboté, L., 2001, The Candelaria–Punta del Cobre iron oxide Cu-Au (-Zn-Ag) deposits, Chile: ECONOMIC GEOLOGY, v. 96, p. 1799–1826.
Marschik, R., Singer, B.S., Munizaga, C., Moritz, R., and Fontboté, L., 1997, Age of Cu(-Fe)-Au mineralization and thermal evolution of the Punta del Cobre district, Chile: Mineralium Deposita, v. 32, p. 531–546.
Marschik, R., Fontignie, D., Chiaradia, M., and Voldet, P., 2003, Geochemical and Nd-Sr-Pb-O isotope characteristics of granitoids of the Early Cretaceous Copiapó plutonic complex (27° 30's), Chile: Journal of South American Earth Science, v. 16, p. 381–398.
Mathur, R., Marschik, R., Ruiz, J., Munizaga, F., Leveille, R.A., and Martin, W., 2002, Age of mineralization of the Candelaria Fe oxide Cu-Au deposit and the origin of the Chilean iron belt, based on Re-Os isotopes: ECONOMIC GEOLOGY, v. 97, p. 59–71.
Maughan, D.T., Keith, J.D., Christiansen, E.H., Pulsipher, T., Hattori, K., and Evans, N.J., 2002, Contributions from mafic alkaline magmas to the Bingham porphyry Cu-Au-Mo deposit, Utah, USA: Mineralium Deposita, v. 37, p. 14–37.
Meinert, L.D., Dipple, G.M., and Nicoescu, S., 2005, World skarn deposits: ECONOMIC GEOLOGY 100TH ANNIVERSARY VOLUME, p. 299–336.
Meyer, C., 1988, Ore deposits as guides to geologic history of the Earth: Annual Reviews of Earth and Planetary Science, v. 16, p. 147–171.
Moss, R., Scott, S.D., and Binns, R.A., 2001, Gold content of eastern Marus basin volcanic rocks: Implications for enrichment in associated hydrothermal precipitates: ECONOMIC GEOLOGY, v. 96, p. 91–107.
Nyström, J.O., and Henriquez, F., 1994, Magmatic features of iron ores of the Kiruna-type in Chile and Sweden: Ore textures and magnetite geochemistry: ECONOMIC GEOLOGY, v. 89, p. 820–839.
Oreskes, N., and Einaudi, M.T., 1990, Origin of rare earth element-enriched hematite breccias at the Olympic Dam Cu-U-Au-Ag deposit, Roxby Downs, South Australia: ECONOMIC GEOLOGY, v. 85, p. 1–28.
Oreskes, N., and Einaudi. M.T., 1992, Origin of hydrothermal fluids at Olympic Dam: Preliminary results from fluid inclusions and stable isotopes: ECONOMIC GEOLOGY, v. 87, p. 64–90.
Oyarzun, R., Rodriguez, Pincheira, M., Doblas, M., and Helle, S., 1999, The Candelaria (Fe-Fe-Au) and Punta del Cobre (Cu-Fe) deposits (Copiapó, Chile): A case for extension-related granitoid emplacement and mineralization processes?: Mineralium Deposita, v. 34, p. 799–801.
Perring, C.S., Pollard, P.J., Dong, G., Nunn, A.J., and Blake, K.L., 2000, The Lightening Creek sill complex, Cloncurry district, northwest Queensland: a source for Fe-oxide Cu-Au mineralization and sodic-calcic alteration: ECONOMIC GEOLOGY, v. 95, p. 1067–1090.
Pollard, P.J., 2006, An intrusion-related origin for Cu-Au mineralization in iron oxide-copper-gold (IOCG) provinces: Mineralium Deposita, v. 41, p. 179–187.
Porter, T.M., ed., 2000, Hydrothermal iron oxide copper-gold and related deposits: A global perspective: Adelaide, Australian Mineral Foundation, 349 p.
——2002, Hydrothermal iron oxide copper-gold and related deposits: A global perspective 2: Adelaide, PGC Publishing, v. 2, 367.
Proffett, J.M. Jr., and Dilles, J.H., 1984, Geological map of the Yerington district, Nevada Bureau of Mines and Geology, Map 77, scale 1: 24,000.
Roberts, D.E., and Hudson, G.R.T., 1983, The Olympic Dam copper-uranium-gold-silver deposit, Roxby Downs, South Australia: ECONOMIC GEOLOGY, v. 78, p. 799–822.
Rogers, J.J.W., and Santosh, M., 2004, Continents and supercontinents: Oxford, Oxford University Press, 328 p.
Seedorff, E., Dilles, J.H., Proffett, J.M. Jr., Einaudi, M.T., Zurcher, L., Stavast, W.J.A., Johnson, D.A., and Barton, M.D., 2005, Porphyry deposits:

Characteristics and origin of hypogene features: ECONOMIC GEOLOGY 100TH ANNIVERSARY VOLUME, p. 251–298.

Seeger, C.M., 2003, Lithology and alteration assemblages of the Boss iron-copper deposit, Iron and Dent Counties, southeast Missouri: Unpublished Ph.D. thesis, University of Missouri-Rolla, 139 p.

Sillitoe, R.M., 2003, Iron oxide-copper-gold deposits: An Andean view: Mineralium Deposita, v. 38, p. 787–812.

Skiöld, T., 1987, Aspects of the Proterozoic geochronology of northern Sweden: Precambrian Research, v. 35, p. 161–167.

Skirrow, R.G., 2008, "Hematite-group" IOCG ± U ore systems: Tectonic settings, hydrothermal characteristics, and Cu-Au and U mineralizing processes *in* Corriveau, L., and Mumin, H., eds., Exploring for iron oxide copper-gold deposits: Canada and global analogues: GAC-MAC-SEG-SGA-2008, Quebec City, May 29–30, 2008, Geological Association of Canada, Short Course Notes.

Skirrow, R.G., and Walshe, J.L., 2002, Reduced and oxidized Au-Cu-Bi iron oxide deposits of the Tennant Creek inlier, Australia: an integrated geologic and chemical model: ECONOMIC GEOLOGY, v. 97, p. 1167–1202.

Skirrow, R.G., Bastrakov, E.N., Barovich, K., Fraser, G.L., Creaser, R., Fanning, M.C., Raymond, O.L., and Davidson, G.J., 2007, Timing of iron oxide Cu-Au-(U) hydrothermal activity and Nd isotope constraints on metal sources in the Gawler craton, South Australia: ECONOMIC GEOLOGY, v. 102, p. 1441–1470.

Smith, M., Coppard, J., Herrington, R., and Stein, H., 2007, The geology of the Rakkurijärvi Cu-(Au) prospect, Norbotten: A new iron oxide-copper-gold deposit in northern Sweden: ECONOMIC GEOLOGY. v. 102, p. 393–414.

Solomon, M., and Groves, D.I., 2000, The geology and origin of Australia's mineral deposits: Hobart Printing Authority of Tasmania, 1002 p.

Sun, S.S., and McDonough, W.F., 1989, Chemical and isotopic characteristics of ocean basalts: Implications for mantle composition and processes: Geological Society of London Special Publication 42, p. 313–345.

Verwoerd, W.J., 1993, Update on carbonatites of South Africa and Namibia: South African Journal of Geology, v. 96, p. 75–95.

Wade, B.P., Barovich, K.M., Hand, M., Scrimgeour, I.R., and Close, D.F., 2006, Evidence for early Mesoproterozoic arc magmatism in the Musgrave Block, central Australia: Implications for Proterozoic crustal growth and tectonic reconstructions of Australia: The Journal of Geology, v. 114, p. 43–63.

Wall, V.J., and Valenta, R.K., 1990, Ironstone-related gold-copper mineralisation: Tennant Creek and elsewhere: Pacific Rim Congress 90: Australasian Institute of Mining and Metallurgy, Melbourne, Australia, Proceedings, p. 855–864.

Williams, P.J., and Pollard, P.J., 2003, Australian Proterozoic iron oxide Cu-Au deposits: An overview with new metallogenic and exploration data from the Cloncurry district, northwest Queensland: Exploration and Mining Geology, v. 10, p. 191–213.

Williams, P.J., Barton, M.D., Johnson, D.A., Fontboté, L., de Haller, A., Mark, G., Oliver, N.H.S., and Marschik, R., 2005, Iron oxide copper-gold deposits: Geology, Space-time distribution, and possible modes of origin: ECONOMIC GEOLOGY 100TH ANNIVERSARY VOLUME, p. 371–405.

Wilson, M.G.C., 1998, Copper, *in* Wilson, M.G.C., and Anhauesser, C.R., eds., The mineral resources of South Africa: Handbook, Council for Geoscience, 16, p. 209–227.