IRON OXIDE COPPER-GOLD (±AG ±NB ±P ±REE ±U) DEPOSITS: A CANADIAN PERSPECTIVE

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IOCG Deposit Types

Definition

Iron oxide copper-gold (IOCG) deposits encompass a wide spectrum of sulphide-deficient low-Ti magnetite and/or hematite ore bodies of hydrothermal origin where breccias, veins, disseminations and massive lenses with polymetallic enrichments (Cu, Au, Ag, U, REE, Bi, Co, Nb, P) are genetically associated with, but either proximal or distal to large-scale continental, A- to I-type magmatism, alkaline-carbonatite stocks, and crustal-scale fault zones and splays. The deposits are characterized by more than 20% iron oxides. Their lithological hosts and ages are non-diagnostic but their alteration zones are, with calcic-sodic regional alteration superimposed by focused potassic and iron oxide alterations. The deposits form at shallow to mid crustal levels in extensional, anorogenic or orogenic, continental settings such as intracratonic and intra-arc rifts, continental magmatic arcs and back-arc basins. Margins of Archean craton where arcs and successor arcs were developed appear to be particularly fertile.

Currently known metallogenic IOCG districts (Fig. 1) occur in Precambrian shields worldwide as well as in Circum-Pacific regions (e.g. Carlon, 2000; Fourie, 2000; Porter, 2000, 2002a and papers therein; Strickland and Martyn, 2002; Gandhi, 2004c; Goff et al., 2004). Though there is no producing mine of this deposit type in Canada, exploration is accelerating throughout the country. The most prospective settings are located in the Proterozoic granitic and felsic gneiss terranes of the Canadian Shield, and in parts of the Cordilleran and the Appalachian orogens. Many share hallmarks of the 3810 Mt Olympic Dam deposit in Australia, the deposit that guides most mineral exploration worldwide (Hitzman et al., 1992; Western Mining Corporation, 2004). Metamorphosed IOCG deposits are known and exploration should also encompass metamorphosed volcano/sedimentary-plutonic belts and their gneissic derivatives.

Many of the Canadian favourable "pinkstone belts" are poorly known or understood. Hence, this synthesis of IOCG deposits focuses on the regional and local geological features that can help unveil prospective zones and targets in terranes that may otherwise be ignored or underexplored.

The recognition of this deposit type was triggered by the 1975 discovery of the giant Olympic Dam deposit in Australia (Roberts and Hudson, 1983) followed by the discovery of Starra (1980), La Candelaria (1987), Osborne (1988), Ernest-Henry (1991), and Alemao (1996). The early discoveries served to define this group of deposits as the IOCG deposit type in the 1990s (Hitzman et al., 1992). Since then, new discoveries, re-classification of existing deposits and worldwide research have led to the recognition of the oxide-mineralizing systems and the publication of a number of landmark papers and volumes (Gandhi and Bell, 1993; Kerrich et al., 2000; Porter, 2000, 2002a; Ray and Lefebure, 2000; Groves and Vielreicher, 2001; Sillitoe, 2003; Barton and Johnson, 2004).

Because of the diversity of IOCG deposits there is debate whether they form a single deposit type or whether they are iron oxide-rich variants of other deposit types. In this synthesis, IOCG deposits are considered a bona fide deposit type. Polymetallic deposits lacking significant iron oxides are not considered herein as IOCG deposits while hydrothermal monometallic, low-titanium magnetite and/or hematite iron deposits (i.e., iron as sole significant metal) and polymetallic iron deposits with Nb and REE as important economic commodities are considered end-members of the IOCG deposits spectrum. This broad approach to IOCG deposits is taken even though it groups together world-class deposit types with deposit types that may not be worthy of discovery in terms of actual mineral economics. This stand is taken because the currently low value monometallic iron deposits outnumber polymetallic ones and serve as important pathfinders for grass roots exploration.

IOCG Deposit Subtypes

A consequence of the diversity in IOCG deposits, and of the brief time span since the recognition of this deposit group, is the diverging opinions on their genesis and the necessity of classifying them. With the current inadequate state of knowledge, genetic classifications are untenable and descriptive ones necessarily oversimplified and somewhat arbitrary. The classification elaborated by Gandhi (2003, 2004a) for the World Minerals Geoscience's Database Project is used herein. It comprises six sub-types named after the world-class to giant deposits or the mineral districts whose characteristics best exemplify the spectrum currently observed (Table 1). Four of them are genetically related to calc-alkaline magmatism and the other two are related to alkaline-carbonatite magmatism.

The Olympic Dam sub-type consists of granite-associated, breccia-hosted deposits where polymetallic ore is spatially and temporally associated with iron oxide alteration and as such share similarities with the iron oxide-rich Cu-Au-U-Ag-REE Olympic Dam deposit at the eastern margin of the Gawler Craton of South Australia (Roberts and Hudson, 1983; Reeve et al., 1990; Hitzman et al., 1992;

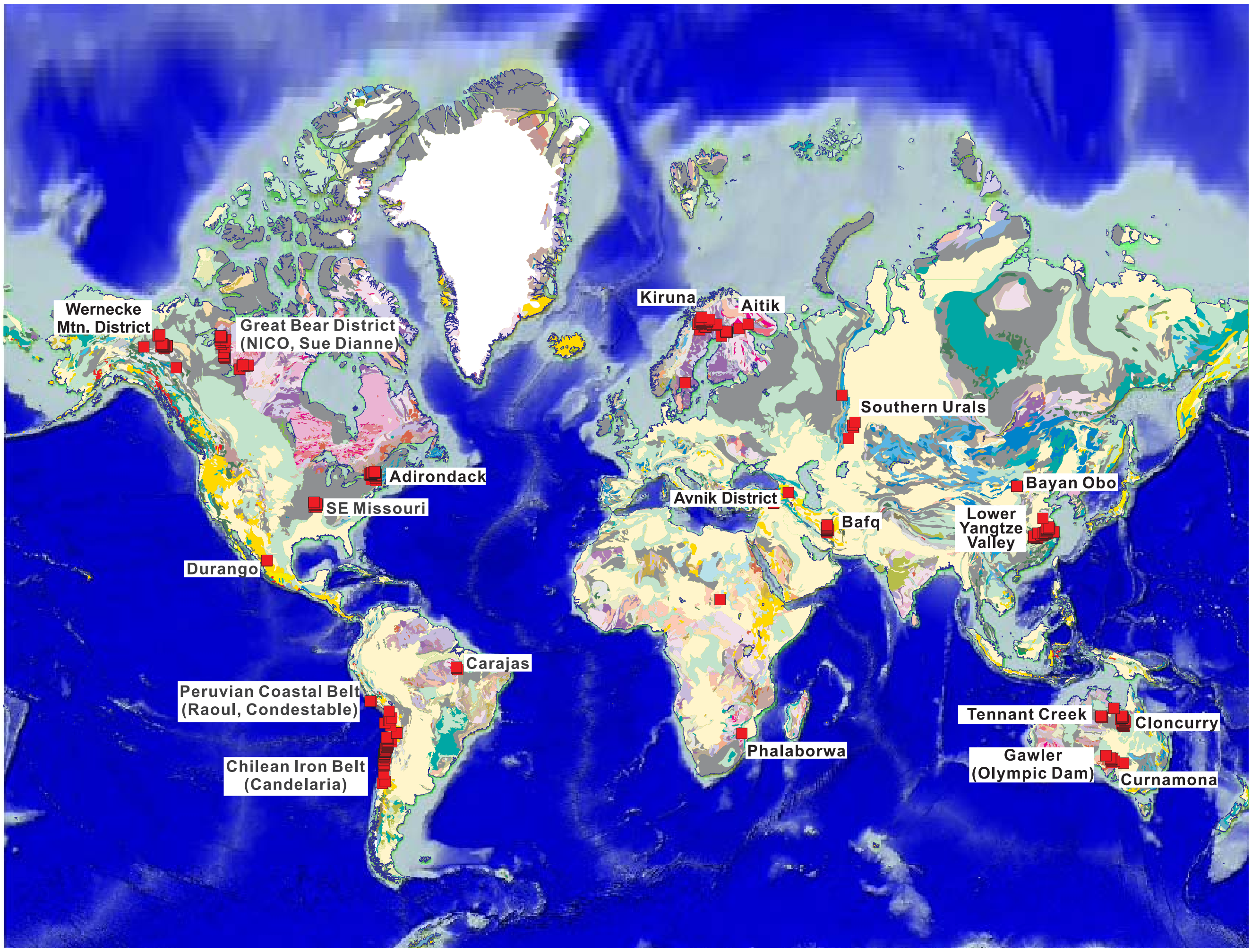

Fig. 1. Distribution of IOCG districts and important deposits worldwide (red dots). Australia: Gawler (Olympic Dam, Acropolis, Moonta, Oak Dam, Prominent Hill and Wirrda Well deposits), Cloncurry (Ernest Henry, Eloise, Mount Elliot, Osborne and Starra deposits), Curnamona (North Portia and Cu Blow deposits) and Tennant Creek (Gecko, Peko/Juno and Warrego deposits) districts; Brazil: Carajas district (Cristalino, Alemao/Igarapé Bahia, Salobo, and Sossego deposits); Canada: Great Bear Magmatic Zone (Sue-Dianne and NICO deposits), Wernecke, Iran Range, West Coast skarns and Central Mineral Belt districts, and Kwyjibo deposit; Chile: Chilean Iron Belt (Candelaria, El Algarrobo, El Romeral, Manto Verde, and Punta del Cobre deposits); China: Bayan Obo deposit (Inner Mongolia), Lower Yangtze Valley district (Meishan and Daye deposits); Iran: Bafq district (Chogust, Chadoo Malu, Seh Chahoon deposit); Mauritania: Akjoujt deposit; Mexico: Durango district (Cerro de Mercado); Peru: Peruvian Coastal Belt (Raul, Condestable, Eliana, Monterrosas and Marcona deposits); Sweden: Kiruna district (Kiirunavaara, Loussavaara), Aitik deposit (also described as a porphyry Cu deposit); South Africa: Phalaborwa and Vergenoeg deposits; USA: Southeast Missouri (Pea Ridge and Pilot Knob deposits); Adirondack and Mid-Atlantic Iron Belt (Reading Prong); Zambia: Shimyoka, Kantonga, and Kitumba prospects.

Johnson and Cross, 1995; Hitzman, 2000; Reynolds, 2000; Ferris et al., 2002; Skirrow et al., 2002 and references therein).

The Olympic Dam deposit is hosted within a 7 by 5 km (in plan), funnel-shaped, hematite-rich hydrothermal breccia (Olympic Dam Breccia Complex, Reeve et al., 1990). The breccia complex comprises a hematite-quartz breccia core, a peripheral hematite-granite breccia and a halo of weakly altered and brecciated granite. The breccias were formed close to the surface through progressive, polyphase hydrothermal brecciation and alteration of the A-type Roxby Downs granite of the Hiltaba intrusive suite (Cross et al., 1993; Haynes et al., 1995; Reynolds, 2000), and are not of a sedimentary origin as originally interpreted (Roberts and Hudson, 1983). Potassic alteration with hematite, sericite, chlorite, carbonate ± Fe-Cu sulphides ± uraninite, pitchblende and REE minerals prevails, and is locally superimposed on a magnetite-biotite alteration (Reynolds, 2000; Skirrow et al., 2002).

The felsic to mafic Hiltaba suite together with the Gawler Range volcanics, forms a very fertile ca. 1.59 Ga extensional volcano-plutonic setting, currently interpreted as an intracontinental back arc in contrast to earlier anorogenic interpretations (Skirrow et al., 2002; Ferris and Schwarz, 2003; see section on continental-scale knowledge gaps further below). The deposit occurs in the vicinity of an Archean craton at the core of a doubly vergent orogen above an anomalous nonreflective lower crust that extends to the Moho forming a major window in an otherwise reflective Moho (Lyons et al., 2004). Like many other IOCG deposits and prospects, Olympic Dam is a blind deposit discovered by its coincident positive magnetic and gravity anomalies during grass roots exploration for mafic volcanic associated copper deposits (Reynolds, 2000). In this sub-type, some 75

Table 1. Classification of magmatic-hydrothermal iron oxide deposits and related Cu Au deposits (after Gandhi, 2003, 2004a).

Source → *Proximal* → *Distal*

Calc-alkaline magma

Iron Skarn-type	Kiruna-type	Olympic Dam-type	Cloncurry-type
Massive magnetite-garnet-pyroxene	Massive magnetite-apatite-actinolite	Breccia (one or more stages), magnetite-hematite matrix	Hydrothermal veins & disseminations in older ‘ironstones’ or FeOx mineralization
Stratabound lensoid & irregular bodies at intrusive contact	Tabular, pipe-like & irregular bodies, dykes & veins	Pipe-like & irregular bodies, vent or fault controlled	Stratabound, breccia or fault controlled
Monometallic Fe and related FeOx-Cu-Au deposits	Monometallic Fe & related Cu-FeOx porphyry deposits	Polymetallic: Fe, Cu, Au, Ag, REE	Polymetallic: Cu, Au, Ag, Bi, Co, W
Alteration: Sodic	Alteration: Sodic	Alteration: Potassic	Alteration: Potassic
Magnitogorsk deposit, Russia	Kiirunavaara deposit, Sweden	Olympic Dam deposit, Australia	Osborne & Starra deposits, Australia

Source → *Proximal* → *Distal*

Alkaline-carbonatite magma

Phalaborwa-type	Bayan Obo-type
Within or marginal to intrusion	Hosted by country rock
Veins, layers, disseminations and aggregates; late intrusive phase	Veins, layers, disseminations and aggregates, stratabound lenses
Low Ti magnetite, apatite, olivine, phlogopite, carbonate, fluorite, Cu sulphides, pyrite, PGE, Au, Ag, uranothorianite, baddeleyite	Magnetite (replacive and/or pre-existing), hematite, bastnaesite, phlogopite, Fe-Ti-Cr-Nb oxides, fluorite, monazite, carbonate
Zoning in ore; Na & K alteration	Zoning in ore; Na & K alteration
Phalaborwa deposit, South Africa	Bayan Obo deposit, China

deposits and prospects are now entered in the World Minerals Geoscience Database (WMD; Gandhi, 2004c).

The Cloncurry sub-type, with 55 examples in the WMD, is named after the Cloncurry district in the Mount Isa inlier of Northwest Queensland, Australia. It comprises deposits where hydrothermal Cu ± Au mineralization overprints pre-existing 'ironstones' or iron formations (Starra, Salobo) or distinctly earlier hydrothermal iron oxide concentrations (Ernest Henry) (Requia and Fontboté, 2000; Gandhi, 2003; Requia et al., 2003). Though host lithologies play an important local role, mineralization is mainly fault or shear controlled (Partington and Williams, 2000; Marshall, 2003). For example, in the ca. 1.50 Ga Ernest Henry deposit, mineralization postdates peak metamorphism of a ca. 1.74 Ga volcanic host and is synchronous with granite intrusions and regional alteration (Mark et al., 2000). Early magnetite-apatite mineralization and associated Na-Ca alteration were followed by brecciation in a zone between two shears, and then overprinted by Cu-Au mineralization. Ductility contrast at the local and regional scale also played an important role (Partington and Williams, 2000; Marshall, 2003). Host lithologies may be significantly deformed and metamorphosed prior to mineralization and granite emplacement (up to upper amphibolite facies), or as at Osborne, mineralization may be metamorphogenic. The Osborne deposit, formerly considered to be of the same age as the other IOCG deposits of the Cloncurry district at ca. 1.5 Ga (e.g. Adshead et al., 1998), is in fact older (1595-1600 Ma) and syn-peak metamorphism (Gauthier et al., 2001). Local remobilization of iron oxides in the host rocks and/or addition of iron oxides from external sources may occur (Partington and Williams, 2000). Potassic and calcic-sodic (Na-Ca) alterations are common and, in many cases, widespread and intense.

The Kiruna sub-type, with more than 355 deposits and prospects, comprises monometallic, low Ti and V magnetite-apatite deposits with little or no Cu and Au (Hitzman et al., 1992; Hitzman, 2000). It is named after the classic Kiruna district in northern Sweden and includes the world class Kiirunavaara massive magnetite deposit, as well as the Luossavaara, Rektorn, Haukivaara, Nukutusvaara, Lappmalmen and Mertainen deposits in Sweden, the Bafq district in Iran as well as several deposits in the Andes (Frietsch et al., 1979; Daliran, 2002; Gandhi, 2003; Sillitoe, 2003). These deposits are generally coeval with, and genetically related to their host volcanic and plutonic rocks (see review in Gandhi, 2003). Their massive veins, tabular, pipe-like, or irregular bodies and associated sodic and calcic-sodic alterations represent a precursor to some significant Cu-Au mineralization both in intracratonic and in continental arc settings (Hitzman, 2000; Mark and Foster, 2000; Mark et al., 2000; Ray and Dick, 2002; Skirrow et al., 2002; Sillitoe, 2003). Large-scale sodic metasomatism results in the formation of very diagnostic albitites.

The Phalaborwa (Palabora) sub-type consists of magnetite-rich deposits formed coevally with and proximal to alkaline-carbonatite intrusions (Groves and Vielreicher, 2001; Goff et al., 2004). Primary characteristics are the presence of apatite and strong fenitization, the strong enrichment in REE, F and P, and the extremely high LREE to HREE ratios. The REE's are contained in apatite and in a variety of REE-bearing phases. Zirconium can be high and resides in baddeleyite. Titanium content of magnetite in the host intrusions is variable (< 1 to 4 wt % TiO_2) and is higher than in magnetite of most IOCG deposits. The lowest Ti contents of magnetite are in the ore zones related to the intrusions.

Among the alkaline-carbonatite intrusions, the 2.06 Ga Phalaborwa Complex in South Africa is exceptional in having an economic grade of copper. It consists of a magnetite-rich pipe-like ore body hosted in a carbonatite phase of an alkaline pyroxenite intrusion. The ore body is zoned, with copper sulphides concentrated in the core, and magnetite toward the margin (Harmer, 2000). Copper sulphides (chalcopyrite or bornite and minor chalcocite) postdate the iron-oxide mineralization. No structural control has been documented for the Phalaborwa Complex, but its setting at the margin of an Archean craton is viewed by Vielreicher et al. (2000) as a key element in the development of the ore deposit.

The Bayan Obo sub-type consists of magnetite-rich, Cu-Au deficient, REE (-Nb) deposits distal to an alkaline-carbonatite plutonic source that display the diagnostic mineral assemblages and metal of the source magmas (Smith and Chengyu, 2000). At the Bayan Obo deposit, the ore occurs as massive, banded and disseminated forms in marble deposited in grabens on the margin of the Archean North China craton. Ore mineralogy, with some 70 minerals, is dominated by magnetite, bastnaesite, fluorite, alkali amphiboles and pyroxenes while alteration assemblage consists of apatite, aegirine, aegerine-augite, fluorite, alkali amphibole, phlogopite and barite (Smith et al., 2000). This mineral suite is diagnostic of an alkaline-carbonatite magmatic source for the mineralizing fluids. In the vicinity of the deposit, the only exposed link with such magmatism is the presence of some carbonatite dykes. The age of mineralization is quoted either as between 555-420 Ma (Chao et al., 1997; Smith et al., 2000) or at 1.3-1.2 Ga (Yang et al., 2003). The fact that marble is a host complicates the recognition of carbonatite in the field, as the two lithologies may look very similar. The lack of significant coeval magmatism but the presence of deep-seated faults active since the Proterozoic time in the area illustrate that significant iron oxide ore may form even if coeval magmatism is volumetrically insignificant as long as channel ways for fluids are available.

The iron-skarn sub-type shares some features with the Kiruna sub-type, and includes major deposits in the southern Urals region and in the Peruvian Coastal Belt (Ray and Lefebure, 2000; Herrington et al., 2002; Injoque, 2002; Gandhi, 2003; Sillitoe, 2003). This sub-type is included in the IOCG clan, because the anhydrous minerals garnet and pyroxene, typical of early prograde alteration in skarn deposits and related to mineralization (e.g. Meinert et al., 2003), are also encountered in atypical iron oxide deposits.

Associated Mineral Deposit Types

On a district scale, IOCG deposits are known to occur in the vicinity of alkaline and calc-alkaline porphyry Cu-Mo or Cu-Au deposits, Cu-Ag manto deposits, volcanic-hosted uranium ore bodies, hematite-rich massive ironstones, sediment-hosted Au-PGE, polymetallic Ag-Pb-Zn±Au veins and SEDEX deposits and rarely near volcanic-hosted massive sulphide deposits (Pollard, 2000; Boric et al., 2002; Grainger et al., 2002; British Columbia Geological Survey, 2003; Sillitoe, 2003). Though graphite is lacking in IOCG settings, there may be an association with hydrothermal iron sulphide Cu-graphite mineralization in spatially distinct areas (cf. Mumin and Trott, 2003). Near surface supergene enrichment of U, Cu and/or Au in blankets or veins may improve the economics of initial mine operations, as is the case for the Igarapé Bahia deposit in the Carajás district, Brazil (Tazava and de Oliveira, 2000). The spatial association of IOCG deposits with essentially coeval SEDEX deposits can be particularly striking even though no genetic link is apparent (e.g. Mount Isa vs Cloncurry district, and Broken Hill vs Olympic Dam in Australia, Kabwe vs the Shimyoka, Kantonga, and Kitumba prospects in Zambia, Sullivan vs Iron Range prospects in Canada; Gandhi and Bell, 1993; Haynes, 2000; Ray and Lefebure, 2000; British Columbia Geological Survey, 2003).

Economic Characteristics

IOCG deposits can have enormous geological resources (Table 2; Figs. 2 and 3) with significant reserves of base, precious and other metals. They are major sources of Fe, Cu, Au, U, REE (LREE), F, vermiculite, significant sources of Ag, Nb, P, Bi, Co; and sources of various by-products including PGE, Ni, Se, Te, Zr. They also contain several associated elements, notably As, B, Ba, Cl, Co, F, Mo, Mn, W, (Pb, Zn).

The 3810 Mt Olympic Dam deposit (Table 2) contains

Table 2. Resources of selected IOCG deposits.

Deposit	Country	Resources[1]	Grade	Key References
Pea Ridge	US	120 Mt	57% Fe	Gandhi, 2003
Kiruna district	Sweden	3400 Mt	60% Fe (400 Mt produced)	Gandhi, 2003
NICO	Canada	42 Mt	0.5g/t Au, 0.1% Co, 0.12%Bi	Goad et al., 2000
		1500 Mt	35% Fe	
Bayan Obo	China	48-100Mt	6% REE_2O_3	Smith and Chengyu, 2000
		1Mt	0.13% Nb	
Phalaborwa	South-Africa	850 Mt	0.5% Cu (+ Au, Ag, PGE, U, Zr, REE, Ni, Se, Te, Bi)	Leroy, 1992
Monakoff	Australia	1 Mt	1.5% Cu, 0.5g/t Au (Pb, Zn, U)	Williams and Skirrow, 2000
Eloise	Australia	3 Mt	5.5% Cu, 1.4g/t Au (+ Fe, Ni)	Williams and Skirrow, 2000
Starra	Australia	7.4 Mt	1.9% Cu, 3.8 g/tAu (ironstone)	Rotherham et al., 1998
Sue Diane	Canada	17 Mt	0.72% Cu, 2.7g/t Ag	Goad et al., 2000
Osborne	Australia	15.5 Mt	3.0% Cu, 1.05g/t Au (metamorphosed)	Gauthier et al., 2001
Ernest Henry	Australia	167 Mt	1.1% Cu, 0.5g/t Au	Williams and Skirrow, 2000
Igarapé Bahia	Brazil	170 Mt	1.5% Cu, 0.8g/t Au	Ronze et al., 2000
Sossego	Brazil	355 Mt	1.1% Cu, 0.28 g/t Au	Haynes, 2000
		380 Mt[2]	0.4% Cu, 0.2g/t Au, 4g/t Ag[2]	Wanhainen et al., 2003
Aitik	Sweden	226 Mt[3]	0.37% Cu, 0.2g/t Au, 3g/t Ag[3]	
		850 Mt		
Candelaria	Chili	470 Mt	0.95% Cu, 0.22g/t Au, 3.1g/t Ag	Marschik et al., 2000
Cristalino	Brazil	500 Mt	1% Cu, 0.30g/t Au	Tallarico et al., 2004
Manto Verde	Chili	600 Mt	0.5% Cu, 0.1g/t Ag	Sillitoe, 2003
Salobo	Brazil	789 Mt	0.96% Cu, 0.52 g/t Au	Souza and Vieira, 2000
Olympic Dam	Australia	3810 Mt	1.1% Cu, 0.4kg/t U_3O_8, 0.5 g/t Au	Western Mining Corp., 2004
		2000 Mt	0.24-0.45% La + Ce; 0.3285% REO	Orris and Grauch, 2002

[1] calculated; [2] produced; [3] reserve.

the world's largest uranium resources (1.4 Mt) and the fourth largest current copper and gold resources with 42.7 Mt and 55.1 M ounces, respectively (Western Mining Corporation, 2004). Resources for individual commodities are as high as some of the best examples of VHMS Au deposits in Canada and porphyry Cu worldwide (Figs. 2 and 3). Ore reserves (proved and probable) were reaching 730 Mt at 1.6 % Cu, 0.5 % U and 0.5 g/t Au in 2003 (Western Mining Corporation, 2003). Rare earths (La and Ce) contents reach 5000 ppm, but in contrast to the Phalaborwa deposit, their recovery is currently not economical (Reynolds, 2000). Production started in 1978 and reached 9 Mt of ore in 2002 (178120 t Cu and 2890 t U_3O_8). The low gold values are not to be underestimated as the large tonnage of IOCG deposits compensates for the very low grades (e.g. Hitzman, 2000).

Several of the giant IOCG deposits belong to the Olympic Dam sub-type (e.g. 600 Mt Manto Verde and 470 Mt La Candelaria), fewer belong to the other sub-types (e.g. Cloncurry sub-type 789 Mt Salobo deposit; Table 2). The Phalaborwa deposit (Table 2) is presently the world's second largest copper mine and has by-products of Au, Ag, platinum group metals, magnetite, P, U, Zr, REE, Ni, Se, Te, and Bi (Leroy, 1992). The Bayan Obo deposit hosts the world's largest resource of rare earths, and is presently the principal rare-earths producer (Orris and Grauch, 2002). In Canada, the largest IOCG deposit is the 42 Mt NICO deposit (Lou Lake) of the Cloncurry sub-type, while the 17 Mt Sue-Dianne deposit of the Olympic Dam sub-type contains metals comparable to those of the Starra deposit in the Cloncurry district (Table 2). It is currently undergoing feasibility studies.

Exploration Properties

The physical, mineralogical and geological properties of IOCG deposits are summarized below to provide insights on what may or may not be detectable by conventional or emergent field, geophysical, geochemical or remote sensing mapping techniques. Details are available in Hitzman et al. (1992), Hitzman (2000), Partington and Williams (2000), papers and references in Porter (2000, 2002a), Ray and Lefebure (2000), Clark (2003), Requia et al. (2003), and Sillitoe (2003).

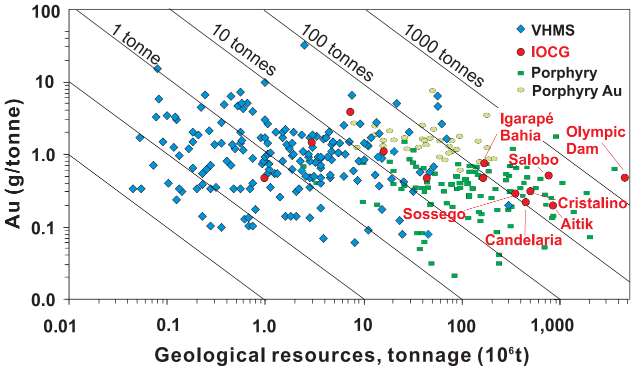

Fig. 2. Au grade and tonnage characteristics of VHMS, porphyry Cu and IOCG deposits from Kirkham and Sinclair (1996), Galley et al. (2005), and Table 2.

Physical Properties

Mineralogy

A striking characteristic of IOCG deposits is their alteration zones. Three main types are found: calcic-sodic, iron and potassic alterations. The calcic-sodic (Na-Ca) alteration zones are regional in scale (>1 km wide) and range from a strong albitization (± clinopyroxene, titanite), such as in the Cloncurry district, to the CAM assemblage of Skirrow et al. (2002) with calc-silicate (clinopyroxene, amphibole, garnet) - alkali feldspar (K-feldspar, albite) ± Fe-Cu sulphides, and various assemblages including albite, actinolite, magnetite, apatite and late epidote (Pollard et al., 1998; Wyborn, 1998; Ray and Lefebure, 2000). If Ca-rich host-rocks are present, Fe-rich garnet-clinopyroxene ± scapolite skarn assemblages may form (e.g. Heff prospect, British Columbia; Candelaria, Chile; Kiruna, Sweden; Shimyoka and Kantonga prospects, Zambia; Ray and Lefebure, 2000; Ray and Webster, 2000). These alterations are early and tend to prepare the ground for the subsequent alterations.

The second, iron-rich stage commonly consists of an influx of magnetite ± biotite as found in the eastern Gawler craton (MB stage of Skirrow et al., 2002). Downes (2003) describes this stage as having an 'ABS' or 'anything but sulphides' composition. He includes within this stage iron oxide (magnetite and hematite), iron carbonate (siderite and ankerite) and iron silicate (chlorite and amphibole, in particular grunerite and hastingsite). This stage is largely sterile except for iron ore and apatite. Magnetite forms at greater depth and/or at higher temperature than the subsequent, more focussed and commonly crosscutting alteration.

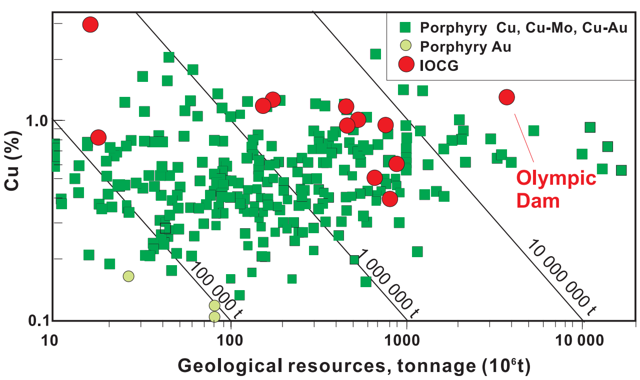

Fig. 3. Cu grade and tonnage characteristics of the geological resources of IOCG deposits with respect to those of porphyry Cu based on Kirkham and Sinclair (1996).

The main ore stage is associated with potassium-iron alteration zones in which either sericite (at Olympic Dam and Prominent Hill) or K-feldspar (most common) prevail as the potassic phase (Skirrow et al., 2002; Belperio and Freeman, 2004). K-feldspar-hematite veins (Wyborn, 1998) or an alteration assemblage of hematite - sericite- chlorite-carbonate ± Fe-Cu sulphides ± U, REE minerals (HSCC of Skirrow et al., 2002) are observed. Intense chloritization may result in almost total destruction of hydrothermal biotite. Other minerals common in the alterations assemblages are quartz, fluorite, barite, carbonate, orthoclase, epidote and tourmaline. Titanite, monazite, perovskite and rutile may also occur and provide a means of establishing directly the age of alteration (as discussed below).

The ore mineral phases vary considerably among the deposits (Ray and Lefebure, 2000). The principal ones are hematite (specularite, botryoidal hematite and martite), low-Ti magnetite, bornite, chalcopyrite, chalcocite and pyrite. Subordinate ones include Ag-, Cu-, Ni-, Co-, U-arsenides, autunite, bastnaesite, bismuthinite, brannerite, britholite, carrolite, cobaltite, coffinite, covellite, digenite, florencite, loellingite, malachite, molybdenite, monazite, pitchblende, pyrrhotite, sulphosalts, uraninite, xenotime, native bismuth, copper, silver and gold, Ag-, Bi-, Co-telluride, and vermiculite. Gangue mineralogy consists principally of albite, K-feldspar, sericite, carbonate, chlorite, quartz (cryptocristalline in some cases), amphibole, pyroxene, biotite and apatite (F- or REE-rich) with accessory allanite, barite, epidote, fayallite, fluorite, ilvaite, garnet, monazite, perovskite, phlogopite, rutile, scapolite, titanite, and tourmaline. The amphibole includes Fe-, Cl-, Na- or Al-rich hornblende (edenite), actinolite, grunerite, hastingsite, and tschermakitic or alkali amphibole. Carbonates include calcite, ankerite, siderite and dolomite. Late-stage veins contain fluorite, barite, siderite, hematite and sulphides.

Textures

The morphology of IOCG mineralization varies significantly and includes breccia zones (Fig. 4), veins, and irregular bodies; stratiform, stratabound, or discordant deposits, and disseminations to massive lenses (skarns, mantos).

The mineralization can be hosted in sub-vertical to sub-horizontal, single or polyphase breccia zones or in mantos, veins, stockwork, volcanic pipes, diatremes, lenses, massive concordant to crosscutting tabular bodies and in rare mineralized clasts. It can also occur as disseminations through host rock or surround single or multiple lenses of massive ore.

The host breccias are commonly heterolithic and composed of distinct angular to sub-angular or more rarely rounded lithic and oxide clasts or fine-grained massive material where fragments may be difficult to recognize. The breccias vary in size from outcrop to mountain scale (1 m^2 to 10 km^2), in colour from grey, to black, greenish or mottled red and pink, and in fragment sizes from <1 cm up to hundreds of metres in length or thickness, making breccias, where present, the most striking elements of IOCG deposits. The

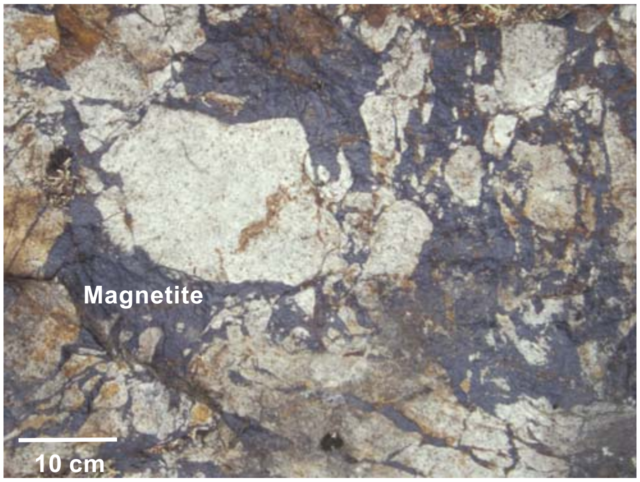

Fig. 4. Magnetite breccia, Kwyjibo deposit, Québec.

Wernecke Breccia in Canada provides spectacular mountain-face examples (Thorkelson, 2000). Brecciation occurs either close to surface or well below surface and fragments can be derived in situ or are remobilized from above or below. Core zones of breccias may contain up to 100% iron ore and grade into crackle breccia, where host rocks display incipient brecciation, to weakly fractured and iron-oxide or carbonate-veined host-rocks at the margins. As such, the boundary of breccias tends to be gradational over the scale of centimetres to several metres. They can also be sharp where they abut against faults or where intrusion of breccia material into country rocks occurs. Diffuse, wavy layered textures of red and black hematite and partial to complete replacement and pseudomorphs of early magnetite or host rock textures (e.g. lapilli) and filling of microcavities by hematite are common (discussed in detail in Ray and Lefebure, 2000). The breccias are generally aligned along fault zones and splays or, in some cases, sub-parallel to strata or intrusive contacts. They may also crosscut or be superimposed concordantly on host lithology or alteration zones.

Hydrothermal breccias can be difficult to distinguish from volcanic breccia and lapillistone. At the Kwyjibo deposit in Québec (Fig. 5) Clark (2003) interprets the main fragmental unit as a breccia zone while Gauthier et al. (2004) interpret it as pyroclastic rock. Breccias have also been mapped as deformed basal conglomerate, which upon re-examination were identified as brecciated calcic to potassic-altered metatonalite (Schwerdtner et al., 2003).

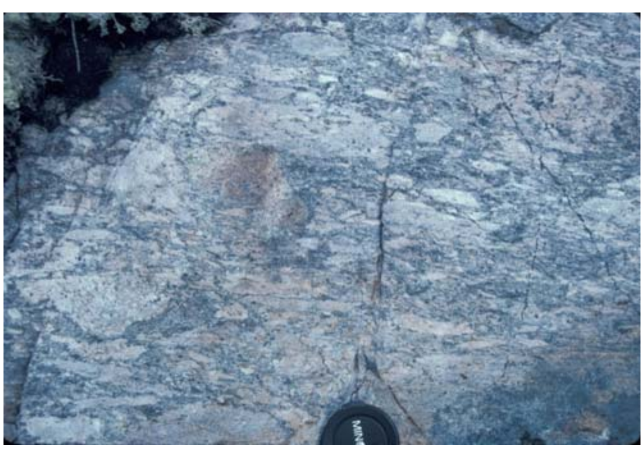

Fig. 5. Outcrop of a fragmental unit at the Kwyjibo deposit, Québec. Lens cap is 6 cm in diameter.

Dimensions and Depth

Iron-rich veins, breccias and tabular zones and alteration halos may reach hundreds of metres in width and many kilometres in length (e.g. the Selwin Line in Australia; Ray and Lefebure, 2000; Sleigh, 2002). As such IOCG deposits are extremely good targets for regional-scale geophysical and geochemical surveys and integrated expert system studies (as discussed below). The deposits can be formed at shallow (Olympic Dam type), moderate (Sossego, Ernest-Henry type) or deep (Salobo) levels within the first 10 km of the crust (Kerrich et al., 2000). Metamorphosed IOCG deposits can be found at any crustal levels including deep crustal ones.

Architecture

Crustal-scale to local fault zones or splay faults control many IOCG deposits (e.g. Adshead-Bell, 1998; Partington and Williams, 2000; Williams and Skirrow, 2000; Sillitoe, 2003). In some deposits, such as Candelaria and NICO, the intersection of highly permeable units with fault zones exerted a favourable control on ore deposition, in others, dilational jogs (Olympic Dam), duplexes, splays on faults and shears (e.g. Carajas district and Monakoff deposit), folding (e.g. Tennant Creek district), or complex intercalation of high and low permeability units influenced fluid flow regime and position of alteration zones, breccias and/or ore deposition (e.g. Cross et al., 1993; Marschik et al., 2000; Partington and Williams, 2000; Skirrow, 2000; Davidson et al., 2002; Grainger et al., 2002; Sillitoe, 2003; Sleigh, 2002; Marshall, 2003). Current research and exploration strategies worldwide emphasize the key role of major structures to channel fluids and source magmas at regional and crustal scales and of competency contrasts to favour the location of ore and breccias. Late-stage fluid fluxes along fault zones may induce magnetite formation or destruction through non-redox transformations, a process described in Ohmoto (2003), and consequently may affect the geophysical response of ore bodies and their magnetite vs. hematite contents and distribution.

Host Rocks

The host rocks of IOCG deposits are varied and do not constitute a diagnostic feature. They encompass coeval or pre-existing sedimentary, mafic to felsic volcanic or plutonic rocks, schists and gneisses that have served as lithological (e.g. due to competency contrast or permeability) or chemical traps for fluids associated with long-lived batholiths or for very reactive fluids associated with short-lived magmatism such as carbonatite stocks (e.g. Mark et al., 2000; Skirrow, 2000; Weihed, 2001; Knight et al., 2002). The sole unifying link is that they formed in globally oxidized settings across which fluids could efficiently flow and/or react.

Examples include: oxidized volcano-plutonic environments, pre-existing iron formation, ironstone or iron-rich metasediments, notably in Cloncurry-type deposits, and permeable, porous or reactive units along or in the vicinity of major faults, splays and their intersections or along major unconformities. Magnetite lavas are also considered possible hosts based on previous interpretations of the El Laco deposits (Naslund et al., 2002). It may be noted, however, that a hydrothermal replacement origin of these magnetite deposits has been recently suggested (Sillitoe and Burrows, 2002; Sillitoe, 2003) and the issue is still under debate.

Chemical Characteristics

The ore/gangue/alteration minerals of IOCG deposits listed above are those associated with evolved felsic I-type and A-type magmas, alkaline-carbonatite magmas, as well as the skarn minerals. These minerals (listed in Table 3), notably the light REE-, Bi-, Co- and U- bearing minerals and rutile have distinctive chemical fingerprints and their mineral chemistry is used as process-forming and source-rock tracers (e.g. Campbell and Henderson, 1997; Morton and Hallsworth, 1999; Mitsis and Economou-Eliopoulos, 2001; Daliran, 2002; Zack et al., 2002). The main ore minerals are iron oxides, Cu-Fe sulphides, uranium oxides and/or REE-enriched minerals combined in diverse metal associations (e.g. Fe-P; Fe-REE-Nb, Fe-Cu-Au, and Fe-Cu-Au-U-Ag-REE). Anomalously high values for Fe, Cu, Au, U, Ag, ±REE's, especially the LREE (Ce, La, Nd, Pr, Sm, Gd), ±Nb ±P ±Co ±F ±B ±Mo ±Y ±As ±Bi ±Te ±Mn ±Se ±Ba ±Pb ±Ni ±Zn provide diagnostic element suites for geochemical exploration. Ore assemblages may appear highly varied but in fact comprise a series of elements that share certain chemical affinities that facilitate their transportation and/or precipitation together. Iron oxide is either co-transported or pre-existing and acts as catalyst in precipitation of other metals (Porter, 2002b).

Some of the ore, gangue and alteration minerals are resistate minerals able to survive weathering and mechanical dispersal (Morton and Hallsworth, 1999). They commonly have a high mode (e.g. up to 60% apatite and 20% iron oxide in some ore at Bayan Obo) and are propitious pathfinders in exploration. Techniques that detect chemical dispersion and *in situ* anomalies are commonly used for IOCG exploration, notably soil/lake/stream sediment surveys, till geochemistry, lithogeochemistry and geophysical (aeromagnetitc, gravity, radiometric) surveys.

Geological Properties

Continental Scale

The attributes of IOCG deposits range widely but a series of common or coincidental features emerge including the proximity of an Archean craton (Groves and Vielreicher, 2001), the location of deposits in extensional settings, the presence of A-type or I-type granites with intermediate to mafic facies indicative of a sustained magmatic system, and a structural, fault or shear control on mineralization (e.g. Partington and Williams, 2000). This diversity reflects a complex interplay between magmatic and hydrothermal fluids, their oxidized host tectonic environments, and the large magmatic systems involved.

Timing with respect to Earth evolution does not appear to be critical in the development of IOCG deposits (Nisbet et al., 2000). Deposits are now known to occur from the Archean, (Salobo and Igarapé Bahia), to the Mesozoic (Chilean Iron Belt) as shown in Table 4 (Requia et al., 2003; Sillitoe, 2003; Tallarico et al., 2004). The Archean ages obtained are significant as they really open Archean terranes to IOCG exploration. The 1.9-1.5 Ga period, however, remains the most fertile period currently documented worldwide (Australia, Canada, Sweden, etc.; Gandhi et al., 2001). The ages given in Table 4 are from U-Pb dating of monazite, titanite and rutile crystallized in alteration and ore assemblages (e.g. Teale and Fanning, 2000; Clark, 2003) or of zircons in genetically related intrusive and volcanic rocks (Johnson and Cross, 1995; Thorkelson et al., 2001a, b). $^{40}Ar/^{39}Ar$ and Re-Os data, on gangue and ore minerals respectively, can also be used (Williams and Skirrow, 2000; Marschik and Fontboté, 2001; Mathur et al., 2002). Titanite and rutile U-Pb ages and biotite, hornblende or muscovite $^{40}Ar/^{39}Ar$ ages obtained from IOCG deposits or prospects in metamorphic terranes should be interpreted with caution as these minerals have low blocking temperatures and ages obtained from their analysis may represent cooling ages.

Discussions of prospective settings for IOCG deposits commonly have, and still focus on intracratonic rift environments (e.g. Kerrich et al., 2000; Ray and Lefebure, 2000; Faure, 2003). This paradigm is a consequence of earlier interpretations of the giant Olympic Dam deposit as plume-related and formed in an intracratonic anorogenic setting. These interpretations hinged on the A-type geochemical signature of the coeval Hiltaba suite granitoids (cf. Giles, 1988; Creaser, 1989; Wyborn et al., 1992).

The term A-type is a geochemical classification scheme for granites that encompasses granites with high SiO_2, Na_2O+K_2O, Fe/Mg ratios, F, Ga, Sn, Y, REE, and high field strength elements (HFSE) such as Zr and Nb (Loiselle and Wones, 1979; Collins et al., 1982; White and Chappell, 1983). The geochemical discriminant diagrams of Whalen et al. (1987) permit distinction of A-type granites from other granite types. A-type granitoids have high crystallization temperatures (e.g. 900-1000°C) sustained by the emplacement of mantle-derived mafic magmas at depth (Creaser et al., 1991). They form through reworking of fertile crustal settings, hence a common spatial association with the margins of Archean cratons (see discussion in Creaser, 1996). Though entrenched in the literature as **A**norogenic (Anderson, 1983; Pitcher, 1993), **A**-type granites are not necessarily Anorogenic or Alkaline. A continental extensional setting is needed but does not have to be intracratonic as it can also be within or inboard of continental magmatic arcs (Collins et al., 1982; Whalen et al., 1987; Creaser, 1996). The same is true for the tectonic setting of alkaline magmas, including carbonatite complexes, and associated mineral deposits (e.g. Wang et al., 2001; Sillitoe, 2002; Mumin and Corriveau, 2004).

Creaser (1996) and others pointed out that orogenic activities were taking place at the time of A-type intrusions in and at the margin of the Gawler craton coevally with IOCG mineralization (e.g. Partington and Williams, 2000).

Table 3. IOCG mineralogy

Mineral	Formula
allanite	$Ca(La,Ce)(Fe^{2+},Mn^{2+})(Al,Fe^{3+})_2[SiO_4][Si_2O_7]O(OH)$
amphibole*	$Ca_2(Mg,Fe^{2+})_5Si_8O_{22}(OH,F)_2$ - $(Na,K)_{0-1}Ca_2(Mg, Fe^{2+}, Fe^{3+}, Al)_5[Si_{6-7}Al_{2-1}O_{22}](OH,F)_2$
apatite, fluorapatite, REE-apatite	$Ca_5(PO_4)_3(OH,F,Cl)$
autunite (secondary U mineral)	$Ca(UO_2)_2(PO_4)_2\cdot 12(H_2O)$
baddeleyite	ZrO_2
barite	$Ba(SO_4)$
bastnaesite (REE carbonates)	$(La,Ce,Y)(CO_3)F$
Bi sulphosalts, Bi telluride	
biotite	$K(Mg,Fe^{2+})_3[AlSi_3O_{10}](OH,F)_2$
bismuthinite	Bi_2S_3
bornite	Cu_5FeS_4
brannerite	$(U,Ca,Ce)(Ti,Fe)_2O_6$
britholite	$Ca_{2.8}Ce_{0.9}Th_{0.6}La_{0.4}Nd_{0.2}Si_{2.7}P_{0.5}O_{12}(OH)_{0.8}F_{0.2}$
carbonate (calcite, ankerite, siderite, dolomite)	
carrolite	$CuCo_{1.5}Ni_{0.5}S_4$
chalcocite (secondary Cu mineral)	Cu_2S
chalcopyrite	$CuFeS_2$
chlorite	$[Mg5(Al,Fe)(OH_8(Al,Si)_4O_{10}]$ $Na_{0,5}(Al,Mg)_6(Si,Al)_8O_{18}(OH)_{12}\cdot 5(H_2O)$
clinopyroxene (aegerine-augite)	$(Na,Ca)(Fe^{2+},Fe^{3+},Mg)[Si_2O_6]$
cobaltite	$CoAsS$
coffinite	$U(SiO_4)_{1-x}(OH)_{4x}$
covellite	CuS
digenite	Cu_9S_5
epidote	$Ca_2Fe^{3+}{}_{2.25}Al_{0.75}(SiO_4)_3(OH)$
fayalite	$Fe^{2+}{}_2(SiO_4)$
florencite	$(Ce,La,Nd)Al_3(PO_4)_2(OH)_6$
fluorite	CaF_2
garnet (andradite, Fe-rich garnet)	$Ca_3Fe_3{}^{2+}(SiO_4)_3$ - $Fe_3{}^{2+}Al_2(SiO_4)_3$
ilvaite	$CaFe^{2+}{}_3(SiO_4)_2(OH)$
K-feldspar + alkali feldspar	$(K,Na)AlSi_8O_8$
loellingite	$Fe^{2+}As_2$
iron oxide	Fe_2O_3
(hematite, martite, magnetite (low Ti), specularite)	
malachite (secondary Cu mineral)	$Cu_2(CO_3)(OH)_2$
molybdenite	MoS_2
monazite	$(Ce,La,Nd,Th)PO_4$
muscovite	$KAl_2(Si_3Al)O_{10}(OH,F)_2$
native bismuth, copper, gold, silver	
olivine	$(Mg,Fe)_2SiO_4$
phlogopite	$KMg_3(Si_3Al)O_{10}(F,OH)_2$
plagioclase (albite)	$NaSi_3AlO_8$
pyrite	$Fe^{2+}S_2$
pyrrhotite	Fe(1-x)S
quartz	(SiO_2)
rutile	TiO_2
scapolite	$(Na,Ca)_4[Al_3Si_9O_{24}]Cl$
sericite	$[KAl_2(OH)_2(AlSi_3oO_{10})]$
sillimanite	Al_2SiO_5
silver telluride, silver/uranium-arsenide	
titanite	$CaTiSiO_5$
tourmaline	$(Na(Mg,Fe,Mn,Li,Al)_3Al_6[Si_6O_{18}](BO_3)_3(OH,F)_4$
uraninite	UO_2
vermiculite	$(Mg,Fe^{2+},Al)_3(Al,Si)_4O_{10}(OH)_2\cdot 4(H_2O)$
xenotime	$(Yb,Y)(PO_4)$
zircon	$ZrSiO_4$

(Na-K amphibole, Cl-rich hornblende, actinolite, ferro-actinolite, ferro-hornblende, grunerite, hornblende, hastingsite, tschermakitic amphibole, edenite)

Table 4. Age distribution of selected IOCG deposits.

Eon	Era	Period	Age (Ma)	Ages of deposits or districts	References
Phanerozoic	Cenozoic		0		
	Mesozoic	Cretaceous, Jurassic, Triassic	200	Candelaria, Punta del Cobre, Raul Condestable 0.115 Ga Mantoverde 0.12 Ga	See Mathur et al., 2002; Sillitoe, 2003 and references therein
	Paleozoic	Permian, Carboniferous, Devonian, Silurian, Ordovician, Cambrian	400	Bayan Obo 0.5 Ga ?	Chao et al., 1997; Smith et al., 2000
Proterozoic	Neoproterozoic	Late Neoproterozoic III	600		
		Middle Cryogenian	800		
		Early Tonian		Kwyjibo 0.98 Ga	Gauthier et al., 2004
	Mesoproterozoic	Late Stenian	1000	Lyon Mt. 1.04 Ga	Selleck et al., 2004
		Middle Ectasian	1200	Bayan Obo 1.3-1.2 Ga ?	See Yang et al., 2003
		Early Calymmian	1400	Ernest Henry >1.51 Ga Olympic Dam 1.59 Ga	Mark et al., 2000
	Paleoproterozoic	Late Statherian	1600	Osborne, Wernecke 1.60 Ga Curnamona ~1.61Ga Sudbury-Wanapitei area 1.7 Ga	Gauthier et al., 2001; Thorkelson et al., 2001b Williams and Skirrow, 2000 Schandl et al., 1984
		Middle Orosirian	1800	Tennant Creek ~1.83Ga Aitik, Sue Dianne, NICO ~1.87Ga Kiruna 1.89-1.88 Ga Phalaborwa 2.06 Ga	See Skirrow, 2000 Gandhi et al., 2001 Romer et al., 1994 Harmer, 2000
		Early Rhyacian	2000, 2200		
		Early Siderian	2400		
Archean	Neoarchean		2600	Igarapé Bahia 2.57 Ga Salobo 2.58 Ga	Tallarico et al., 2004 Requia et al., 2003
			2800		

In contrast, tracing an intracontinental rift setting for the Olympic Dam area is extremely difficult (cf. chain of 'evidence' in Johnson and Cross, 1995). Several authors stress the importance of magnetite-bearing I-type granites (see Partington and Williams, 2000) and calc-alkaline affinities (Gandhi, 2003) in the formation of IOCG deposits, in line with the work of Creaser et al. (1991) that documents the evolution of A-type granites as part of the I-type granite series.

The recognition of juvenile material and syntectonic plutonic phases among the Hiltaba suite raises an alternative paleotectonic interpretation: an intracontinental, extensional back-arc setting possibly related to basaltic under-plating during crustal thinning (Ferris et al., 2002; Giles et al., 2002). With this new interpretation a shift in paradigm is underway as strong analogies can now be drawn between Proterozoic and Andean IOCG deposit settings. Gandhi (2003, 2004a) proposes two main series for IOCG-related magmatism: a calc-alkaline (Kiruna, Olympic Dam and Cloncurry sub-types) and an alkaline series (Phalaborwa and Bayan Obo sub-types).

IOCG deposits are genetically associated with, but can be spatially distinct from large-scale magmatism that combines voluminous felsic magmatism with mafic and intermediate facies either within bimodal or more continuous series. For example, the A-type Hiltaba plutonic suite, coeval with Olympic Dam, is granitic to monzodioritic and related to the bimodal Gawler Range volcanic suite; the Ernest Henry, Starra and Lightning Creek deposits are related to I-type, magnetite-series diorite to alkali-feldspar granite (Williams and Naraku batholiths; Wyborn et al., 1992; Perring et al., 2000, 2001; Marshall, 2003); and the 2576±8 Ma Salobo deposit is coeval with 2573±2 Ma A-type granitic magmatism, etc. (e.g. Giles, 1988; Creaser, 1996; Requia et al., 2003). The presence of intermediate rocks such as diorite and granodiorite as well as mafic rocks are becoming more and more critical in the evaluation of prospective districts based on unveiled magmatic associations, especially in the Andes but also in the Gawler craton itself (Creaser, 1996; Wyborn, 1998; Nisbet et al., 2000; Sillitoe, 2003). Magmatic-hydrothermal stages associated with the differentiation of alkaline-carbonatite magmas can generate magnetite-rich deposits in a manner comparable to I-type calc-alkaline or A-type magmas and have led to the significant Phalaborwa and Bayan Obo deposits.

IOCG districts are largely associated with the margin of Archean cratons. Intracratonic to continental-arc extensional and transtensional settings with narrow rift structures and regional-scale, long-lived, brittle to ductile fault zones are most commonly the host of IOCG deposits (Hitzman, 2000; Sillitoe, 2003). The close relationships between the Andean polymetallic and copper-deficient IOCG deposits, massive magnetite deposits, manto-type and small porphyry Cu deposits, and, where carbonates abound, calcic skarn deposits (Sillitoe, 2003) illustrate how fertile magmatic arcs can be.

Metallogenetic District Scale

The significant metallogenic IOCG districts such as the Gawler Range and Cloncurry districts in Australia, the Carajas district in Brazil and the Chilean Iron Belt (Fig. 1) enclose several mineral deposit types in association with large-scale, high-temperature magmatic suites (A-type granite, diorite, etc.) and crustal-scale fault zones. For example, in the Gawler craton, an orogenic gold province is now recognized to the west of the IOCG Olympic Dam province. Both are coeval and associated with the same granitic suite (Ferris and Schwarz, 2003). Essentially coeval and to the east is the giant Proterozoic Broken Hill SEDEX Pb-Zn deposit and to the northwest the Archean craton hosts the granulite-facies Challenger gold deposit (cf. Tomkins and Mavrogenes, 2002).

Hosts to mineralization can vary from volcanic to sedimentary to intrusive, and widespread magmatism may (Olympic Dam) or may not (Bayan Obo) be observed at the level of exposure of an IOCG district. Nevertheless evidence for a magmatic association prevails (e.g. Marshall, 2003) and where it is observed, it can either be predominantly felsic (e.g. Olympic Dam) or intermediate (e.g. Andes) in composition (Creaser, 1989; Sillitoe, 2003), and calc-alkaline or alkaline in character (Gandhi, 2003). Felsic to intermediate plutonic suites with associated mafic magmas are important to recognize during grass roots exploration and regional scale mapping. In the absence of significant coeval mafic to intermediate intrusions (plutons, dyke swarms), such a diagnostic can come from the observation of mafic-felsic magma mingling textures within large granitoid intrusions or composite dykes (Fig. 6; Vernon, 2000).

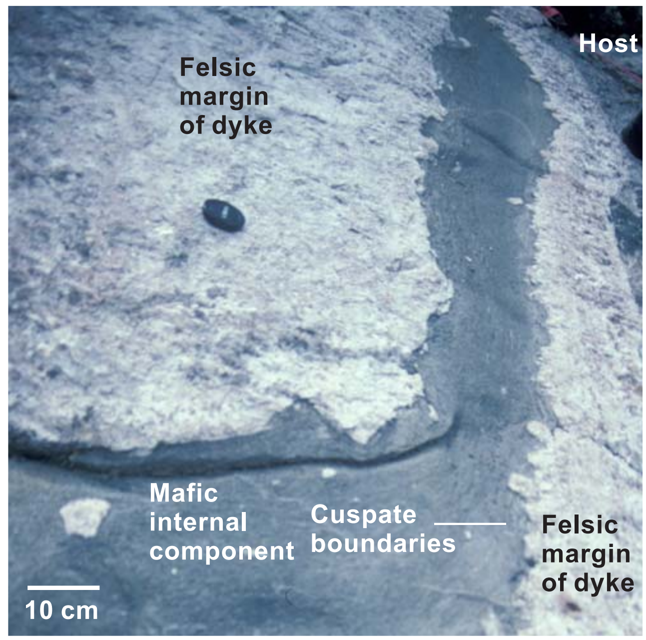

Fig. 6. Composite dyke with cuspate boundaries between mafic and felsic components point to emplacement of coeval mafic and felsic magmas across a magnetite breccia at the Kywjibo deposit, Québec.

Though mineralization is coeval with, and genetically related to volcanic and plutonic rocks (Creaser and Cooper, 1993; Johnson and Cross, 1995; Belperio and Freeman, 2004), the magmatic nature of fluids and metals remains contentious (cf. Barton and Johnson, 1996, 2000, 2004; Haynes, 2000; Skirrow et al., 2002). Fluids that can account for oxide-rich but sulphide-deficient ore need to be saline and relatively oxidized. Their primary source(s) can be magmatic, metamorphic, evaporitic, or brines, etc. However, magmas play a significant role in providing the thermal regime necessary for very efficient fluid flow, mixing and metal recharge. By doing so, magmatic fluids will be mixed with other fluids if available making ultimately the source of fluids complex to decipher. The sizeable anomaly in reflectivity in the lower crust underneath the Olympic Dam deposit may be the fingerprint of the fluid recharge zone needed to form giant deposits while the intricate crustal-scale network of fault zones exemplified what is envisioned as potential fluid pathways (Lyons et al., 2004).

Extensional and transtensional faults can channel hot deep-seated fluids upward and cold surface-waters downward, allowing for fluid mixing, large-scale alteration and mineralization. The depth at which fluid and metal recharge and discharge take place will influence the resulting structure, alteration and mineralization patterns as reviewed in Kerrich et al. (2000). Calcic-sodic alteration zones are commonly zones of fluid recharge in base and ferrous metals. Focussed potassic alterations and iron oxide(s) matrix breccia are zones of up flow and discharge of metals while laterally extensive K-feldspar-dominated alteration in oxidized (hematite stable) continental and transitional marine settings environment may represent recharge zones (Barton and Johnson, 2004). The role of evaporite for recharge has been debated and the reader is referred to Barton and Johnson (2004) for a presentation of the various alternatives and impacts of fluid types on footprints of IOCG deposits.

In the Cloncurry district (East Mount Isa Block), magmatic fluid sources, not metamorphic or meteoric waters, were involved in the formation of regional Na-(Ca) alteration, most magnetite alteration and Cu-Au mineralization (e.g. Ernest Henry, Mt Elliot deposits; Marshall and Oliver, 2003). In contrast, magmatic fluids do not appear to have been involved in the formation of some pre-existing ironstones (e.g. ironstone hosts to Starra Cu-Au mineralization) and possibly some magnetite alteration at Osborne (Davidson, 1989), providing evidence that non-magmatic ironstones of metamorphosed or metamorphogenic origin can act as suitable chemical hosts for Cu-Au mineralization (Marshall, 2003).

What does abound in IOCG districts is mono- or polyphase iron oxide(s) matrix breccia at a local to a regional scale (e.g. Reeve et al., 1990; Hitzman, 2000). This leads to spectacular outcrop exposures and/or to significant magnetic and gravity anomalies, keys to mineral exploration at the district scale.

Though the processes and events that lead to giant deposits and to significant metallogenic districts are the topic of significant research worldwide, the empirically observed association between SEDEX and IOCG deposits provides a way to target prospective areas for grass roots exploration at a district scale. Exploration based on Broken Hill-type indicator minerals (e.g. Mn in garnet, Zn in gahnite, staurolite, etc.; Spry and Wonder, 1989) has been successful in finding SEDEX and Pb-Zn±Cu VHMS deposits in metamorphosed supracrustal belts but the approach fails to unveil Pb-Zn-Mn deficient, Cu-Au sulphide- or oxide-rich deposits. This is an important aspect to take into account during prospectivity and vector studies for IOCG deposits in Canada. Current research on rutile and other mineral indicators will significantly impact mineral indicator surveys currently mainly used for diamond, VHMS and SEDEX exploration (e.g. Spry and Wonder, 1989; Gale et al., 2003). Until vectors to ore are determined precisely by ongoing studies, the close association between SEDEX and IOCG deposits will provide a useful empirical vector.

The close association between monometallic iron and polymetallic IOCG deposits represents another empirically derived vector to target prospective metallogenic districts. Known IOCG districts commonly comprise a train of iron oxide-rich deposits and prospects along linear arrays more than 100 km long and >10 km wide, with a 10-30 km spacing of the deposits along a crustal-scale fault zone, either exposed or cryptic, and their subsidiary brittle fractures, ductile fault zones and narrow rifts (Ray and Lefebure, 2000; Sleigh, 2002; Belperio and Freeman, 2004). Consequently, linear distributions of iron prospects are more prospective than sparsely distributed ones.

<u>Deposit Scale</u>

At the local scale, IOCG deposits are detectable by basic to sophisticated geological, geochemical, remote sensing and geophysical techniques. Tracers of mineralization extend commonly for several kilometres (1 to 6 km) over a width of several hundred metres while the deposit itself may range between 0.5 and 1 km in length and a few hundred metres in width. With their common coincident gravity and magnetic anomalies, exploration relies heavily on ground and airborne magnetic surveys complemented by existing gravity data or acquisition of target specific data (e.g. Gow et al., 1994; Smith, 2002). The gravity response is a consequence of the high density of the iron oxides and mineralization while the magnetic response reflects the proportion of magnetite in the iron oxides and less commonly of pyrrhotite in the deposit.

The presence of U-rich mineralization with km-scale potassic alteration halos leads to radiometric anomalies detectable by airborne surveys with line spacing less than 1000 m over exposed or shallow seated deposits. U/Th and K/Th ratios are particularly useful as Th varies within a small range so the addition of U and K are readily detected (Gandhi et al., 1996; Smith, 2002). The deposits, through their large disseminated mineralization zones, have a good induced polarization and resistivity response, while the breccia core tends to be electrically connected and conductive (e.g. Candelaria deposit, Ryan et al., 1995; Ray and Lefebure, 2000). Induced polarization and electromagnetic surveys are thus useful exploration tools to complement the magnetic and radiometric surveys (see Smith, 2002 and references therein).

Structural studies on regional and local scales, including remote-sensing data, are also important considering that IOCG deposits are structurally controlled (e.g. through long-lived brittle-ductile faults, shear zones and narrow grabens or rifts, splay-offs, dilational jogs and strata-bound zones of high permeability in the vicinity of fault zones).

Alteration zones are distinctive in the field and the overprinting of Cu-Au mineralization on an earlier magnetite-rich alteration is diagnostic of IOCG processes (Etheridge and Bartsch, 2000). Hence geochemical surveys and mapping of alteration zones are important components of IOCG exploration strategies at the deposit scale to further results of similar initiatives at the district scale.

In metamorphic terrains, mineralization may postdate metamorphism (e.g. at Ernest Henry), coincide with the last stages of orogenesis (e.g. at Monakof), be coeval with peak metamorphism and anatexis (e.g. at Osborne; Gauthier et al., 2001) or predate metamorphism altogether. The textures and in some cases the mineral assemblages of the alteration zones and ores may change dramatically during metamorphism. Exploration for IOCG deposits therefore needs to take into account what their gneissic derivatives would look like. For example, unmetamorphosed K-Fe-rich alterations consist of biotite, K-feldspar, sericite, magnetite, carbonates, actinolite, and/or chlorite. The metamorphosed equivalents at the upper amphibolite and granulite facies will largely keep the same composition, though more dehydrated, and will correspond to a variety of quartzo-feldspathic gneisses with biotite, magnetite ± sillimanite ± garnet and/or cordierite ± hornblende and/or orthopyroxene. The hydrothermal origin of the mineralized gneiss protolith may be difficult to recognize in the field if it is associated closely with the gneissic rocks derived from magnetite- and/or, hornblende-bearing granitoids. If sericite is very widespread, the rock may be even mapped as metapelite (sic) (Corriveau et al., 2003). The calcic alteration might produce a variety of calc-silicate rocks that may end up being mapped as metasediments, especially if 'metapelites' are found in the vicinity. It can also produce amphibolite and hornblendite with Na-Al rich hornblende (edenite), magnetite, plagioclase (likely oligoclase), with or without orthopyroxene. In extreme cases it can also result in the formation of albitites. As for any hydrothermally derived rock, the metamorphosed equivalent of some of the minerals may be unusual, providing a tool for protolith assessment and a vector for exploration (Corriveau et al., 2003). Metamorphosed IOCG deposits could occur at any crustal levels following orogenic tectonic juxtapositions hence prognostication for IOCG prospective districts should also include metamorphosed terranes, even those metamorphosed at granulite facies.

Another aspect of metamorphosed IOCG ore is that if breccia formed in the first place because a host rock was competent, then it may remain competent during metamorphism and appear little deformed even if metamorphosed. More ductile units would take up the strain leaving IOCG mineralization looking apparently younger than they are (Corriveau et al., 1998; Bonnet and Corriveau, 2003).

Canadian Metallogenic Districts

Distribution of Prospective IOCG Districts

From a Canadian perspective, the demonstration that intracontinental extensional magmatic arc settings are fertile for IOCG deposits is critical as it significantly furthers analogies between the Canadian 1.9 to 1.5 Ga continental arc settings and the Gawler Range volcano-plutonic setting hosting the Olympic Dam and Prominent Hill deposits (Creaser, 1996; Gandhi et al., 2001; Gandhi 2003). Prime prospective IOCG districts in Canada (Fig. 7) are in the Proterozoic (1.9-1.5 Ga) granitic and gneissic belts of the Canadian Shield and in the ancestral North American components of the Phanerozoic Cordilleran orogen. The districts in the Canadian Shield have 1) known large-scale oxide-rich breccia zones, and/or 2) A-type granite or large-scale magmatism of more intermediate composition, and /or crustal-scale fault zones. Similar geological settings in the Cordilleran and the Appalachian orogens are also favourable (i.e., terranes bounded by fault zones and associated with A-type granitic magmatism and previously known deposits/prospects with a variety of commodities including Fe, U, Cu or Au).

Three IOCG deposits are currently known in Canada (Fig. 7), two have calculated resources: the 42 Mt Co-Au-Bi NICO and the 17 Mt Cu-Ag Sue-Dianne deposit in the Northwest Territories (Table 2; Goad et al., 2000; Gandhi, 2003). They both belong to the Great Bear magmatic zone, a 1875-1845 Ma volcano-plutonic continental arc terrane formed at the western margin of the Archean Slave craton and extending southeastward along the Great Slave Lake shear zone (Gandhi et al., 2001; Ross, 2002; Gandhi, 2003). The third documented IOCG deposit is the Kwyjibo deposit located in the Canatiche complex of the eastern Grenville Province, Québec (Clark, 2003; Gauthier et al., 2004). Though found in a Mesoproterozoic arc terrane, this deposit is currently interpreted as Neoproterozoic based on U-Pb dating of allanite, titanite, perovskite and zircon at ca. 972 and ca. 951 Ma from a mineralized sample and a mineralized dyke (Gauthier et al., 2004).

Beside the Great Bear magmatic zone and the Manitou district hosting Kwyjibo, other prospective Proterozoic IOCG districts with significant Cu, Au, U or Fe prospects include (Fig. 7) (1) the Paleoproterozoic Eden polymetallic mineral belt hosting the Eden Lake REE-rich carbonatite complex in the Trans-Hudson Orogen, (2) the Paleoproterozoic Central Mineral Belt across arc terranes of the Makkovick, Churchill and Grenville provinces in Labrador, (3) the Mesoproterozoic Wernecke Breccias and the Iron Range in Proterozoic basins of the Cordillera, (4) the Nipigon Embayment and the Sault Ste Marie area in the Mid-Continent Rift system, and (5) the Sudbury-Wanapitei area of the Southern Province (Badham, 1978; Schandl et al., 1984; Gates, 1991; Rogers et al., 1995; Goad et al., 2000; Thorkelson, 2000; Thorkelson et al., 2001a, b; Marshall and Downie, 2002; Mumin, 2002a, b; Deklerk, 2003; Marshall et al., 2003; Mumin and Trott, 2003; Schneiders et al., 2003; Syme, 2003; Atkinson et al., 2004; GSNL National Mineral Inventory Number, 013J/12/U 001 006 in Geological Survey of Newfoundland and Labrador, 2003). Phanerozoic settings include the Lemieux Dome, the Avalon zone, the Cobequid-Chedabucto Fault Zone, and the Lepreau Iron mine in the Appalachian orogen, and the Insular Range skarn deposits and the Heff deposit in the Cordillera (Fig. 7).

Iron oxide deposits have been important sources of iron in the past and still contain significant iron resources. Since their iron ores were not systematically analyzed for the entire spectrum of IOCG-associated metals, they form today a first-order target for IOCG exploration. They provide a means to define prospective districts and sites for detailed exploration. This approach is used in emerging exploration plays such as those along the Cobequid-Chedabucto fault zone, the Wernecke Breccia and the Central Labrador Mineral Belt (e.g. Downes, 2003; Marshall et al., 2003).

Great Bear Magmatic Zone (1.88-1.85 Ga), Northwest Territories

The Great Bear magmatic zone hosts examples of three IOCG deposit types (Gandhi, 2003, 2004b). Kiruna-type magnetite-apatite-actinolite veins are numerous and associated with early quartz monzonite plutons. The Olympic Dam-type Sue Dianne deposit and the Mar, Nod, Fab and Damp prospects are hosted by dacite-rhyolite ignimbrites and flows and include high grade uranium mineralization.

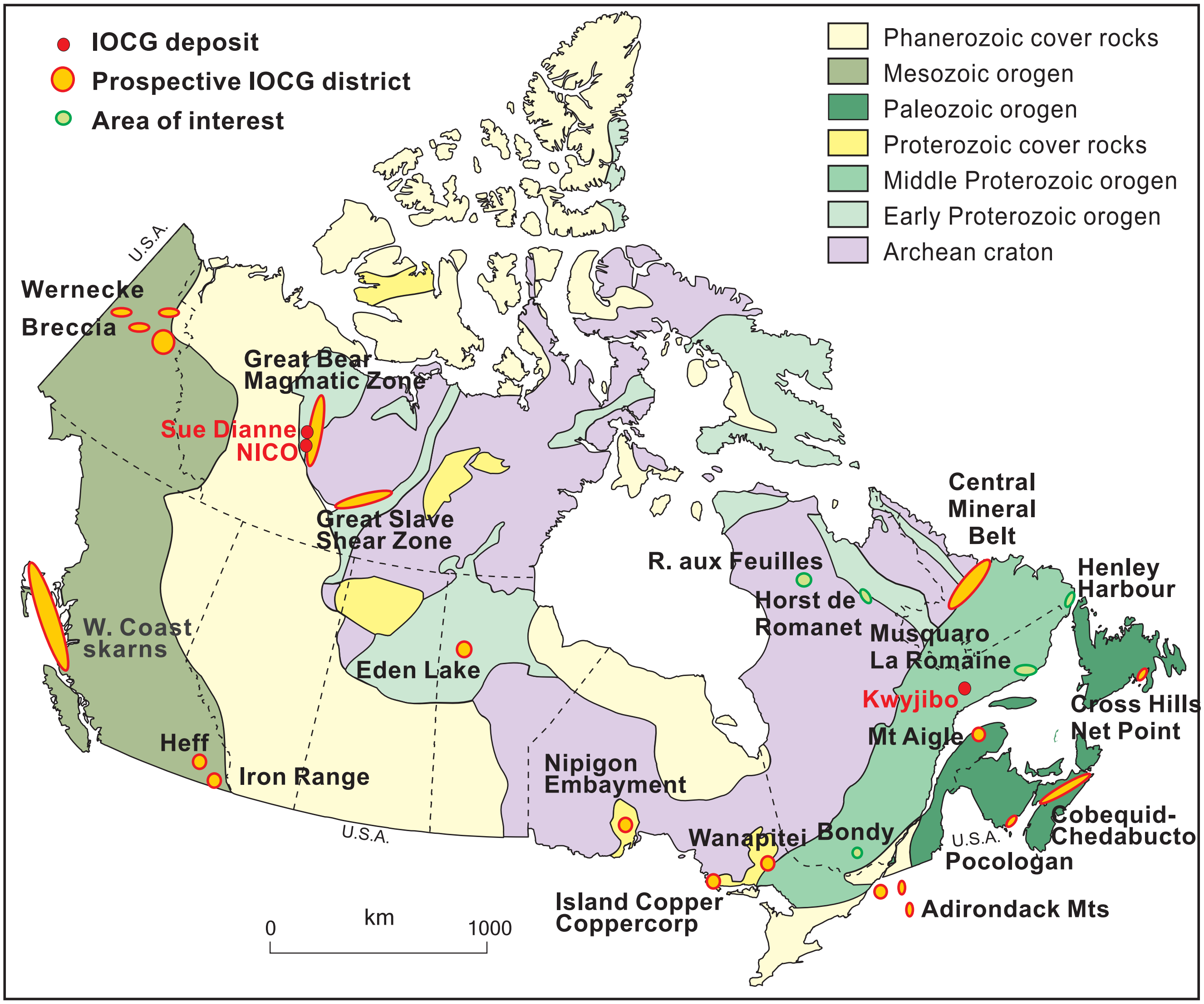

Fig. 7. Prospective districts for polymetallic IOCG deposits in Canada.

The Sue-Dianne deposit (Table 2) is hosted within a structurally controlled diatreme breccia complex above an unconformity with the metamorphic basement (Goad et al., 2000). The Co-Au-Bi NICO deposit is hosted in amphibole-magnetite-biotite schists and ironstones unconformably underlying rhyolites of the Great Bear magmatic zone (Goad et al., 2000; Gandhi, 2001). Ore mineralogy is varied and includes Fe- and Cu-sulphides, native gold and bismuth, Bi telluride and sulphosalts, bismuthinite, cobaltite and loellingite, among others. Current resource estimates (Table 2, Goad et al., 2000) are being upgraded following the positive results of recent drilling programs. The timing and setting of the Great Bear magmatic zone share similarities with the Wathamun-Chipewyan batholiths of the Trans-Hudson orogen to the south, a target for IOCG exploration (Mumin and Corriveau, 2004).

Eden Lake Carbonatite Complex (1.80 Ga), Manitoba

The Eden Lake REE-rich carbonatite complex and its network of high-grade but narrow REE-Y-U-Th veins (Mumin, 2002a, b) was discoevered during a Brandon University, Manitoba Geological Survey-sponsored, reconnaissance study to assess Manitoba's potential to host IOCG deposits. The complex (> 30 km^2) consists of early 1.87 Ga A-type granitoids and mafic rocks (Halden and Fryer, 1999; Mumin, 2002a) intruded by a magmatic and hydrothermal network of carbonatite veins, dykes and plugs, breccia, fenitic alteration zones and 1.80 Ga syenite (Mumin and Trott, 2003; Rare Earth Metals Corporation, 2003). Though consisting of A-type granitoids and alkaline rocks, the complex is not anorogenic but marks the end of deformation in the polyphase Eden Deformation Zone (Mumin and Corriveau, 2004). The spatial association of the Bayan Obo deposit with carbonatite dykes makes the Eden Lake deposit very prospective for IOCG mineralization, but currently no major iron alterations has been observed.

Central Mineral Belt (1.89-1.71 Ga), Labrador

The Central Mineral Belt of southern Labrador hosts numerous Cu, U and REE showings and prospects including the Michelin uranium deposit (Gandhi, 1978, 1986; Evans, 1980; Wardle et al., 2002; Geological Survey of Newfoundland and Labrador, 2003). The belt exceeds 250 km in length and displays a spatial association with a crustal-scale fault adjacent to amalgamated Archean cratons. 1.89-1.87 Ga calc-alkaline continental magmatic arc and successor rifted or back-arc 1.86-1.85 Ga volcano-sedimentary basins hosting voluminous felsic A-type melts were subjected to polyphase transpression and metamorphism and then intruded by A-type granitoids between 1.74 and 1.71 Ga (cf. Ketchum et al., 2002; Sinclair et al., 2002). The regional-scale Na-(Ca) alteration, the focussed Fe-(K-U-Cu-Mo) mineralization, the variety of mineral prospects and the series of orogenic events in the Central Mineral Belt make for a very prospective IOCG district in Canada (Marshall et al., 2003). Moreover, the orogenic setting is similar to that of the 1.74-1.71 Ga Killarney Magmatic Belt in the western Grenville Province, which is associated with the Sudbury-Wanapitei series of prospects of the Southern Province (Rathbun (Fe), Skead (Au), Wanapitei (Au, Ag), Glad (Au, Cu, Ni), Ashigami (Au Ag), Skadding (Au)).

Wernecke Breccias (1.60 Ga), Yukon

"Wernecke Breccias" is a collective term for a curvilinear array of Mesoproterozoic breccia bodies extending over a 50000 km2 area across the Wernecke and Ogilvie mountains, Yukon, including the Coal Creek, Hart River and Wernecke inliers (cf. Bell, 1986; Thorkelson, 2000). The breccias cut greenschist-facies Paleoproterozoic sedimentary rocks and 1.71 Ga diorite intrusions and enclose fragments of non-deformed volcanic rocks apparently not preserved in the exposed tectonostratigraphic record (Delaney, 1981; Thorkelson, 2000; Thorkelson et al., 2001a; Brideau et al., 2002; Laughton et al., 2002). Brecciation, hydrothermal sodic-potassic-calcic alteration and associated Cu-Co-Au-Ag-U mineralization took place at ca. 1.60 Ga (Thorkelson et al., 2001b; Deklerk, 2003). Hematite is the main iron oxide but magnetite is locally important. The Wernecke Breccias share physical and mineralogical characteristics with the Olympic Dam breccias, including an attenuated continental crust setting (Hitzman et al., 1992; Thorkelson, 2000).

Iron Range District (1.47 Ga), Southeastern British Columbia

The Iron Range district forms a belt of iron oxide mineralization that extends intermittently for 20 km along the Iron Range Fault system in the Canadian Cordillera (Stinson and Brown, 1995; Ray and Webster, 2000; Webster and Ray, 2002; BC Minfiles 082FSE014 to 28 and 092, and 082FNE132, 2003 in British Columbia Geological Survey, 2003). The fault cuts across folded clastic sedimentary rocks and gabbro sills of the 1.47 Ga Mesoproterozoic intracratonic basin that hosts the Sullivan Pb-Zn-Ag deposit (e.g. Anderson and Davis, 1995; Schandl and Davis, 2000). The fault zone is interpreted as an intracratonic rift-related normal fault that was active during sedimentation. It was episodically reactivated and acted as a channel for sill emplacement as well as for the fluids that caused polyphase hydrothermal alteration and deposited iron oxides mineralization (Stinson and Brown, 1995; Marshall and Downie, 2002). An intense linear magnetic anomaly overlaps the belt mineral occurrences with peak magnetic susceptibility values coinciding with massive lenses of magnetite. A gamma-ray spectrometric survey detected elevated eTh/K values along the Iron Range fault and interpreted them to correlate with albite-rich alteration and breccia zones (Marshall and Downie, 2002).

Kwyjibo Deposit (0.97 Ga), Québec

Kwyjibo is a replacive, Cloncurry-type, iron oxide Cu-REE-Mo-F-U-Au deposit hosted in a deformed 1.17 Ga A-type granite of the Canatiche orthogneiss-paragneiss-granite complex in the eastern Grenville Province of Quebec (Clark 2003; Gobeil et al., 2003; Gauthier et al., 2004). Seven main prospects form the deposit but others occur to the south and west. Most prospects have polymetallic enrichments in Cu, REE, Y, P, F, and Ag and are anomalous in Th, U, Mo, W, Zr, and Au associated with 0.97 and 0.95 Ga hydrothermal veins and stockworks that replace earlier, locally folded, magnetite-rich alteration zones in the form of disseminations, stockworks, breccia, semi-massive and massive bodies in the host leucogranite (Fig. 4). Other iron oxide bodies are monometallic and akin to magnetite ± apatite, Kiruna-type mineralizations (Clark, 2003; Gauthier et al., 2004). Focused potassic, sodic-calcic, calcic-silicic, fluoritic, phosphatic, silicic, hematitic, and sodic alterations are observed. Coincident features relevant to mineralization include the presence of: (1) brecciated (pyroclastic or hydrothermal?) rocks (Fig. 5), (2) calc-silicate rocks, (3) composite mafic-felsic intrusions, including a dyke with cuspate boundaries (Fig. 6), and (4) SEDEX-type mineralization in the vicinity of the prospects (MRNFP, 2001; Clark, 2003; Gauthier et al., 2004; Clark and Gobeil, submitted).

Cordilleran and Appalachians Prospective Settings

The Heff Cu ± Au ± REE ± P-bearing magnetite skarn deposit comprises a magnetite-bearing garnet-pyroxene skarn alteration hosted by limestone and associated with minor dioritic intrusions. Pods and massive lenses of magnetite, up to 10 m thick, host disseminations and veinlets of sulphides. Samples of mineralized skarn share similarities with many IOCG deposits by having more than 25% Fe (magnetite), anomalous gold and copper, and light REE enrichment (BC Minfile 092INE096, in British Columbia Geological Survey, 2003).

Polymetallic iron oxide Cu, iron oxide Cu-Au-Ag, Cu-Mo and Pb-Zn-Ag mineralizations are found in the vicinity of the Shickshock-Sud fault zone in the Appalachian orogen of Québec (e.g. Lac à l'Aigle and adjacent prospects; Beaudoin, 2003). Mineralized subsidiary faults crosscut the Lemieux Dome, a sub-circular structure with faulted sedimentary rocks, marginal felsic volcanic and pyroclastic rocks and a mafic to felsic dyke swarm emplaced along fault zones. The prospects comprise a series of quartz-chalcopyrite-dolomite veins and polyphase hematite-quartz-dolomite vein and breccia complexes that may extend for hundreds of meters. As such, the setting shares affinities with the

Olympic Dam sub-type but the presence of iron skarn sub-type showings is also significant.

In the Appalachian orogen, the other extensively explored areas for IOCG deposits are: the Avalon zone (Cross Hill and Net Point prospects; Newfoundland; GSNL National Mineral Inventory Number, 001M/10/Cu 005 and 001M/12/Cu 006 in Geological Survey of Newfoundland and Labrador, 2003), the Cobequid-Chedabucto Fault Zone separating the Avalon and Meguma terrane (Mt Thom and Bass River prospects; Nova Scotia; O'Reilly, 1996, 2002), and the Lepreau Iron mine in the Pocologan metamorphic suite (New-Brunswick; Barr et al., 2002; NB deposit database, URN 590 in New-Brunswick Department of Mines, 2003).

Other Areas of Interest

A review of the literature provides additional means of identifying prospective geological settings. Following are some of the examples:

- the Rivière aux Feuilles district in the northern Superior Province of Québec (Vernot prospects; MRNFP, 2001);
- the Romanet horst within the Labrador trough of the New Québec orogen in Québec (MRNFP, 2001);
- the 1.74-1.70 Ga Killarney Magmatic Belt that intrudes the Huronian Supergroup and gneisses of the southwestern Grenville Province in Ontario (Rogers et al., 1995; Carr et al., 2000);
- the Henley Harbour area in the eastern Grenville Province where coincident U and Cu anomalies and associated Ag, As and Mo anomalies in lake sediments are found in the granitoid-dominated 1.65-1.45 Ga Pinware magmatic arc terrane (Gower et al., 1995);
- the 1.50 Ga eastern extension of the Wakeham Group and La Romaine supracrustal belt in the eastern Grenville Province (Corriveau et al., 2003); and
- the 1.40-1.35 Ga Bondy Gneiss Complex in the western Grenville Province (Blein et al., 2003, 2004; Fu et al., 2003).

Genetic and Exploration Models

The span of deposit types associated with iron oxide settings has led Porter (2002b) to advocate that "iron-oxide rich 'oxide mineralizing systems' may represent the converse of the iron-rich reduced systems on which attention has been focussed for so long". This author also points out that if public geosciences and industry grass roots exploration "were to concentrate on the 'oxide alteration/mineralizing systems', other large, as yet unrecognized, ore deposits of different commodities and ore classes may be recognized, or existing deposits may be 're-classified' and better appreciated".

Major IOCG provinces are commonly associated with crustal-scale structures and large-scale magmatic events that drive large-scale fluid flow into mid to upper crustal levels along fault zones, other discontinuities and permeable units. Mixing of magmatic fluids with near surface meteoritic fluids or brines is commonly invoked. Also invoked is a role of evaporites as the source of NaCl in the mineralizing solutions to carry the metals and to generate regional-scale sodic alteration (Barton and Johnson, 1996). The presence of evaporite is, however, not an essential pre-requisite for the formation of IOCG deposits (Nisbet et al., 2000) as many have magmatic fluid signatures (e.g. Marshall, 2003). A-type granites or alkaline intrusions, however, are considered critical, though in some cases the source may be distal from the deposit as in the case of the Bayan Obo deposit. Consequently, a lack of surface expression of magmatism does not necessarily translate into unfavourability.

Advances in genetic/exploration models of the last decade are reviewed in Porter (2000, 2002a), and more comprehensively by Hitzman (2000) while the implications for exploration are discussed by Nisbet et al. (2000) and Barton and Johnson (2004). It is apparent from these papers that there are currently a lot more knowledge gaps to fill regarding the processes and types of fluids that lead to IOCG deposits, than models that are not in dispute.

Sophisticated tools, soft (qualitative to semi-quantitative) and hard (numerical) modeling can be applied to IOCG systems as they are used for other deposit types (e.g. modeling of fluid flow, 3D to 4D structural-lithological architecture, etc.). A large volume of public domain geological, geophysical and geochemical datasets can already be modeled using factual approaches for regional investigations (e.g. Mumin, 2002b). Vector analyses, such as those for VHMS deposits for example (Gale, 2003), can be useful on a deposit or district scale due to metal, alteration, mineral and elemental zoning around deposits (e.g. Goad et al., 2000). Geographic Information System (GIS)-based mineral prospectivity analysis at continent and district scales is emerging and uses a variety of mathematical methods such as weights of evidence, fuzzy logic, and neural networks. These evolved models integrate lithogeochemistry, soil and sediment geochemical surveys, geophysical anomalies, bedrock geology, remote-sensing lineament analysis, proximity to certain key elements of a chosen metallogenic model, stable and radiogenic isotopes, fluid inclusion, etc. The GIS database can be stored, retrieved and interrogated to generate hypothesis-based prospectivity maps (e.g. Venkataraman et al., 2000; Harris et al., 2001; Lamothe and Beaumier, 2001, 2002; Lamothe, 2003; Mukhopadhyay et al., 2003). Such expert systems are at the frontier of our current knowledge but their success is bound to be as good as the data that is entered in the system in the first place.

Knowledge Gaps

In Australia, the search for and the discoveries of IOCG deposits has significantly increased Australian resources in several commodities (Porter, 2002b). Thirty years after the initial IOCG discovery, large government- and industry-based joint ventures and consortium are still being set up to further the understanding of such oxide mineralizing systems and their link to sulphide mineralizing systems (e.g. CSIRO with AMIRA International, CGM, CODES, EGRU, GEMOC, Geoscience Australia, the State and Territory Geological Surveys, the Cooperative Research Centers (CRC LEME, pmd*CRC), the Broken Hill Initiative, and the Flagship initiative). In Canada, this trend is emerging

(Camiro, DIVEX, MDRU, MERC, etc.) but most prospective settings are only mapped at a reconnaissance scale and a majority of them were mapped prior to the recognition of IOCG deposits. Canadian efforts to fill in current knowledge gaps include, among others:

- scoping and targeted geosciences initiatives in frontier Proterozoic felsic plutonic and gneissic terrains of the Churchill (Trans-Hudson orogen), Grenville and Bear provinces, and in the Nipigon Embayment (Mumin, 2002b; Corriveau et al., 2003; Syme, 2003; Atkinson et al., 2004) (N.B., these efforts are strongly limited by available government funding);
- industry- and government-supported research including consortium such as Consorem, Camiro and Divex (e.g. Faure, 2003; Hunt and Baker, 2003);
- re-assessment of iron and uranium deposits and prospects by government surveys and exploration industry, up-dating of government mineral deposits files and delivery of promotional documents including web-based flyers accessible worldwide (e.g. BC and Yukon Minfiles, Québec SIGEOM fiches de gîtes, etc.);
- mineral exploration by major and junior companies targeting previously known districts or frontier terranes with a large variety of commodities (U, Fe, Au, etc.) and major fault zones; and
- production of mineral potential maps using geomining data (e.g. Lamothe, 2003).

These initiatives have already led to the discovery of the significant Eden Lake REE-rich carbonatite complex, the Kwyjibo IOCG deposit and to the reinvestigations of Appalachian fault zones (e.g. Mumin, 2002a; Beaudoin, 2003; Clark, 2003; Downes, 2003; Gauthier et al., 2004).

In Canada, mineral exploration for sulphide-rich mineralizing systems has led to the discovery of major base metal and gold deposits in the Archean greenstone belts and to the development of prosperous mining camps. These camps are now mature, and leading-edge research currently aims at deciphering the complex processes that led to the formation of their giant ore deposits.

Canadian plutonic and gneissic felsic terranes may be very fertile in IOCG deposits and other Cu-Au systems. A corollary to Porter's statement on oxide versus sulphide mineralizing systems (cf. Porter, 2002b) may be that the currently largely uncharted Canadian 'pinkstone belts', the plutonic and gneissic felsic belts, may represent the converse of the greenstone belts on which attention has been focussed for so long. If governments and industry consortiums were to concentrate on bringing the geoscientific infrastructure of plutonic and gneissic belts up to modern standards other large as yet unrecognized 'oxide alteration/mineralizing systems' and their concealed ore deposits may be recognized and existing systems may be 're-classified' and better appreciated.

Canadian plutonic and gneissic belts may play the role in the twenty first century that greenstone belts played in the twentieth century: to host major mining camps and sustain rejuvenation and replenishment of mineral resources. If so, a key to the renewal of metal resources of Canada will be to direct public and academic geoscientific efforts toward providing a modern geological infrastructure for the exploration of frontier high-grade metamorphic and plutonic terrains of the Canadian Shield and ancestral North America and their coeval and successor volcano-sedimentary settings.

A general paucity of knowledge about many gneissic and plutonic belts and the need to adapt the robust exploration methods and models developed for sulphide mineralizing systems in greenstone belts lead to innovative ways to extract useful information from the current knowledge base in order to predict prospectivity of Canada's geological frontier terranes. Coincidental features among different mineralizing contexts (e.g. SEDEX or volcanic hosted uranium deposits with IOCG) and key IOCG pathfinders serve as guide for the prospectivity of uncharted terranes.

The spatial distribution of Proterozoic gneissic and plutonic terranes along the margin of the Precambrian Shield makes the search for IOCG deposits even more attractive. Knowledge-driven IOCG-related research, exploration and exploitation represent key elements of diversification for the sustainable development of northern and remote communities across Canada.

The search for iron oxide Cu-Au-Ag-U-P-REE-Bi-Co (IOCG) deposits requires that public geosciences adapt their current expertise and survey tools to granitic and gneissic frontier terranes while integrating basin analysis and mineral deposit studies as diverse as volcanic-hosted massive sulphides, uranium and SEDEX deposits. Transient processes seem to play a major role in the formation of IOCG deposits (e.g. the importance of magmatic-hydrothermal fluids, mixing of downward and upward migrating fluids in active fault zones, etc) and this is in itself a major challenge. The realm of parameters that need to be taken into account challenges current expertise and exploration techniques. The search for IOCG deposits needs to significantly evolve to meet the challenge posed by remote and complex Canadian geological and geographic terrains. In Australia, research consortiums that involved not only metallogenists from academia and industry but also regional field geologists and research scientists from national and territorial governments have proved successful. Such an approach would benefit Canada as well.

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