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IOCG ENVIRONMENTS IN CANADA: CHARACTERISTICS AND GEOLOGICAL VECTORS TO ORE

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Abstract - Iron oxide copper-gold (IOCG) deposits challenge mineral explorationists by their extraordinary variety of styles, their extensive but typically unrecognised footprint, and at least in Canada, their geological, geographic and logistical environments. Canada's many prospective, but largely virgin orogenic terranes of all ages host some of the world's greatest field exposures of IOCG deposits. Their study better constrains the geotectonic settings, geological field characteristics, alteration zoning patterns and geophysical guides to exploration. Superb glacially-polished cross-sectional exposures of polymetallic magnetite- to hematite-group IOCG and associated iron oxide-apatite (IOA) deposits in the Great Bear Magmatic Zone, Northwest Territories, place the variety of volcano-plutonic associated IOCG deposits into a continuum that evolves to and is associated with porphyry and epithermal styles of mineralisation, broadening the potential impact of exploring Canada's remote territories.

As with global analogues, IOCG deposits in Canada cluster in mineral districts that populate entire belts. Commodities and mineralisation styles are most varied in the Port Radium-Echo Bay district at the northern end of the Great Bear Magmatic Zone, while production from the Au-Co-Bi NICO and Cu-Au-Ag Sue-Dianne deposits in the south is planned for 2012 and large under-explored hydrothermal systems occur in between these districts. Extensive prograde and retrograde alteration and breccias show commonalities and systematic development of alteration patterns, brecciation and mineralisation that provide a useful framework for regional exploration and mapping. Crustal-scale fault control on the development of IOCG systems is common and exemplified, among others, by the Phanerozoic Cobequid-Chedabucto Fault Zone in the Appalachian orogen. Multi-stage development of IOCGs during orogenic processes is well illustrated by the Mesoproterozoic Manitou Lake district of the Grenville Province, while the Archaean Shebandowan greenstone belt demonstrates that some of Canada's traditional VMS and Au mining districts hold potential for Archaean and Palaeoproterozoic IOCG deposits. Finally, the 3D high-mountain exposures of the Yukon's Wernecke Breccia is Canada's best contribution to case examples of IOCG settings with no outcropping coeval magmatic bodies. Collectively, Canadian IOCG settings with their regional-scale intense hydrothermal systems and great variety of deposit types provoke economic geologists to develop comprehensive IOCG deposit models that provide effective guides and methods for exploration.

Introduction

The bulk of the world's known iron-oxide copper-gold deposits occur in Proterozoic terranes and are of Proterozoic age (e.g., Olympic Dam; Williams *et al.*, 2005). Examples of Archaean-age IOCG deposits are currently relatively rare, although the Archaean Carajás district in Brazil contains the world's largest known concentration of large-tonnage IOCG deposits (e.g., Sossego, Salobo, Igarapé Bahia/Alemão, Cristalino, Igarapé Cinzento/Alvo GT46; Xavier *et al.*, this volume). New age dating is also unveiling Archaean components to some polyphase IOCG deposits (e.g., Guelb Moghrein; Meyer *et al.*, 2006) and some Proterozoic IOCG deposits occur within Archaean terranes (e.g., Alvo 118 and Breves in the Carajas district, Tallarico *et al*., 2004; Aldan Shield, Soloviev, this volume). Phanerozoic examples are common in the Andes and have the best-constrained geodynamic settings (Sillitoe, 2003). The distribution of prospective geological environments for IOCG deposits in Canada mirrors the global pattern (Fig. 1; Corriveau, 2007). IOCG mineralisation is most common in Proterozoic settings: Great Bear Magmatic Zone (Northwest Territories), Wernecke Breccia (Yukon), Manitou Lake district (Quebec), Mid-Continent Rift (Ontario), Southern Province (Ontario) and Central Mineral Belt (Labrador). Validation of the IOCG model is in progress for three Archaean settings in the Abitibi and Shebandowan greenstone belts (Ontario, Quebec; Furic and Jébrak, 2005; Tremblay and Koziol, 2007; Kontak *et al.*, 2008a), while Phanerozoic IOCG mineralisation occurs in the Appalachian Orogen (Nova Scotia, Newfoundland, Quebec) and in several areas within the Cordillera (British Columbia, Yukon). The gold-cobalt-bismuth-copper-bearing NICO deposit in the Great Bear Magmatic Zone is the first bona fide IOCG discovery in Canada (Goad *et al.*, 2000; Fortune Minerals, 2008).

In this paper we briefly review key characteristics of IOCG deposits pertinent to exploration in Canada, then update knowledge on Canadian examples and prospective settings. Current exploration results that suggest potential new settings are briefly discussed. In particular, we review recent advances in the Great Bear Magmatic Zone (GBMZ), Wernecke Breccia, Manitou district, Central Mineral Belt (CMB), Cobequid-Chedabucto Fault Zone (CCFZ) and Shebandowan greenstone belt, and conclude with remaining frontiers such as the Bondy gneiss complex in the Grenville Province. We discuss alteration zoning and vectoring approaches that have proven effective in well- to poorly-exposed geological terranes in Canada, including highly

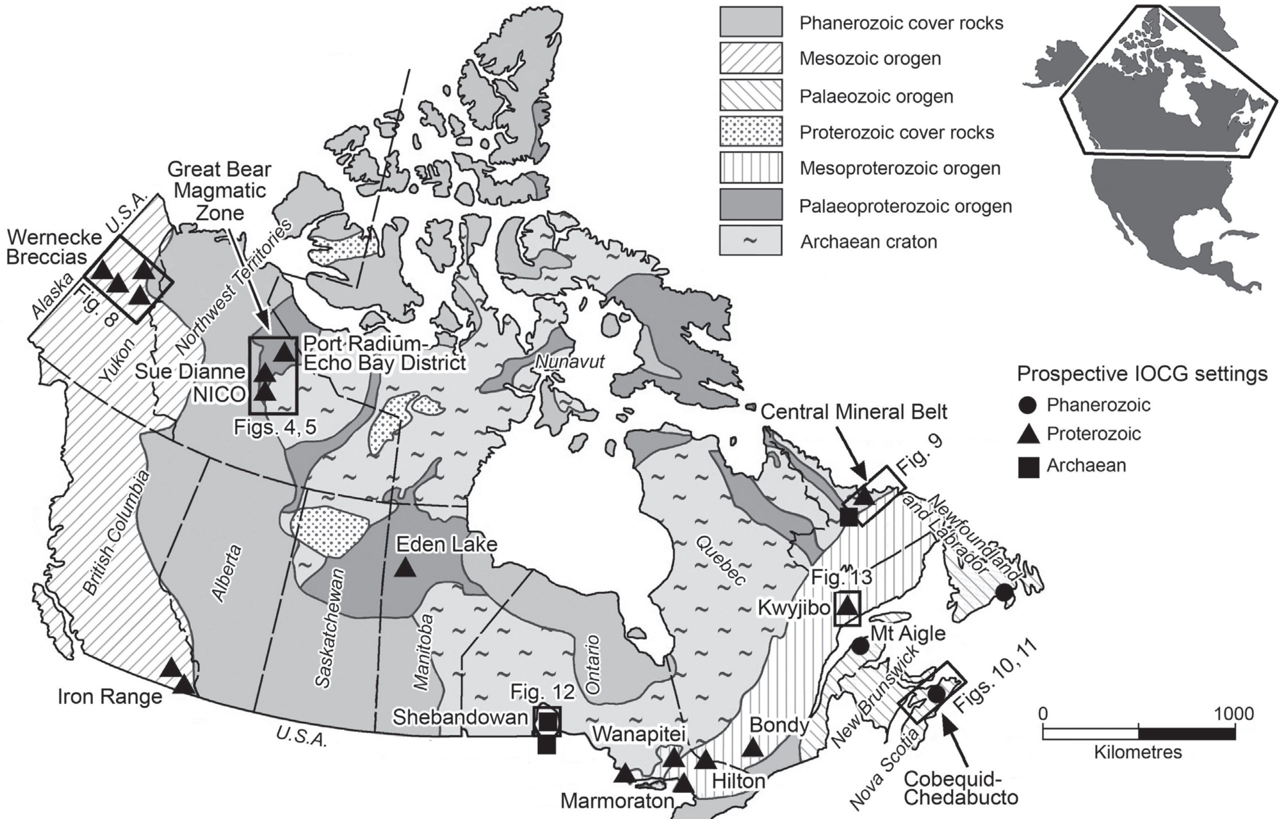

Figure 1: Prospective IOCG settings and known IOCG mineralisation in Canada.

metamorphosed regions and illustrate challenges in dating polyphase mineralisation. The well-exposed IOCG systems of Canada highlight commonalities in regional- to deposit-scale alteration and zoning patterns, geotectonic setting, crustal- to local-scale structures and magmatic association. The extraordinary range of IOCG and affiliated deposits falls into a continuum with porphyry and epithermal deposit types. Collectively, this documentation of IOCG systems and affiliated deposits significantly broadens the potential impact of exploring for this style of deposit in Canada's virgin terranes.

IOCG Deposits

Characteristics

Iron oxide copper-gold deposits include a range of hydrothermal mineral deposits that contain copper, with or without gold, as well as abundant magnetite and/or hematite with Fe:Ti ratios greater than those in most igneous rocks and bulk crust. The deposits exhibit structural control at both the regional and deposit scale. Large-scale magmatism is important to the genesis of many IOCG deposits (Williams *et al.*, 2005), although the deposits are not necessarily centered on a single causitive intrusion. Common to all IOCG deposits are metalliferous zones within regional-scale hydrothermal alteration systems that comprise extensive, intense, and diagnostic sodic (albite or scapolite), calcic-ferrous (±sodic) (amphibole-magnetite), potassic-ferrous/ferric (biotite/K feldspar-magnetite) and/or potassic-ferric (K feldspar/sericite-hematite-chlorite-carbonate) hydrothermal alteration zones. The alteration characteristics are not all necessarily present for any one deposit. Commodities are less diagnostic than alteration types, since IOCG deposits can host significant quantities of base metals (copper, iron, lead, zinc, nickel), precious metals (gold, silver, platinum-group elements), strategic metals (bismuth, cobalt, rare earth elements, vanadium) and uranium, either as economic metals or as by-products.

This combination of metals is atypical, in that many of the above elements do not normally precipitate together in a single deposit (e.g., copper and gold under reducing and uranium under oxidising hydrothermal conditions, rare earth elements associated with alkaline magmatism, nickel and platinum-group elements associated with mafic magmatism). Ore grades are intermediate to low (0.3 to 3 wt.% Cu; 0.2 to 5 g/t Au; 1 to 5 g/t Ag) and size can potentially be very large (up to 9080 Mt @ 0.87% Cu, 0.27 kg/t U_3O_8, 0.32 g/t Au, 1.50 g/t Ag, + 151 Mt @ 0.99 g/t Au, Olympic Dam deposit, BHP Billiton, 2009). There are many variations in commodities, grade and size including transitions from Olympic Dam to essentially barren iron oxide-apatite (IOA) deposits (e.g., El Romeral and Kiruna), to IOAs with appreciable copper (e.g., Marcona with 1.94 Gt @ 55.4% Fe, 0.12% Cu; Chen 2008), to copper deposits with or without gold (Mina Justa with 346.6 Mt @ 0.71 % Cu, 3.8 g/t Ag and 0.03 g/t Au; Chen, 2008), to iron oxide rare-earth deposits such as Bayan Obo (Smith and Chengyu, 2000). Industrial minerals, carving and lapidary stones have also been extracted from some IOCG deposits and their alteration systems.

Alteration diagnostic of IOCG deposits can form in nearly any host rocks, although feldspathic precursors appear to be most favourable (Nisbet *et al.*, 2000). Early sodic (±calcic) and calcic-ferrous (±sodic) (magnetite) alteration zones are commonly laterally extensive and rich in albite and amphibole-magnetite±apatite respectively. Their outcrops are striking and so in Canada they have been mapped in some areas prior to any clear definition of the IOCG deposit type (e.g., in the GBMZ; Hildebrand, 1986; Gandhi, 1992; Reardon, 1992). These alteration zones demarcate prospective areas at the regional scale and may host iron-oxide apatite deposits, but are largely barren in terms of polymetallic IOCG mineralisation, unless accompanied by high-temperature potassic-ferrous/magnetite (HT K-Fe) and/or lower-temperature potassic-ferric/hematite-hydrolitic (LT $K-Fe^{3+}-H_2O-CO_2$) alteration types with associated breccias. These latter alteration types host most of the polymetallic IOCG mineralisation (Williams *et al.*, 2005). Skarns and associated mineralisation may also form in IOCG systems where carbonate or carbonaceous host rocks are present (e.g., Wang and Williams, 2001; Franchini *et al.*, 2007), or develop as part of IOCG alteration sequences where earlier carbonate alteration has taken place (Mumin *et al.*, 2010). Mineralisation occurs as breccias, veins, stockworks and stratabound to discordant replacement (disseminations to massive lenses). Fluids can alter precursor rocks over square kilometres, both chemically and texturally (Fig. 2; Mumin *et al.*, 2007). The sequential development of alteration types and the systematics of metal precipitation with respect to the development of alteration provide a framework to aid the exploration for IOCG deposits (Fig. 3; Corriveau *et al.*, 2010).

IOCG deposits typically occur in clusters and form significant mineral districts that may extend for several hundreds of kilometres, commonly along a continental arc- or an orogen-parallel crustal-scale structural zone and its splays (Sillitoe, 2003; Austin and Blenkinsop, 2008; Clark *et al.*, 2010). Structural control on deposition, alteration, and distribution of ore zones, deposits and districts starts at the orogenic scale (e.g., Olympic Dam; Drummond *et al.*, 2006). More local structures create dilational zones and breccias in mechanically competent host rocks and partially control alteration pathways (Nisbet *et al.*, 2000). Deposits may be the sum of coalescing hydrothermal cells (Williams *et al.*, 2005; Mumin *et al.*, 2007) while the varied commodities and mineralisation styles result from complex processes that involve a variety of fluid, metal and heat sources, and evolving fluid-rock interactions (Williams *et al.*, 2005). A continuum with porphyry and epithermal systems is illustrated below by some Great Bear Magmatic Zone examples. Both polymetallic deposits devoid of significant iron oxides, and iron oxide-apatite deposits ("Kiruna-type" /IOA) are not classified as IOCG deposits *per se.* As per some polymetallic niobium and rare earth element magmatic-hydrothermal iron deposits and some uranium deposits with appreciable iron oxide in the ore gangue, the IOA deposits share significant affinities with IOCG deposits in terms of alteration development and ore-forming processes (Williams, 2010a), and can be parts of regional-scale polymetallic IOCG systems. In parts of the GBMZ, IOA and other non-IOCG styles of mineralisation show a continuum of characteristics related to the same magmatic-hydrothermal processes. IOCG systems develop in settings as distinct as: (1) volcano-plutonic belts in continental settings, particularly in continental magmatic arcs, back-arcs and far-field back-arcs; (2) sedimentary basins and metasedimentary rocks with or without exposures of magmatism coeval with mineralisation; (3) alkaline stocks and their country rocks; and (4) metamorphic terranes (Sillitoe, 2002, 2003; Betts and Giles, 2006; Clark *et al.*, 2010).

Key geological criteria for the development of giant polymetallic, uranium-rich hematite-group IOCG deposits worldwide are discussed in Skirrow (2010) and include: (1) the presence of felsic subaerial volcanic rocks and high-level intrusions, including granites with an A-type chemistry; (2) a transition from compressional to extensional regimes during magmatism and alteration; (3) evidence of coeval subvolcanic to epithermal settings and older sedimentary basins; (4) crustal-scale structural pathways for magmas and fluids; (5) crustal thermal anomalies; (6) reaction of oxidised, magnetite-forming fluids; and (7) fluid mixing. Evolving high- to lower-temperature alteration systems across extensive areas lead to different styles of mineralisation that can have significant variance, even within a kilometre radius. If taken individually, these prospects can be interpreted as distinct deposit types belonging to separate mineralisation processes (e.g., epithermal vein deposits, skarn, porphyry, volcanic-hosted uranium, etc.; Mumin *et al.*, 2007, 2010). This may have inhibited recognition of IOCG productive systems in the past, but is currently viewed more holistically in combination with alteration mapping as another tool to recognise IOCG systems in virgin territories. The development of such exploration models and methodologies suitable for grassroots exploration is greatly needed in Canada, where prospective settings for IOCG deposits (Fig. 1) are largely underexplored and even as yet unknown (cf. Mumin and Perrin, 2005; Corriveau, 2007; Mumin *et al.*, 2007, 2010). In recent years however, comprehensive scoping studies, acquisition of high-resolution airborne magnetic and radiometric data, geological research, development of new exploration tools and models, and regional- to deposit-scale mapping projects have been undertaken by a collaboration between governments, academia and industry to support the emerging IOCG exploration across the nation (Thorkelson, 2000; Goad *et al.,* 2000; Gobeil *et al.*, 2003; Jackson, 2008; Kontak *et al.*, 2008b; Ootes *et al.*, 2008; Sparkes and Kerr, 2008; Staples *et al.*, 2008; Harvey *et al.*, 2009; McMartin *et al.*, 2009; Beaudoin and Dupuis, 2010; Clark *et al.*, 2010; Corriveau *et al.*, 2010; Mumin *et al.*, 2010). These tools, practical guides and models for exploration are applicable to a wide range of geotectonic settings found across Canada, including highly metamorphosed terranes up to granulite facies (Bonnet and Corriveau, 2007; Corriveau *et al.*, 2007).

IOCG Districts and Settings

Geological settings prospective for hosting IOCG deposits in Canada typically consist of volcano-plutonic belts with voluminous calcalkaline to A-type granites and deep-seated, crustal-scale fault zones that largely belong to Proterozoic or Phanerozoic continental convergent margins built on Archaean or Proterozoic crust. These include the Great Bear Magmatic Zone in the Northwest Territories, the Trans-Hudson Orogen in Manitoba, the Central Mineral Belt in Labrador and the Cobequid-Chedabucto Fault Zone in Nova Scotia (1). Formerly known for its vein-type uranium and silver mines, the Great Bear Magmatic Zone is currently the most prospective IOCG mineral belt in Canada and also has potential for porphyry copper and epithermal type deposits. This belt, and a few other prospective settings of Canada, satisfy geological criteria proposed by Skirrow (2010) for hosting uranium-rich hematite-group IOCG deposits as highlighted in their description below. Excellent cross-sectional exposures of hydrothermal alteration zones, breccias coeval and spatially associated with sub-volcanic intrusions, volcanic belts and calcalkaline to A-type granites constrain the giant systems of the Great Bear Magmatic Zone to being magmatic-hydrothermal in origin (Hildebrand, 1986; Goad *et al.*, 2000; Gandhi *et al.*, 2001; Mumin *et al.*, 2007, 2010). In contrast, the extensive curvilinear array of 1.6 Ga Wernecke Breccias, their polymetallic uranium-bearing prospects, and IOCG type mineralisation in the Wernecke and Ogilvie mountains (Yukon; Fig. 1) crosscut Palaeoproterozoic metasedimentary rocks without any evidence of outcropping coeval magmatic suites (Thorkelson, 2000). For these reasons, polymetallic, iron-oxide bearing deposits in the Wernecke Breccia have been interpreted as a non-magmatic example of IOCGs, although potential magmatic input is starting to be advocated (Hamilton and Buchan, 2007; Kendrick *et al.*, 2008). In some cases, such as in the Manitou district of the Grenville Province (Fig. 1) and the Cobequid-Chedabucto Fault Zone (Fig. 1), multiple orogenic, metamorphic, deformational and/or magmatic events complicate interpretation of the geodynamic settings and timing of key events responsible for the mineralisation, even where hydrothermal minerals can be dated. In other cases the IOCG-like systems have been totally metamorphosed to gneiss complexes such as in the western Grenville Province of Quebec (Corriveau *et al.*, 2007). Finally, other settings are just emerging as exploration targets for IOCG deposits, including the Archaean Shebandowan (Fig. 1) and Abitibi belts of Ontario and Quebec. In the following sections we describe selected prospective Canadian IOCG districts and raise some of the key questions that remain to be resolved.

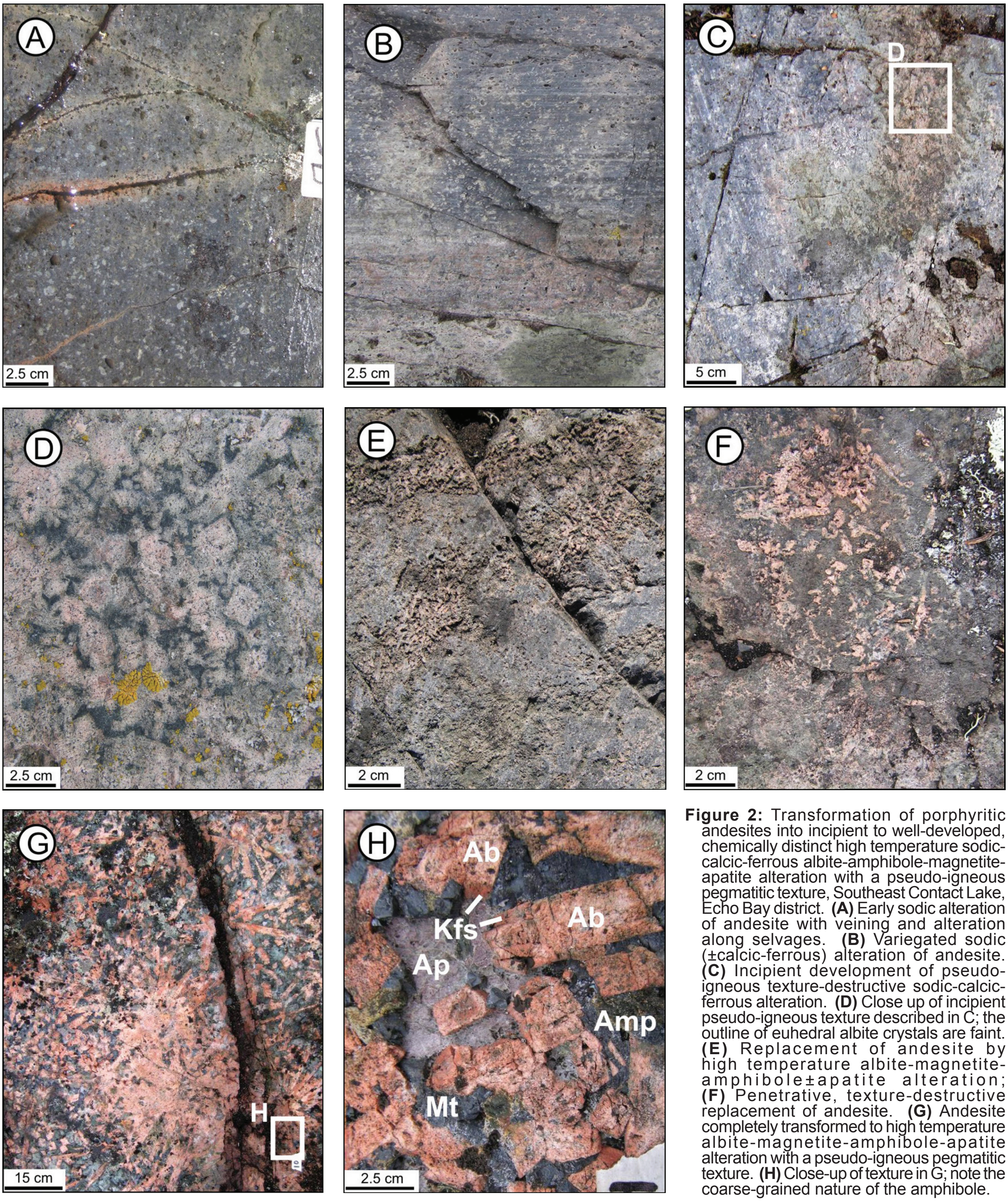

Figure 2: Transformation of porphyritic andesites into incipient to well-developed, chemically distinct high temperature sodic-calcic-ferrous albite-amphibole-magnetite-apatite alteration with a pseudo-igneous pegmatitic texture, Southeast Contact Lake, Echo Bay district. **(A)** Early sodic alteration of andesite with veining and alteration along selvages. **(B)** Variegated sodic (±calcic-ferrous) alteration of andesite. **(C)** Incipient development of pseudo-igneous texture-destructive sodic-calcic-ferrous alteration. **(D)** Close up of incipient pseudo-igneous texture described in C; the outline of euhedral albite crystals are faint. **(E)** Replacement of andesite by high temperature albite-magnetite-amphibole±apatite alteration; **(F)** Penetrative, texture-destructive replacement of andesite. **(G)** Andesite completely transformed to high temperature albite-magnetite-amphibole-apatite alteration with a pseudo-igneous pegmatitic texture. **(H)** Close-up of texture in G; note the coarse-grained nature of the amphibole.

Great Bear Magmatic Zone

The Great Bear Magmatic Zone (GBMZ) is a Palaeoproterozoic calcalkaline volcano-plutonic arc developed along a continental convergent margin between 1.88 and 1.84 Ga. It overlies a Palaeoproterozoic, ca. 2.1 to 1.88 Ga magmatic arc, the Hottah terrane, accreted to the western margin of the Archaean Slave craton during the short-lived ~1.90 to 1.88 Ga Calderian orogeny (Fig. 4; Hildebrand *et al.*, 1987, 2010; Gandhi and van Breemen, 2005). Felsic and intermediate magmatism prevails, forming batholiths, sub-volcanic intrusions and volcanic rocks that extend along the entire magmatic belt, with only a few intrusions being present beyond the eastern limit of the Great Bear Magmatic Zone, the major, north-trending, vertical Wopmay fault zone (also named the 'medial zone'; Hildebrand *et al*., 2010). Coeval mafic magmatism occurs as minor volcanic rocks within the GBMZ and as the ca. 1.87 Ga Mara River sheets (including the Peninsular sills) that predate the Ghost River mafic dyke swarm and the Morel sills in the Wopmay orogen and adjacent Slave craton (Buchan *et al*., 2010; Hildebrand *et al*., 2010). Regional-scale IOCG-type hydrothermal systems, coeval with volcano-plutonic activity, are documented throughout the length of the exposed GBMZ. Structural breccias and a few IOCG environments occur along the Wopmay fault zone (e.g., Montreuil *et al*., 2009), although most known IOCG environments are to its west. Magmatic activity, a thermal catalyst and fluid source for the hydrothermal activity, ceased at 1.84 Ga, likely as a result of eastward collision of an exotic (Fort Simpson) terrane with the western margin of Hottah terrane. This event may have contributed to the development of a network of northeast-trending dextral transcurrent fault systems that locally host giant quartz veins and appear to extend from crust to upper mantle (Wu *et al.*, 2005). Alternatively, Mumin *et al.* (2009) interpret the northeast faults as transform displacements of southeast trending extensional corridors, all synchronous with an extensional episode of GBMZ development to which hydrothermal activity would be related. The GBMZ is exposed for over 450 km between Great Slave and Great Bear lakes, and is interpreted to be at least 1200 km in length based on basement magnetic signatures that continue north and south under Palaeoproterozoic and Phanerozoic sedimentary cover (Fig. 4, Bleeker and LeCheminant, 2008; Hildebrand *et al*., 2010 and references therein). A modern-day analogue for the GBMZ is the Ryukyu arc, where continental arc magmas were emplaced after arc-continent collision and orogenic collapse, on top of the eroded collision zone (Hildebrand *et al*., 2010). This interpretation currently supersedes previous back-arc basin analogies of Hoffman and McGlynn (1977) and Cook *et al.* (1998). Reworked Archaean rocks of the Slave craton extend as far west as the Wopmay fault zone and isotopic signatures of GBMZ volcanic and plutonic rocks do not record the presence of Archaean crust under the GBMZ (Hildebrand *et al*., 2010). However, magnetotelluric studies suggest that the Slave craton has a resistive wedge-shaped Archaean lithospheric root that tapers down westward nearly reaching at depth the location of the exposed segments of Hottah terrane. A resistive cratonic root imaged to depths of ca. 200 km also occurs below the Hottah terrane and both are separated by a less resistive region beneath the Great Bear magmatic zone. Discontinuities between these lithospheric components are sharp. In the magnetotelluric model, the Wopmay fault zone only extends to the mid-crust where it intersects the Archaean lithospheric wedge (Spratt *et al*., 2009). Currently known IOCG environments in the GBMZ occur above some of the major lithospheric discontinuities imaged by Spratt *et al.* (2009). Overall, the lithospheric architecture, as imaged by magnetotelluric, teleseismic and seismic LITHOPROBE SNORCLE surveys, bears similarities to the architecture of the Gawler craton below the Olympic Dam deposit in Australia. At Olympic Dam, the lithospheric architecture includes tapering out of a resistive Archaean lithospheric root, the extremity of which is directly under Olympic Dam, as well as significant discontinuities (cf. Drummond *et al.*, 2006; Cook *et al*., 1998; Snyder, 2008; Spratt *et al.*, 2009). Work in progress is attempting to better frame the crustal architecture of the Great Bear Magmatic Zone in light of new geological and geophysical data, such as high-resolution airborne magnetic and radiometric surveys (NTGO, 2006, 2008; Harvey *et al*., 2009), and recognition of the presence of a Palaeoproterozoic red-bed basin beneath the Phanerozoic cover that may have originally been interpreted as a Great Bear magmatic arc reflector (Bleeker and Lecheminant, 2008 versus Cook *et al*., 1999).

Former GBMZ metal production was from quartz, Fe-Mn-carbonate and hematite-bearing epithermal veins hosting sulphides and arsenides with Cu, U, Ag±Co, Bi, Pb or Cu, Ag±Pb, Zn, Co, Bi and U. These mines resulted from an early phase of exploration and development starting in 1930 (Badham, 1978). A second major phase of exploration, geoscience knowledge acquisition and geophysical surveys (high-resolution government airborne radiometric eK, eTh and eU, and ground gravity; Charbonneau, 1988; Hetu *et al.*, 1994; Gandhi *et al.*, 1996) in the 1980s and 1990s led to the recognition of extensive zones of hydrothermal alteration diagnostic of IOCG systems (Hildebrand, 1983, 1986; Reardon, 1992; Gandhi, 1994; Gandhi and Bell, 1996). However, the first successful application of the IOCG

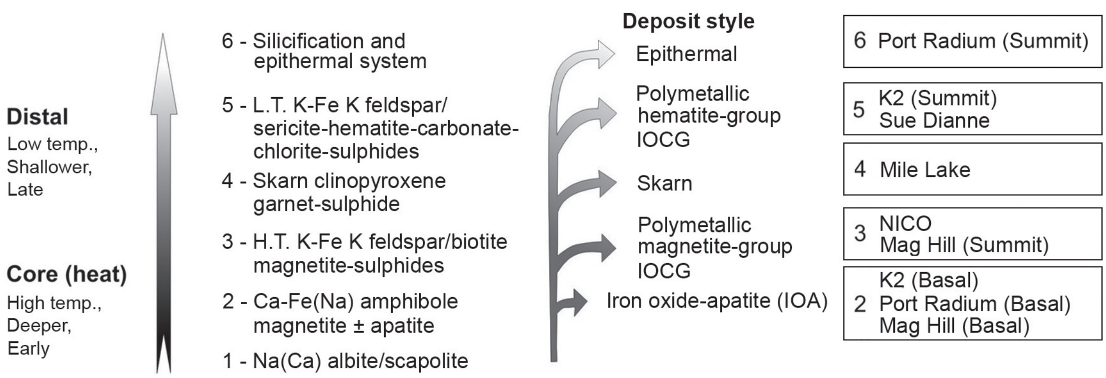

Figure 3: Continuum of hydrothermal alteration in IOCG systems and associated deposits (after Corriveau *et al.*, 2010). Examples of mineralisation associated with each stage of alteration in the GBMZ are given as references.

deposit model during an exploration program in Canada took place after 1995 and led to discovery of the *NICO* deposit (Goad *et al.*, 2000). Current mineral exploration is concentrated in a north-south trending belt near Great Bear Lake (Port Radium-Echo Bay and Camsell River districts, northern GBMZ) whereas known deposits (the Au-Co-Bi-Cu *NICO* and Cu-Au-Ag *Sue-Dianne* deposits), are under development in the southern GBMZ (Fig. 4). These IOCG districts and series of showings extend laterally along the full extent of the belt, particularly near its western contact with Phanerozoic and underlying Proterozoic cover (Mumin *et al.*, 2010).

Hydrothermal alteration patterns for the various deposits in the GBMZ follow a common theme with local variations. They are discussed and modelled in detail by Goad *et al.* (2000) and Mumin *et al.* (2007, 2010) based on field mapping and drilling. Alteration progresses systematically outwards from sub-volcanic intrusions as zones characterised by albite, magnetite-amphibole with or without apatite, biotite and/or potassic feldspar, phyllic, epidote-chlorite-carbonate-sericite-hematite and quartz-carbonate-hematite assemblages. There is considerable spatial overlap and overprinting of alteration assemblages in both prograde and retrograde sequences, and a continuum with porphyry and epithermal systems is quite evident as will be discussed below. Currently, the best understood and most examined systems are located in the Port Radium-Echo Bay district and at the *NICO* and *Sue-Dianne* deposits, although another district is emerging at the past-producing Terra mine area in the Camsell River district (Fig. 4; Walker and Rajnovich, 2007).

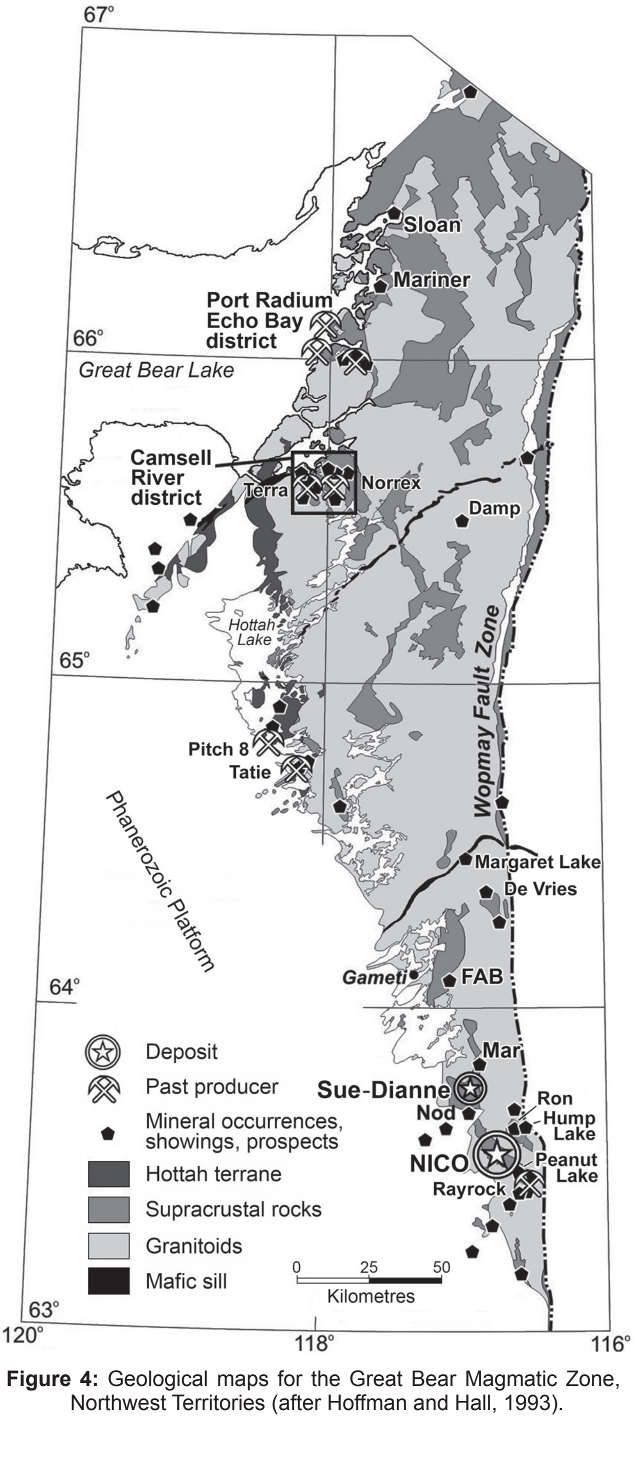

Figure 4: Geological maps for the Great Bear Magmatic Zone, Northwest Territories (after Hoffman and Hall, 1993).

Northern GBMZ, Port Radium-Echo Bay District

The Port Radium-Echo Bay district of the GBMZ constitutes a very well preserved 1.87 to 1.86 Ga stratovolcano complex with spatially extensive hydrothermal alteration, abundant mineral showings and past-producing mines (Fig. 5A). The complex is dominantly composed of porphyritic to amygdaloidal andesitic tuff, flows, breccia and debris flows, with coeval diorite/monzodiorite subvolcanic stocks and plutons. Most of these intrusions are internally potassic altered to an assemblage resembling monzonite in apical or peripheral regions, and hence the term "monzodiorite" which has come into common usage, actually refers to potassic-altered diorite. The complex has been described as a collapsed cauldron with a crudely circular and inward dipping structure (Hildebrand, 1983). Asymmetry in the collapse structure (or broad folding of cauldrons as per Hildebrand, 1984) provides a southern cross-sectional exposure of the complex and its alteration types. The Contact Lake subvolcanic intrusion occurs at the base of the cross-section and is structurally overlain by a ca. 5 km thick hydrothermally altered andesitic succession. Remnants of a ~15 km diameter ring-like structure (Port Radium Formation) circumscribe the volcanic centre and are well exposed at the western edges of the complex (Fig. 5A). This ring structure comprises an up to ~500 m thick unit of finely laminated to graded tuff and epiclastic sediments with interlayered thin pyroclastic and ignimbrite sheets (Hildebrand, 1983; Mumin *et al.*, 2007, 2010). Additional successive pyroclastic tuff rings are exposed nearer the volcanic centre (Cameron Bay Formation; Hildebrand, 1983). The youngest significant geological units consist of arkosic sandstones and conglomerates, best preserved in the collapsed centre of the complex. From the nature of superimposed hydrothermal alteration (mainly hematitic and potassic), it appears that the arkose-conglomerate may also be a synvolcanic feature, although late in the construction of the stratovolcano. Large gabbroic sills and stocks are locally exposed in the centre and peripheral regions of the complex. They are up to 1 km thick, 4 km in length, postdate the collapse structure, are not hydrothermally altered and belong to the same suite as the 1740 Ma Cleaver dyke dated in the Camsell River district (Irving *et al.*, 2004). A similar age has been obtained on such a dyke at Echo Bay (van Breemen and Corriveau, unpublished data, 2009). An older suite of microdioritic to gabbroic sills and dykes are hydrothermally altered and thought to be coeval with the volcanic activity.

The Echo Bay stratovolcano complex is hydrothermally altered throughout most or all of its exposed extent (Reardon, 1992; Mumin *et al.*, 2007). It is also well

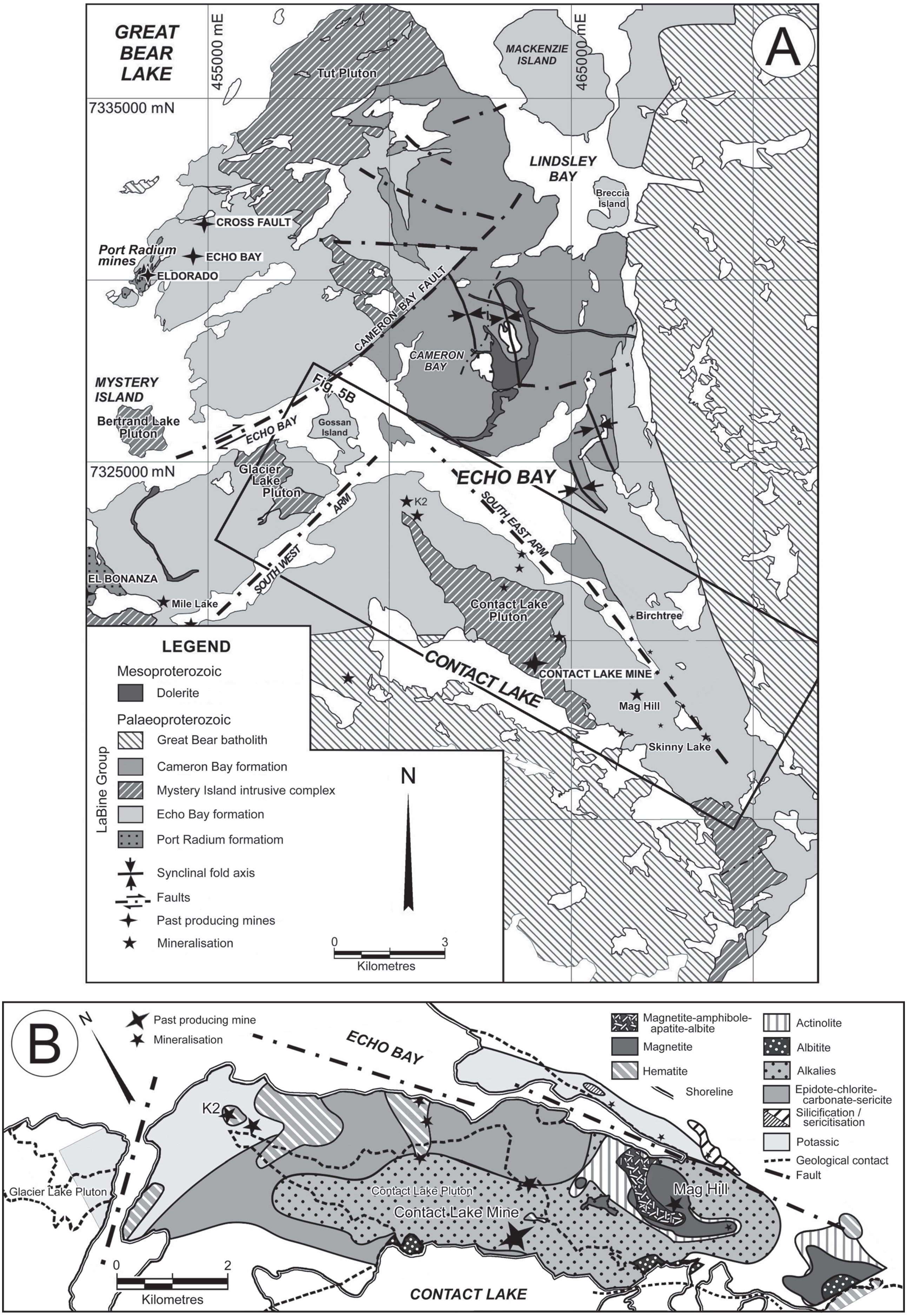

Figure 5: (A) Simplified geology of the Port Radium–Echo Bay district after Hildebrand (1983). **(B)** Alteration zones superimposed on host geology map units from Fig. 5A (dashed lines) of the Contact Lake Belt (modified from Mumin *et al.*, 2007). Alkalies = sodic (±calcic) alteration and/or potassic (K feldspar) alteration.

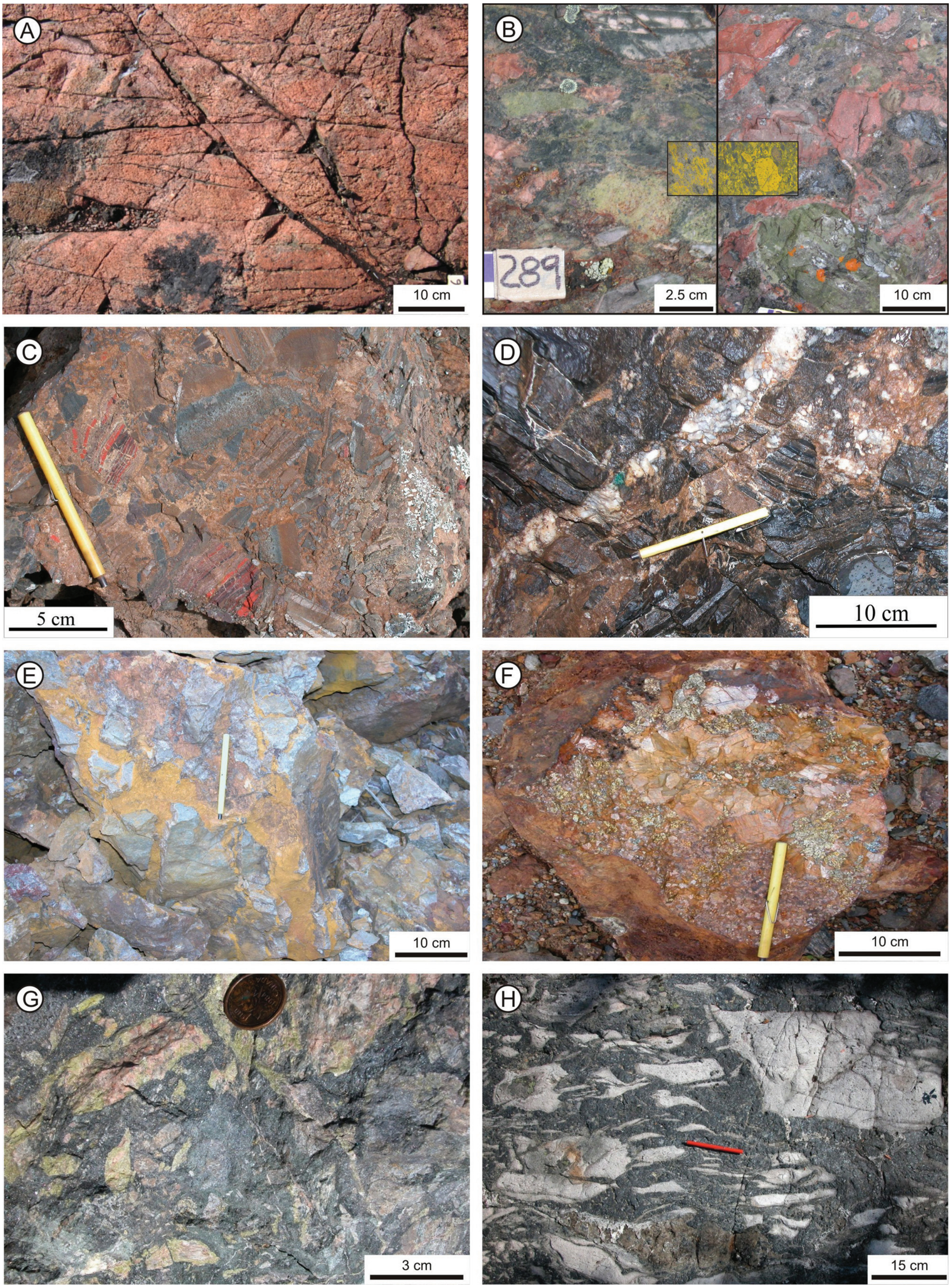

Figure 6: (A) K feldspar alteration after porphyritic andesite (Port Radium-Echo Bay district, GBMZ). **(B)** Mile Lake breccia, GBMZ: left - skarn breccia; right - K feldspar alteration overprint on skarn breccia; inset - stained slab highlighting K feldspar alteration in yellow. **(C)** Wernecke Breccia: partly hematised clasts of Wernecke Supergroup in a matrix dominated by iron carbonate. **(D)** Wernecke Breccia: in situ siltstone of the Quartet Group disrupted by hydrothermal iron carbonate. Note malachite in carbonate vein. **(E)** Hydrothermal breccia with ankerite veins, Londonderry district, CCFZ. **(F)** Coarse-grained ankerite-siderite-chalcopyrite-pyrite vein, Copper Lake, CCFZ. **(G)** Hydrothermal breccia with magnetite-chlorite-hematite matrix, North Ogden, CCFZ. **(H)** Hydrothermal breccia: clasts of felsic rock with magnetite cement in the Josette prospect, Manitou Lake district.

mineralised, including four past-producing mines and numerous significant and minor mineral showings (Mumin *et al.*, 2010). The alteration sequence is modelled by Mumin *et al.* (2007, 2010) as progressive outward mineral zoning from sub-volcanic diorite/monzodiorite intrusions to the andesitic wallrocks. It is described in detail in the aforementioned papers and in Corriveau *et al.* (2010). These include sodic±calcic (albite±amphibole), calcic-iron±sodic (magnetite-actinolite-apatite±albite), high-temperature and lower-temperature potassic-iron (K feldspar-biotite-magnetite and sericite-hematite respectively, ± local skarn alteration), phyllic (quartz-sericite-pyrite), propylitic (chlorite-epidote-carbonate±sericite-albite) and distal to late epithermal quartz-carbonate-hematite veins. These alteration types occur as replacive impregnations, veins, stockworks or breccias. Replacive alteration is mild to intense, texture pseudomorphing to texture destructive, variegated to massive, stratabound to clearly crosscutting and monomineralic to polymineralic. Veins, stockworks and hydrothermal breccias crosscut early replacive alteration and commonly have replacive alteration selvages. Hydrothermal breccias developed in earlier units, commonly in volcanic-related breccias, complicating breccia analysis.

Notwithstanding local overprinting, systemic alteration zoning is observed away from the Mystery Island suite sub-volcanic diorite intrusions exposed in the complex (Fig. 5B). Within these intrusions, and commonly straddling their contact with andesite and associated rocks, albitic alteration occurs as veins or as replacement, forming in the most extreme cases massive albitite in the andesitic host rocks. Albitite is best developed proximal to the subvolcanic intrusions. Albitite occurs locally as enclaves within the diorite intrusions south-east of the tip of the Echo Bay South East Arm (*Southeast Echo Bay*), and the intrusions and their albitised host rocks are locally brecciated at their margins (*Mile Lake*; Fig. 5A). Albitite and Mystery Island suite intrusions are crosscut by veins of magnetite, magnetite-actinolite or actinolite±magnetite and apatite. Variegated replacement-type potassic alteration is common and gives a dark brick-red colour to the white or pale pink-coloured albitite. At *Mag Hill* (Fig. 5B), albite occurs in abundance with magnetite-actinolite-apatite, forming a km-scale zone of alteration that fully replaces andesite from the margin of the diorite intrusion outward. With a pseudo-pegmatitic field texture consisting of cm to tens of cm euhedral crystals of albite (± potassic rims) and interstitial coarse-grained magnetite, apatite and amphibole, this alteration resembles an igneous rock. A few kilometres outward from the intrusion, this pseudo-pegmatitic alteration becomes variegated and its intensity wanes with well formed to incipient pseudo-pegmatitic textures fading into the andesitic host, providing conclusive evidence of its hydrothermal origin (Fig. 2). Such textures are observed in other systems of the GBMZ, with some also showing *in situ* replacement of their host (Hildebrand, 1986; Corriveau *et al.*, 2010). Massive and vein-type vanadiferous magnetite-actinolite-apatite alteration occurs at *Mag Hill*, below the *K2* showings and adjacent to the past producing Port Radium uranium-silver-copper veins (includes *Echo Bay* and *Eldorado*), and is comparable to IOA in the classification scheme of Williams (2010a). Magnetite-actinolite±apatite veins occur either with or without K feldspar selvages (*Southeast Echo Bay*), whereas the replacive alteration is commonly overprinted by potassic (K feldspar) and subsequently by chlorite alteration (*Mag Hill*). K feldspar-magnetite alteration is the most visible form of high-temperature potassic-iron alteration in the field, although biotite is also present in variable amounts. Such zones grade into intense potassic alteration at the magnetite-hematite transition (Fig. 6A) and lead to overprinting of K feldspar by lower-temperature hematitic mineral assemblages. More distal zones may be intensely silicified, such as at Breccia Island, a type of silicification reminiscent of the barren hematite-silica rich zones of Olympic Dam (e.g., Reynolds, 2000). A mild replacement-type potassic alteration also typically envelops the diorite and albite alteration in a spatially extensive zone. In its most extreme expression, potassic alteration converts host rock andesites, and sometimes marginal and apical portions of the sub-volcanic intrusions, to massive felsites comprised of >80% hydrothermal K feldspar.

In contrast to the north-south variation from high to lower temperature alteration observed at surface in the eastern and central segments of the Contact Lake belt, in the western part of the belt (*K2 prospect*), high temperature assemblages (amphibole-magnetite) occur at depth below the lower temperature hematite-bearing alteration and mineralisation exposed at surface. This sharp change in the spatial variation of high to lower temperature alteration along the belt suggests that alteration took place before and during an episode of tilting of the andesitic volcanic pile of the Echo Bay complex, an observation compatible with an episode of tectonic exhumation during build-up of the hydrothermal system. If this was the case, some tilting of the volcanic pile would be in part significantly older than the subsequent folding documented across the entire GBMZ (Hildebrand *et al.,* 2010).

The "inner" zones of IOCG type sodic, calcic-iron, high-temperature and lower-temperature potassic-iron alteration grade distally (and to structurally higher levels) to an "outer" potassic halo with phyllic alteration comprising sericite, quartz and pyrite diagnostic of an epithermal system (Fig. 5B). Typically, rocks of the phyllic zone are completely recrystallised to the new assemblage, yet porphyritic and amygdaloidal textures of the primary andesite are perfectly preserved. Phyllic altered rocks are commonly intermixed with potassic alteration. Where they are exposed at surface, they make spectacular and readily visible gossans due to the "sulphur burn" from weathering pyrite. The most distal outer zone of hydrothermal alteration is characterised by various assemblages of chlorite, carbonate, epidote, sericite, quartz and/or albite typical of a propylitic zone. As with phyllic alteration, 'propylitic' zones are characterised by pervasive recrystallisation of the primary assemblage, although primary igneous textures are well preserved. Veins of prograding, higher-temperature assemblages are commonly superimposed on earlier lower-temperature alteration. Late epithermal quartz and/or carbonate±hematite veins also crosscut all other alteration zones. These veins typically host sulphides, arsenides and/or pitchblende, with varying Cu, Ag, U, Co, Bi, Pb, Zn and Au contents. Tourmaline is abundant in some areas, generally superimposed on potassic or phyllic alteration zones and in some instances associated with economic mineralisation (*K2* and in the southern GBMZ at *NICO*).

Current geochemical modelling of the Contact Lake belt (Montreuil *et al*., 2009) highlights that metals were sourced in part within host intermediate rocks, liberated through strong leaching of mobile and 'immobile' elements (e.g., LILE, REE, Co, Ni, Zn, Nb, Ta and to a lesser extent Zr and Hf) during severe and extensive sodic influx that led to albite alteration. Leached elements have in part subsequently precipitated during intense potassic alteration in the presence of iron oxide. In contrast, a magmatic-hydrothermal fluid associated with the final evolution of felsic magmas would best account for the overall chemical signature of a pseudo-pegmatitic alkali-rich alteration (currently largely albite) associated with an apatite-magnetite-amphibole assemblage. Growth of hydrothermal zircons at 1869±9 Ma in albitite is coeval with Great Bear batholith magmatism (ca. 1873 to 1865 Ma) and the new 1872±2 Ma age for the Mystery Island suite diorite intrusion along which the Contact Lake belt hydrothermal system was developed (Montreuil *et al*., 2009).

At least nine distinct styles of mineralisation are documented in the Echo Bay area. These include: (1) vanadium-bearing IOA-type magnetite-actinolite-apatite replacement bodies, breccias and stockworks (e.g., the *Port Radium mines* and *Mag Hill* - Fe-V; Breen and Mumin, 2008); (2) massive hematite replacement lenses (*Southeast Echo Bay + K2*); (3) volcaniclastic-hosted iron oxide-sulphide-arsenide replacement and breccia bodies (*Port Radium* - Zn, Pb, Ag, Cu, Co, Ni); (4) polymetallic andradite-vesuvianite-diopside-epidote-K feldspar skarn *(Mile Lake* - Cu, Zn, Pb, Ag, Mo, W; Fig. 6B); (5) complex iron oxide-potassic-phyllic-quartz-tourmaline-'propylitic' hydrothermal breccias (*K2*, Cu, Au, Ag, Co); (6) crackle breccia zones with chlorite, pyrite and chalcopyrite (*Stevens Island*); (7) phyllic-potassic-iron zones with disseminated and vein Zn, Pb, Cu, Ag sulphides (*Echo Bay* Mine, *Skinny Lake*); (8) phyllic-potassic alteration with disseminated and vein Ag±Cu (*Southeast Echo Bay*); and (9) epithermal veining, ranging from giant barren quartz to polymetallic quartz-carbonate-hematite-sulphide-arsenide veins e.g., *Eldorado, Echo Bay, Contact Lake* (Fig. 5A) and *El Bonanza* (2.5 km west of *Mile Lake*) mines with variable U, Cu, Ag, Co, Bi, Ni, Pb and Zn contents; Mumin *et al*., 2007, 2010). If the rest of the mineralisation in the GBMZ that is currently known to be associated with IOCG-type systems is considered, the number of distinct mineralisation types increases substantially. The range of seemingly disparate deposit types forms a ternary continuum of overlapping volcanic associated magmatic-hydrothermal mineral deposits between IOCG, porphyry copper and epithermal types (Mumin *et al.*, 2010). Those associated with the IOCG phase of the system can be placed within the framework of the zoning model in Fig. 3. This model is derived from the Echo Bay stratovolcano complex and other IOCG systems of the GBMZ, and recognised alteration zoning in worldwide IOCG deposits (Haynes, 2000; Marschik and Fontboté, 2001; Oliver *et al.*, 2004; Mark *et al.*, 2006) as discussed in Corriveau *et al.* (2010).

Southern Great Bear Magmatic Zone

Two important deposits occur in the southern GBMZ. The *NICO* Au-Co-Bi-Cu deposit, scheduled to begin production in 2012, comprises magnetite-group IOCG mineralisation rich in arsenopyrite. The pre-production reserves are 31.7 Mt at 0.91 g/t Au, 0.12% Co, 0.16% Bi and 0.04 % Cu (Fortune Minerals Limited news release, January 14, 2010). The *Sue-Dianne* Cu-Au-Ag breccia complex, situated 24 km north of *NICO*, is a "classic" "Olympic Dam style" hematite-group IOCG deposit that grades from magnetite-hosted (chalcopyrite-rich) in the deeper levels to hematite-hosted (chalcopyritey-bornite-digenite-chalcocite-rich) in its upper, nearer-surface portion. A diatreme and structural breccia complex emanates from the apex of a porphyritic intrusion illustrating a close transition of IOCG to alkalic porphyry copper-gold systems (Mumin *et al*., 2010). The Canadian NI 43-101 compliant resource is 8.4 Mt @ 0.80% Cu, 0.07 g/t Au, 3.2 g/t Ag (Hennessey and Puritch, 2008). These IOCG deposits, adjacent uranium and iron mineral occurrences, and associated magnetite-rich, K feldspar and magnetite-to-hematite vein, breccia, and replacive alteration are hosted in supracrustal remnants of Treasure Lake Group marine metasedimentary rocks and overlying 1.86 Ga rhyolite to rhyodacitic volcanic complex (Faber Group). Granitoids of the Marian River Batholith underlie and intrude the Treasure Lake Group, and are source plutons for, and partially intrude volcanic rocks. The Treasure Lake Group, which has a maximum age of 1885 Ma, consists of medium-bedded marine wacke, siltstone, arkose, turbidite and minor carbonate units. It is interpreted to have been deposited near the leading edge of the Hottah terrane shortly before collision with the Slave craton and is mostly deformed and metamorphosed in the vicinity of the Wopmay fault zone and at the contact with large granitic plutons (Gandhi and van Breemen, 2005; Jackson, 2005, 2008; Bennett and Rivers, 2006b). Remnants of the Treasure Lake Group remain trapped between the subvolcanic Marion River Batholith and its overlying volcanic pile. Porphyry stocks and bimodal porphyritic dyke swarms link the sub-volcanic batholith with zones of economic mineralisation at *Sue-Dianne* and *NICO* respectively (Goad *et al*., 2000; Mumin *et al*., 2007, 2010; Jackson, 2008).

Economic mineralisation at *NICO* occurs stratigraphically downward for ~300 m from the Treasure Lake Group contact with the overlying felsic volcanic pile, within strongly altered siltstone and arkose. Mineralisation forms a series of subparallel stratabound lenses, individually up to ~50 m in thickness and ~1 km in length, hosted by intense hydrothermal iron oxide (magnetite dominant)-hornblende-biotite-K feldspar±tourmaline±carbonate, carbonate-magnetite or K feldspar replacement alteration, veins, stockwork and breccia. At depths below 300 m, metasediments are hornfelsed, presumably due to contact with the immediately underlying Marion River Batholith. The general outward progression of alteration minerals at NICO, from core to periphery, includes albite, magnetite±pyrrhotite or pyrite, magnetite-hornblende-biotite-tourmaline, hematite-hornblende-biotite, biotite, K feldspar and distal sericite. The most peripheral and/or youngest hydrothermal effects include giant quartz complexes and quartz-epidote veining and alteration. Alteration and brecciation occurred episodically with many examples of prograde and retrograde overprinting. Brecciation and intense K feldspar and other alteration styles are common at the interface of porphyritic dykes and altered sediments and within some of the mineralisation zones (Corriveau *et al*., 2010). Laminated metasedimentary rocks are locally intensely and pervasively replaced by magnetite leading to rock types with the appearance of iron formation. Magnetite and hematite commonly replace and overprint iron-rich biotite and hornblende alteration, while biotite and hornblende assemblages can overprint magnetite and all can overprint or be overprinted by potassic alteration (Goad *et al*., 2000; Corriveau *et al*., 2010). The strong stratigraphic control over alteration and mineralisation at NICO is further evident in the sharp transition in alteration type at the volcanic-metasedimentary unconformity. Here, biotite or magnetite-hornblende-tourmaline-biotite altered siltstone and wacke pass rapidly into massive and extensive reddish-orange felsite (K feldspar) alteration of rhyodacite

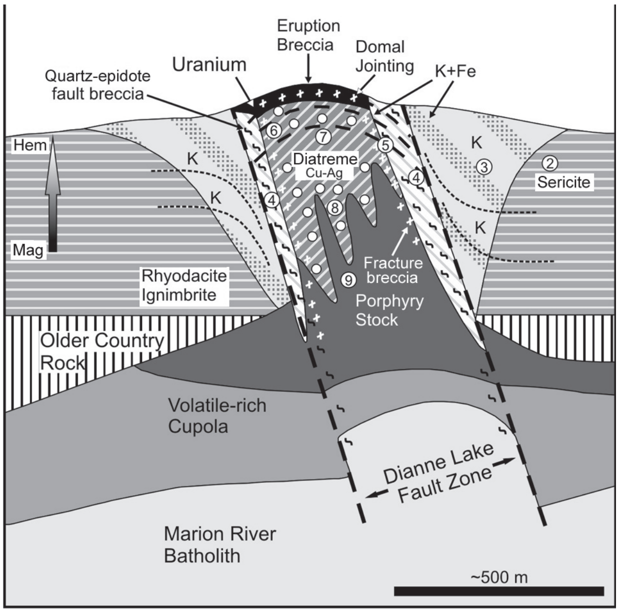

Figure 7: Schematic model of the Sue-Dianne breccia complex (after Mumin et al., 2010). Numbers correlate with Table 1.

ignimbrite. Fracture-controlled mineralisation and alteration is also common (on-going research; Mulligan, 1995; Goad *et al*., 2000). Breccias abound and include maar breccia, diatremes, heterolithic breccia and agglomerate. In addition, structural and hydrothermal breccia occurs within the volcanic sequence, at the unconformity between overlying Faber Lake volcanic rocks and underlying Treasure Lake Group metasedimentary rocks, and along minor to deposit-scale fault zones, fractures, contact of porphyries and possibly sedimentary layering (on going research; Shepley, 1999; Goad *et al*., 2000). Fault zones that cut across the entire area postdate the intrusion of porphyry (Gandhi and Lentz, 1990), and a few transect the NICO ore zone.

At *NICO*, Au, Co, Bi and Cu mineralisation is thought to have occurred in two distinct phases: (1) an early iron oxide event dominated by magnetite with minor chalcopyrite, native bismuth and possibly some gold; and (2) the main economic mineralisation during a later overprinting phase, dominantly of cobaltian arsenopyrite, cobaltite, bismuthinite, native gold, Au-Bi-Te alloys and pyrite±chalcopyrite. The economic sulpharsenides are superimposed directly over the hydrothermal magnetite-hornblende-biotite alteration precursor in what is believed to be a retrograde and possibly convective stage of the hydrothermal system (Goad *et al*., 2000; Mumin *et al*., 2010).

The *Sue-Dianne* Cu-Au-Ag deposit is located 24 km north of *NICO*, also in the southern GBMZ. It comprises a structural-hydrothermal breccia complex (diatreme) constrained entirely within the northeast-trending Dianne Lake fault where it intersects the north trending MAR fault (Goad *et al*., 2000). Host rocks for the complex are well preserved rhyodacite ignimbrite sheets (Gandhi, 1989). Hydrothermal breccias emanate from the apex of an albitised porphyry stock. They extend upwards for approximately 300 m where they apparently breached the surface, and are now capped by a fall-back breccia and palaeoregolith. Structural preparation preceded the hydrothermal event, weakening host rocks and providing a conduit for rapid ascent and outgassing of the porphyry stock. Textural evidence indicates the structures were active both during and after mineralisation. Clasts within the diatreme are strongly K feldspar ±epidote, chlorite,

Table 1: Hydrothermal alteration zoning at Sue-Dianne (after Mumin *et al*., 2010).

Distal	1. Quartz, silicification (distal)
	2. Sericite
	3. K feldspar
	4. Quartz-epidote-K feldspar (probable retrograde)
	5. K feldspar-hematite ± chalcocite, covellite
	6. Hematite-K feldspar-chlorite, epidote, fluorite, garnet, ± bornite, chalcocite, digenite, chalcopyrite
	7. Magnetite-hematite-K feldspar-epidote-garnet-fluorite-chlorite-chalcopyrite-pyrite
	8. Magnetite-pyrite-K feldspar-epidote
Core	9. Albitised feldspar porphyry

hematite and sulphide altered, and are composed of rounded to sub-angular fragments of welded and crystal tuff, with occasional altered clasts of the porphyry stock. The core of the complex comprises clast and matrix supported diatreme breccia, and grades outwards into structurally controlled fracture breccia. Magnetite, hematite, K feldspar, chlorite, epidote, garnet, fluorite, chalcopyrite and pyrite make up the hydrothermal matrix. Distal hydrothermal effects are most evident as giant quartz veins, stockwork and breccia complexes, and silicification, accompanied by minor K feldspar, epidote, sericite and/or hematite. The deep core of the deposit is barren magnetite-pyrite. This grades upwards to magnetite-hematite-chlorite-epidote-fluorite andradite-chalcopyrite matrix breccias. The distal (and structurally higher level) parts of the systems are dominated by hematite with bornite mineralisation (Table 1; Fig. 7; Goad *et al*., 2000; Mumin *et al*., 2010).

At the *NICO* and *Sue-Dianne* deposits, the IOCG alteration formed coeval with extrusion of GBMZ volcanic rocks. The interface between the pre-existing Treasure Lake Group metasedimentary rocks and the volcanic pile served as a major stratigraphic barrier, and along with permeable sedimentary layers, assisted lateral fluid migration and stratabound alteration, brecciation and mineralisation at *NICO*. The fluid migration barrier at the base of the volcanic pile resulted from an early phase of laterally extensive K feldspar alteration that created widespread and impermeable felsites. The hydrothermal potassic alteration is known to occur over an area exceeding 16 km^2 (Hetu *et al*., 1994; Goad *et al*., 2000).

Similarly, alteration systems at *DeVries* and *Margaret lakes* formed prior to and at the onset of Great Bear magmatism, and display well exposed relationships between alteration, magmatic injection, brecciation and mineralisation. These areas and the *FAB Lake* region are also part of inliers of GBMZ volcanic rocks with high-level porphyries emplaced above Treasure Lake Group metasedimentary rocks and surrounded by GBMZ granitoids (Jackson, 2008). At *DeVries Lake*, wackes and siltstones of the Treasure Lake Group host early stratabound alteration and veins that are folded and crosscut by syn-tectonic granitic dykes dated at 1878±4 Ma, an age coeval with emplacement of GBMZ quartz-feldspar porphyries at 1877±3.3 Ma (Bennett and Rivers, 2006a; Ootes *et al*., in press). These early alteration types include: (1) *lit-par-lit* (bedding parallel) albite, amphibole and magnetite alteration with K feldspar overprint; (2) crosscutting granitic veins intimately associated with pods of coarse-grained, folded and boudinaged magnetite; (3) magnetite-bearing breccias that are gradational with boudinage, shearing and granite injection in magnetite-altered sedimentary rocks; (4) sulphide-bearing shear zones injected with granite dykes; and (5) folded tourmaline veins with minor uraninite and brecciated biotite-rich alteration proximal to sulphide mineralisation. A late-stage potassic (K feldspar) to epidote-chlorite-sericite alteration forms well developed networks of parallel veins with selvages preferentially infiltrating the quartz wacke beds (Landry, 2006). These selvages led to the development of stratabound alteration of minor extent (tens of centimetres), compared to more extensive early stratabound sodic, calcic, iron and potassic assemblages. The veins crosscut the early *lit-par-lit* alteration, the 1877±3 Ma foliated pink porphyry unit, and younger granites (1874±3.3 Ma) and diorites (1871±3.6 Ma; Bennett and Rivers, 2006a). Regional alteration between *FAB, DeVries* and *Margaret lakes* has not been documented in detail but albite and amphibole-magnetite alteration of volcanic rocks and porphyries are observed, including albitites, magnetite and amphibole veins and many mineral occurrences (Ootes *et al.*, 2008, in press). Adjacent to a fault zone, massive albitite replaces Treasure Lake Group, overprinting the sedimentary layering and developing a system of parallel amphibole veins that resemble sedimentary layering, but crosscut remants of it. Crackle breccias with albitite fragments and amphibole matrix develop along parallel vein networks over tens of centimetres thickness and a few metres length. The amphibole veins are boudinaged, and like the breccia they are deformed next to the fault zone. A suite of ca. 1866±5 Ma aplite dykes postdate all major magmatic and most alteration events in the area apart from late-stage potassic alteration. Several showings occur within *lit-par-lit* altered Treasure Lake Group sedimentary rocks. Tourmaline-rich veins contain uraninite, molybdenite, chalcopyrite, pyrite, minor magnetite and minor rare earth element mineralisation, and have been known since the 1960s (Thorpe, 1972) (e.g., Nori/RA prospect; Gandhi, 1994; Jackson, 2008; Ootes *et al.*, in press). Recently identified Cu, Au, U and W mineralisation, with elevated Ag and Zn, is hosted within magnetite-altered Treasure Lake Group sedimentary enclaves in a granitic pluton at *Margaret Lake*, and breccia-hosted Cu-U mineralisation occurs proximal to a K feldspar-amphibole-magnetite alteration corridor at *FAB Lake* (Gandhi, 1994; Ootes *et al.*, 2008, in press).

Wernecke Breccia

Wernecke Breccia is the collective name given to a widespread group of Mesoproterozoic, variably mineralised breccias documented in separate areas within the Wernecke and Ogilvie mountains of the Yukon Territory (Fig. 8). The breccia cross-cuts strata of the Palaeoproterozoic Wernecke Supergroup, which are exposed in various windows through Palaeozoic cover rocks. The Wernecke Breccia has been investigated in the Wernecke, and to a lesser extent in the Ogilvie mountains, and is the subject of a separate paper in this volume (Hunt *et al.*, 2010), and therefore is not reviewed in detail herein.

The ~13 km thick Wernecke Supergroup consists mostly of fine-grained terrigenous and carbonate rocks older than 1610±30 Ma, and is interpreted to comprise a possible intracratonic rift basin whose stratigraphic base is not exposed (Thorkelson, 2000; Furlanetto *et al.*, 2009). The Wernecke Supergroup is subdivided into three conformable groups, from base to top: (1) Fairchild Lake Group (siltstone, sandstone and minor carbonate); (2) Quartet Group (siltstone, sandstone, mudstone and minor silty dolomite); and (3) Gillespie Lake Group (orange dolomite with minor intercalations of sand and clay). The Wernecke Supergroup is locally overlain by the amygdaloidal, intermediate to mafic Slab volcanics in the Wernecke Mountains. No volcanic rocks have been found in the Ogilvie Mountains, but rare amygdaloidal (i.e. high level) mafic dykes occur. Dykes and intrusions of diorite, syenite, gabbro and lesser basalt cut the Wernecke Supergroup. In the Wernecke Mountains, the dioritic to syenitic Bonnet Plume River series of intrusions are dated at 1720 to 1710 Ma (Thorkelson *et al.*, 2001).

The rocks described above are host and parent material for the Wernecke Breccia, thought to have formed at approximately 1600 Ma (Thorkelson, 2000). Breccia zones range in area from 0.1 to 10 km^2 (outcrop to mountain scale), are grey (sodic) to mottled red and pink (potassic) in colour, and vary in clast size from <5 centimetres up to hundreds of metres (Thorkelson, 2000; Thorkelson *et al.*, 2001). Their location is controlled by curvilinear structures in the Wernecke Mountains and by linear eastnortheast-trending structures in the Ogilvie Mountains (Fig. 8). A single structure, which is traceable for around 100 km across two different Proterozoic windows, controls the distribution of most of the Wernecke Breccia in the Ogilvie Mountains.

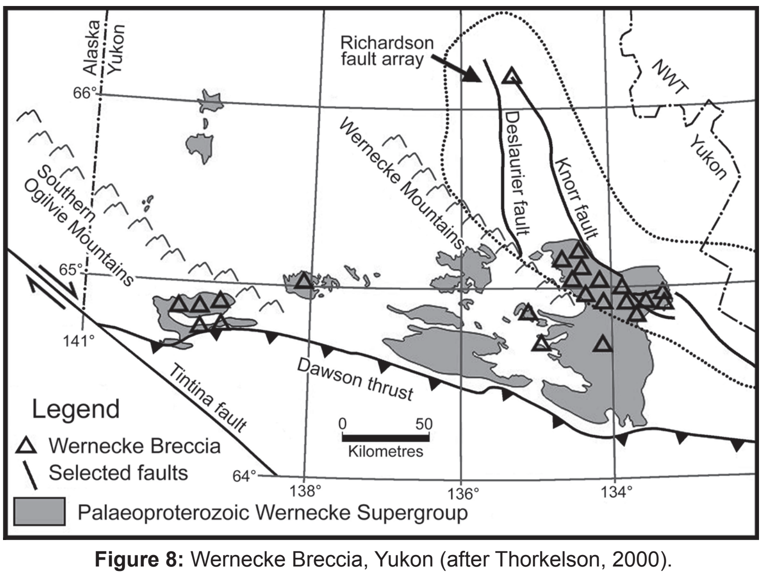

Figure 8: Wernecke Breccia, Yukon (after Thorkelson, 2000).

Hydrothermally altered and mineralised breccia occurs locally throughout the Wernecke Breccia. The breccia typically consists of subangular, altered clasts in a fine-grained matrix of rock fragments with varying amounts of hydrothermal carbonate, albite, K feldspar, hematite, magnetite or chlorite (Fig. 6C). The clasts are predominantly of Wernecke Supergroup sediments, although some igneous rock (locally including Slab volcanics) clasts also occur. Clasts are commonly altered to carbonate, albite or hematite. Some contain veins of hematite that do not penetrate into the matrix, indicating multiple episodes of hydrothermal activity and brecciation. Transitions from undisturbed host rock to veined (carbonate±quartz) and broken host rock (Fig. 6D) to Wernecke Breccia are common, and occur over intervals of 5 to 500 m. Trace to significant amounts of Cu, Co, Au and U occur in and/or immediately adjacent to the hydrothermal matrix breccia.

Initial exploration within the Wernecke Supergroup focussed on their sediment-hosted lead-zinc potential. After the discovery of mineralised Wernecke Breccia, the emphasis shifted to uranium in the late 1970s, and then to copper-gold in the 1990s and early in this decade, as the IOCG model was applied. Current investigations are focussed on uranium-bearing IOCG type deposits. At least 65 IOCG prospects are known in the Wernecke Mountains (Hunt *et al.*, 2010). Some of the better intersections from early exploration include: 22.9 m @ 0.75% Cu; 110 m @ 0.3% Cu and 0.06 g/t Au; 75 m @ 0.41% Cu and 0.3 g/t Au; and 21 m @ 2.0% Cu, 0.2 g/t Au and 0.2% Co (Caulfield *et al.*, 1994; Gorton and Stammers, 2000). Recent copper-gold exploration has produced drill intersections such as 88.5 m @ 0.55% Cu and 0.11 g/t Au; and 17.3 m @ 1.84% Cu and 0.53 g/t Au (Fronteer Development Group website, 2009). At the *Igor* prospect, recent drilling into an iron oxide-rich body of Wernecke Breccia returned a best result of 140 m @ 0.76% Cu, 0.042% U_3O_8 and 0.05 g/t Au, including an interval of 7 m @ 7.37% Cu, 0.417% U_3O_8 and 0.33 g/t Au (Cash Minerals News Release, January 23, 2008). The *Igor* prospect has an associated gravity high. Approximately 40 small copper-gold showings have been defined in the western part of the breccia in the Ogilvie Mountains. Grab samples confirm the presence of anomalous copper, gold, cobalt and silver (Setterfield and Tykajlo, 2003a), while similar samples in the eastern part of the Ogilvie Mountains yielded anomalous copper and gold levels (Falls and Baknes, 1995).

Central Mineral Belt

The Central Mineral Belt (CMB) in central Labrador, is a northeast-trending, 260 × 75 km corridor of Proterozoic volcanic and sedimentary rocks with associated granites. It hosts numerous copper, uranium and REE showings and prospects, including the *Michelin* and *Kitts* uranium deposits (Gandhi, 1986; Wilton, 1996; Wardle *et al.*, 2002; Sparkes and Kerr, 2008). The mineral belt was developed on the amalgamated Superior and Nain Archaean cratons and the intervening Archaean Core Zone of the Churchill Province that contains an assemblage of gneisses, mafic to felsic metavolcanics and granitoids, and minor mafic to ultramafic intrusions. The CMB comprises six main volcano-sedimentary groups, variably separated by faults, unconformities, granites of various ages, or Archaean rocks. These are the Post Hill, Moran Lake, Aillik, Bruce River, Letitia Lake and Seal Lake groups (Fig. 9; the Post Hill and Aillik groups were previously known as the Lower and Upper Aillik groups respectively; Ketchum *et al.*, 2002). These volcanic and sedimentary groups formed through a series of magmatic events summarised as follows. Calc-alkaline magmatism was generated in a continental magmatic arc between 1895 and 1870 Ma across the amalgamated Archaean cratons. This was followed by the development of an 1883 to 1850 Ma successor rifted or back-arc volcano-sedimentary basin hosting voluminous felsic A-type melts of the Aillik group, and synvolcanic quartz-feldspar porphyries (cf. Ketchum *et al.*, 2002; Sinclair *et al.*, 2002; Hinchey and LaFlamme, 2009). Between 1815 and 1780 Ma, the area was intruded by felsic to intermediate plutons and quartz-feldspar porphyries, some of which crosscut and hence place a minimum age on uranium mineralisation. The belt was then subjected to transpression at amphibolite-facies (Hinchey and LaFlamme, 2009; Sparkes and Dunning, 2009). A subsequent period of transpression, this time at greenschist facies, was accompanied by the emplacement of A-type granitoids between 1740 and 1710 Ma (Ketchum *et al.*, 2002).

The Post Hill Group (eastern CMB) consists of quartzite, argillite and variably deformed, locally pillowed, basalts. A lateral equivalent (Moran Lake Group) in the central part of the CMB contains argillites, lesser arenites, silicate facies iron formation and dolostones, all overlain by a pillowed basalt sequence (Joe Pond Formation) up to 2 km thick (Ryan, 1984). The age of these groups is thought to be on the order of 2180 to 2010 Ma (Sparkes and Kerr, 2008).

The Aillik Group is less deformed and metamorphosed, and consists of early sediments interlayered with dacite to rhyolite flows, overlain by pillowed to possibly subaerial basalt flows, followed in turn by subaerial rhyolites and volcaniclastic sandstone, dominantly of pyroclastic origin. Most of the Aillik Group occurs in the central and northeast part of the CMB, although an outlier is found 50 km to the southeast near the coast (Fig. 9). Dates for extrusive rocks of the Aillik Group and inlier range from approximately 1883 to 1856 Ma (Ketchum *et al.*, 2002; Hinchey and LaFlamme, 2009).

The Bruce River Group, which unconformably overlies the Moran Lake Group and earlier granites, contains the Heggart Lake, Brown Lake and Sylvia Lake formations. The Heggart Lake Formation consists of conglomerates, sandstones and minor mafic and felsic lava flows, and defines a local graben (Ryan, 1984). The Brown Lake Formation has a basal conglomerate that is distinguished by its bright red weathering and abundant red sandstone clasts, overlain by a >1 km thick volcaniclastic sandstone. The Sylvia Lake Formation, which is approximately 8 km thick, consists of two megacycles of mafic to felsic volcanics of high-potassium calcalkaline and shoshonite affinities, both dominated by the felsic component, and is host to numerous base metal and uranium showings (Ryan *et al.*, 1987). Ignimbrite from the Sylvia Lake Formation has been dated at 1649 Ma (Schärer *et al.*, 1988). Fluorite is locally present.

The Letitia Lake Group (Fig. 9) is a restricted sequence of peralkaline felsic volcanic rocks that has been dated at 1327 Ma (Thomas, 1981). The Seal Lake Group crops out extensively in the western portion of the CMB and may be up to 14 km thick (Fig. 9; Ryan, 1984). It contains interlayered quartzite, arkose, shale and oxidised, amygdaloidal basalt units, all intruded by dolerite to gabbro sills. The Seal Lake Group is interpreted to have been deposited in a rift basin under terrestrial to shallow marine conditions. A sill within the group has been dated at 1250 Ma (Wilton, 1996).

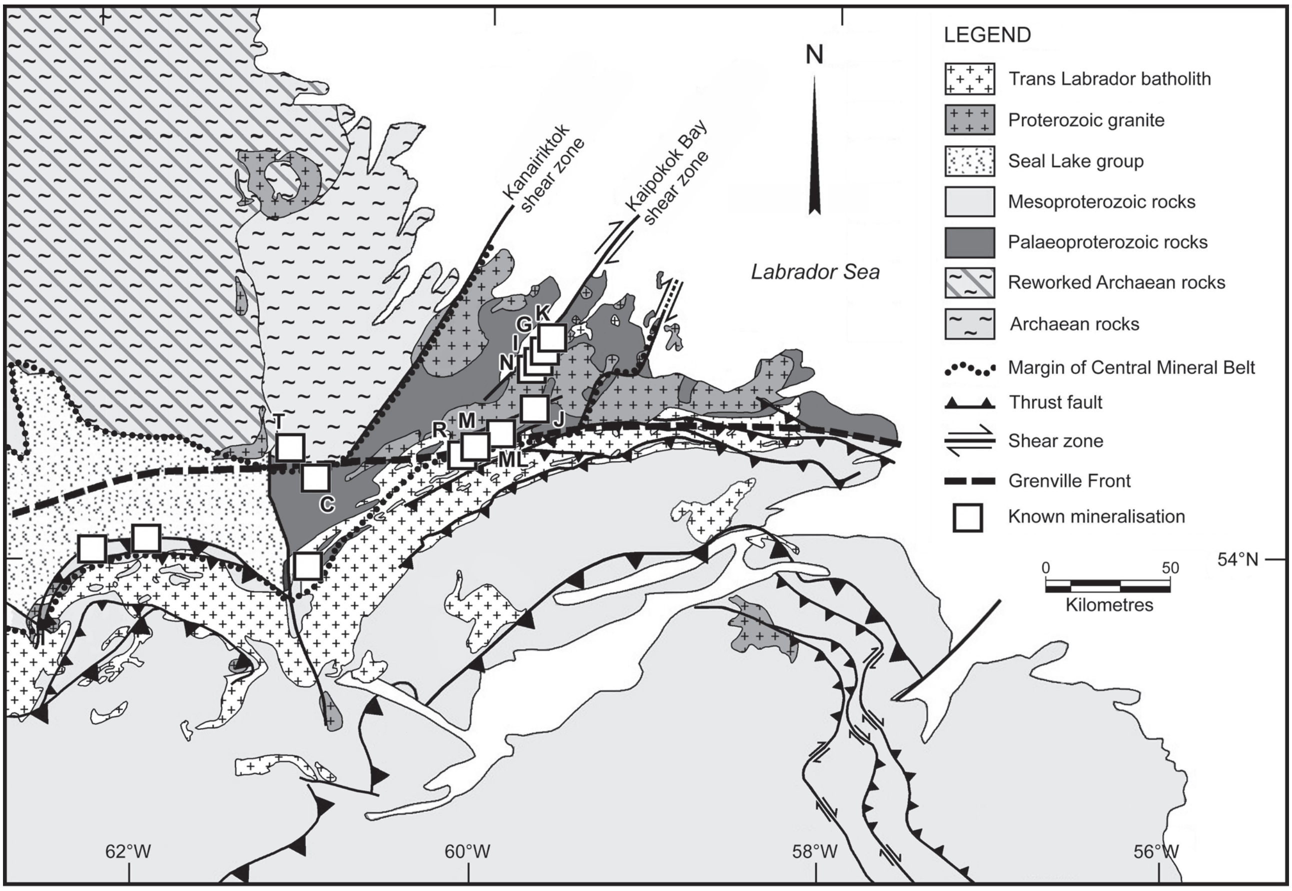

Figure 9: Geological map of the Central Mineral Belt (CMB), Labrador (after Davenport *et al.*, 1999; Gower *et al.*, 2008b). Note that the Aillik, Post Hill, Moran Lake and Bruce River groups together comprise the Palaeoproterozoic rocks; while the Letitia Lake Group is included in the area shown as Mesoproterozoic rocks within the CMB. Known mineralisation: Kitts (K), Gear (G), Inda (I), Nash (N), Jacques Lake (J), Mustang Lake (ML), Michelin (M), Rainbow (R), C Zone (C), Two Time (T).

Numerous A-type granitoid plutons have intruded the above groups and are widely distributed in the Central Mineral Belt. Geochronological work has enabled division of the plutons into four main suites (Sparkes and Kerr, 2008), with ages of 1895 to 1870 Ma, 1815 to 1790 Ma, 1740 to 1710 Ma and 1650 to 1640 Ma (intrusive equivalent of Bruce River Group). The 1654 to 1646 Ma Trans-Labrador Batholith is an eastnortheast-trending, 600 km long by up to 100 km wide belt of plutonic rocks that intruded pre-Labradorian Laurentian foreland to the north, straddles the Grenville Front to the south, and forms the southern border of the CMB (Fig. 9; Ryan, 1984; Kerr, 1989; Gower and Krogh, 2002). The batholith contains, among other phases, quartz monzonite, granite (locally with rapakivi textures), hornblende granodiorite, and differentiated diorite (Ryan, 1984). Much of the batholith consists of A-type granitoids (Kerr, 1989).

Conceptually, the CMB is a very attractive province for IOCG exploration. Repeated development of extensional basins was apparently due to reactivation of a long-lived zone of major crustal weakness. Felsic and mafic volcanics, many of which were subaerially deposited, are abundant. Major episodes of granitic magmatism occurred in the Archaean, and throughout the development of the CMB. Terrestrial oxidising conditions are evident in all units later than the Post Hill Group. The CMB is also an important metallogenic province, with abundant showings of various mineralisation styles (Wilton, 1996). On conceptual grounds, the Bruce River and Aillik groups are considered to be the most prospective. This is based on the abundance of subaerial volcanism, link to A-type magmatism, their contained Cu and U showings, and widespread sodic metasomatism (Aillik Group).

Mineralisation

The CMB contains a wide variety of mineralisation styles (see Wilton, 1996; Sparkes and Kerr, 2008). The Post Hill and Moran Lake groups host VHMS showings and uranium mineralisation. The Aillik Group contains significant uranium mineralisation, as well as skarn and possibly porphyry style polymetallic mineralisation, while the Bruce River Group hosts widespread copper and uranium mineralisation of uncertain origin. The Letitia Lake Group has intriguing REE mineralisation and the Seal Lake Group contains over 250 copper±silver occurrences in basalts and sediments. Mineralisation described as magmatic-hydrothermal with IOCG affinity occurs in the Post Hill, Aillik and Bruce River groups, as well as in Archaean granite adjacent to the latter group (Fig. 9).

The *Two Time Zone*, in the western half of the CMB, occurs within strongly brecciated and fractured Archaean granites to diorites. It comprises uranium mineralisation within a breccia, cemented by hematite-chlorite-carbonate (Ross, 2008). Mineralisation is found within eight subparallel, tabular lenses that collectively form a 500 m long zone, hosted by a steeply dipping, northwest-striking structure. The total resource defined to date is approximately 2700 tonnes of U_3O_8 at an average grade of 0.055% U_3O_8. The mineralisation, which is considered to be IOCG-style, and potentially of Archaean age, is similar to that at the nearby *Upper C zone* occurrence in the Moran Lake Group (Ross, 2008; Sparkes and Kerr, 2008).

The *C Zone* deposit, located 15 km to the southeast of the *Two Time Zone*, contains structurally controlled uranium-copper mineralisation in fractures and shear zones at the contact between the Moran Lake and Bruce River groups (Morgan and Giroux, 2008). It is divided into the *Upper C*, hosted by mafic volcanics of the Joe Pond Formation, and the *Lower C*, which occurs in sandstone and lesser conglomerate of the Heggart Lake Formation (Morgan and Giroux, 2008). At this locality, rocks of the Moran Lake Group have locally been thrust over the Bruce River Group. Mafic host rocks to the Upper C mineralisation are strongly brecciated, hematised, and albitised, with lesser amounts of chlorite and iron carbonate, and minor magnetite. Uranium typically occurs as fine-grained disseminated uraninite, locally with chalcopyrite, and commonly with chlorite, all of which infill small fractures in brecciated rocks. The sandstone host to the *Lower C* is chloritised and overprinted by hematite, commonly with around 2% associated pyrite (Morgan and Giroux, 2008). The *C Zone*, which has a strike length of 1300 m, has significant vanadium, with grades typically in the 0.06 to 0.11% V_2O_5 range, as well as local ore grade copper and silver. The latest mineral resource estimate is approximately 3630 t of U_3O_8 in the *Upper C* at an average grade of 0.03% U_3O_8, and 725 t of U_3O_8 in the *Lower C* at an average grade of 0.05% U_3O_8 (Morgan and Giroux, 2008). Several other polymetallic prospects occur along strike at roughly the same stratigraphic level. There are also a number of uranium and/or copper occurrences within the Bruce River Group, although none have yet been shown to have significant potential.

Approximately 120 km to the eastnortheast of the *Two Time Zone*, in the eastern half of the CMB, the Post Hill Group hosts the partially delineated *Kitts* uranium resource (Fig. 9). This deposit, which was estimated to contain 0.185 Mt @ 0.73% U_3O_8 (~1350 t U_3O_8) based on drilling in the 1970s (Sparkes and Kerr, 2008), occurs within mafic volcaniclastic rocks and sediments, and is surrounded by a halo of sodium-enriched rocks (Gower *et al.*, 1982). Mineralisation is folded, and hence older than 1.80 Ga, and a younger uraninite age is likely recording a remobilisation event (Sparkes and Kerr, 2008). Other deposits which define a trend extending for 15 km to the southwest from *Kitts,* include *Gear, Inda* and *Nash*. The *Gear* deposit, 7 km southwest of *Kitts*, is hosted mainly by Post Hill argillite. The mineralised zones are pseudo-brecciated by biotite±carbonate veinlets, with alteration consisting of pervasive chlorite±actinolite±epidote, and local hematite-magnetite. Sulphides within the mineralised zone (pyrrhotite, chalcopyrite and pyrite) are disseminated, but also occur as stringers and fracture fillings (Cunningham-Dunlop and Lee, 2008). A resource of 0.67 Mt @ 0.08% U_3O_8 (540 t of U_3O_8) has been calculated, based on drilling to date (Aurora Energy Resources website, 2009). Limited grab sampling (10 samples) of selected sub- and outcropping mineralisation with visible sulphides has confirmed the presence of copper and gold in the uranium zone with values of from 300 ppm to 2.81% Cu and <0.01 to 540 ppb Au (Smith *et al.*, 2004). The *Inda* deposit, 3.5 km southwest of *Gear*, lies at the contact between amphibolites and mafic metasediments of the Post Hill Group, and felsic volcanics of the Aillik Group, with mineralisation occurring in both suites (Cunningham-Dunlop and Lee, 2008). A resource of 4.5 Mt @ 0.065% U_3O_8 (2925 t of U_3O_8) has been estimated, based on drilling to date (Aurora Energy Resources website, 2009). Mineralisation in the felsic volcanics has accompanying hematite-albite and/or magnetite, whereas that within the mafic metasediments and amphibolites is associated with carbonate-chlorite-actinolite±pyrite alteration, similar in style to *Gear*. Drilling indicates that the deposit also contains significant Cu and Ag, typically found in proximity to the uranium bearing zones, associated with chalcopyrite, pyrite and pyrrhotite. Similarly, the *Nash* deposit, within 2 km to the southwest of *Inda*, has mineralisation in Post Hill mafic metasediments, and alteration that includes accessory biotite, calcite, chlorite, actinolite, magnetite and albite. Cunningham-Dunlop and Lee (2008) report that elevated but uneconomic amounts of Cu and Ag occur with the U. The individual deposits of this group all occur at a similar stratigraphic level, although they are interpreted to have strong structural controls (Cunningham-Dunlop and Lee, 2008).

The most important uranium deposits of the CMB are hosted by felsic to intermediate volcanic rocks within the main outcrop of Aillik Group stratigraphy. The *Michelin* uranium deposit (50 km southwest of *Kitts*; Fig. 9) contains several subparallel, *en-echelon* mineralised zones which collectively define a structurally controlled, tabular deposit 1200 m long, up to 750 m deep and as much as 40 m thick (Cunningham-Dunlop and Lee, 2008; Sparkes and Kerr, 2008). Uranium is associated with visually intense hematite staining of host rock but without notable iron enrichment as well as with widespread albitisation. Other alteration minerals include accessory magnetite, biotite, chlorite, hornblende, pyroxene and actinolite. The current resource figure (measured, indicated and inferred) for the *Michelin* deposit is 46 300 t of contained U_3O_8 in ore with a grade of 0.11% U_3O_8 (Cunningham-Dunlop and Lee, 2008). The *Jacques Lake* prospect, which is located 35 km eastnortheast of *Michelin*, has a global resource in the order of 7850 t of U_3O_8 (Cunningham-Dunlop and Lee, 2008). It is hosted by mylonitic intermediate volcanics with pervasive hematite staining and albite alteration (up to 9.5 wt.% Na_2O), as well as strong magnetite-actinolite-carbonate±biotite veining (Sparkes and Dunning, 2009). A post-mineralisation felsic dyke with an age of 1801±0.9 Ma provides a minimum age for the ore (Sparkes and Dunning, 2009). The *Rainbow* deposit (3 km southwest of Michelin) has a current resource of 1725 t U_3O_8, hosted by pyroclastic rocks of the Aillik Group (Cunningham-Dunlop and Lee, 2008). The main lens is 140 m long by 80 m deep and up to 15 m wide. The mineralisation at *Michelin*, *Jacques Lake* and *Rainbow* may be localised by a regional shear zone, which may also control the *Mustang Lake* mineralisation (8 km northeast of Michelin), which has a best intersection of 9.1 m @ 0.12% U_3O_8 (Sparkes and Kerr, 2008).

The CMB has been included in recent Canada-wide reviews of prospective IOCG environments (Setterfield, 2006; Corriveau, 2007). It satisfies many of the geological criteria observed in mineral provinces with significant potential for uranium-rich polymetallic IOCG deposits, as defined by Skirrow (2010), although the magnetite-rich parts of such systems have either never been formed, exposed or identified. Sparkes and Kerr (2008) note that "*The diversity of uranium mineralisation in the CMB is bewildering...*" and indeed mineralisation occurs in a wide variety of host rocks and apparently in different episodes. This is consistent with the observation that IOCG deposits elsewhere may have multiple ages and host rocks, even within the same geological domain (this paper; Gelcich *et al.*, 2005; Chen, 2008). The important deposits and occurrences of the CMB discussed above, all have some of the attributes of IOCG systems, without having the widespread brecciation or as extensive development of iron oxide alteration that is associated with many IOCG systems. However, all have some degree of hydrothermal iron oxide and/or iron carbonate alteration. Widespread albitisation is common, and more local alteration includes actinolite, chlorite and biotite, although their development is less intense than in most IOCG deposits. Anomalous to ore-grade copper and silver are common, and significant vanadium zones are similarly known. Valenta (2006) and Cunningham-Dunlop and Lee (2008) favour an IOCG origin for deposits/occurrences in the prolific Post Hill and Aillik groups, although their origin remains uncertain and is the object of comprehensive government and academic research and mapping programs in partnership with industry (Hinchey and LaFlamme,

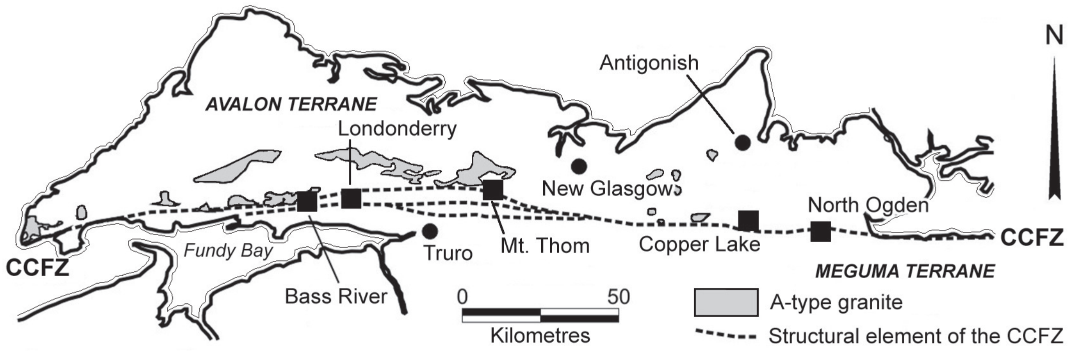

Figure 10: Cobequid-Chedabucto Fault Zone, Nova Scotia (information from Keppie, 2000).

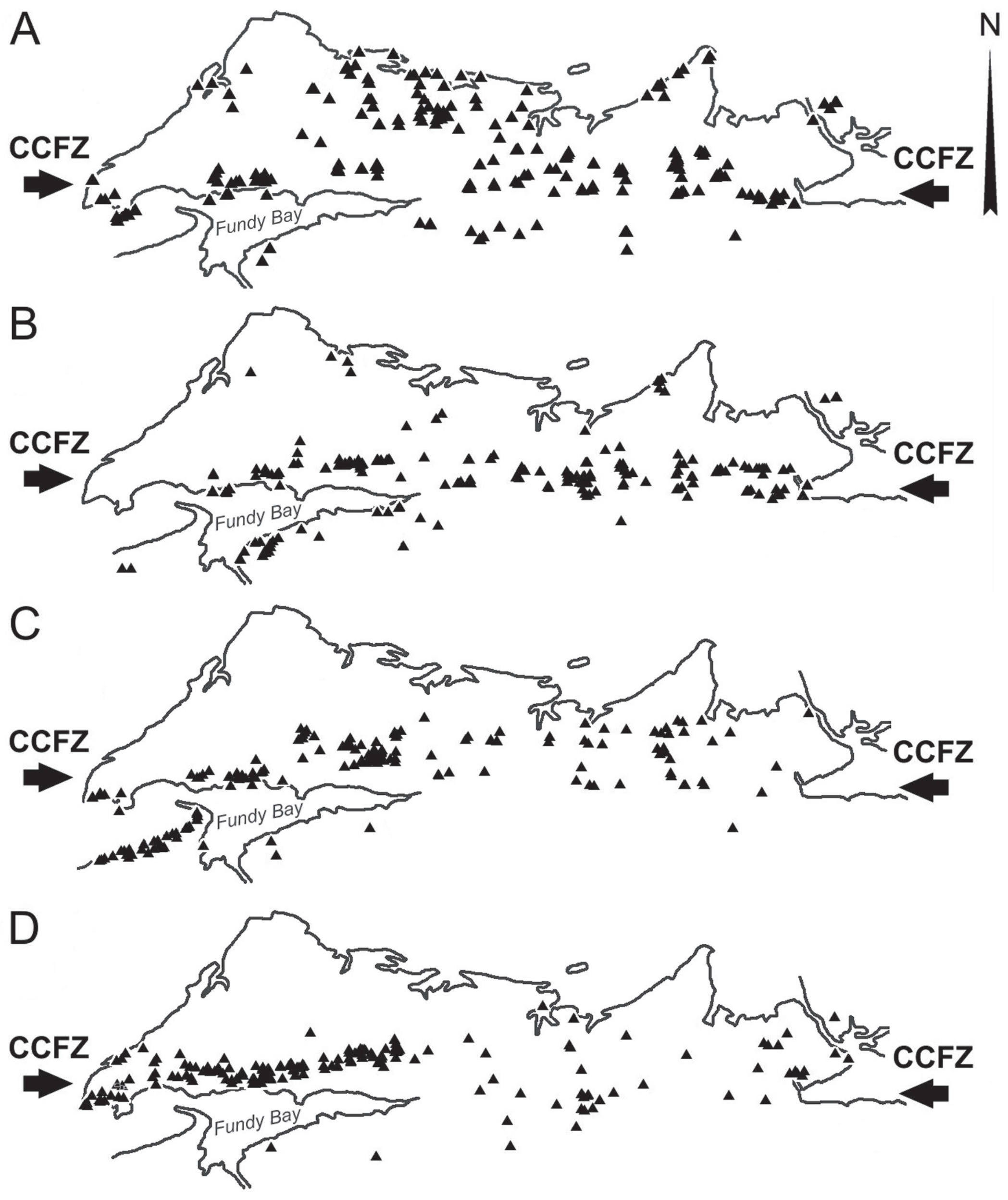

Figure 11: Location of mineral occurrences and stream sediment anomalies in northern Nova Scotia (from Setterfield and Downes, 2005). **(A)** Copper mineral occurrences; **(B)** iron occurrences; **(C)** ankerite occurrences; **(D)** copper in stream sediment anomalies - triangles >90 percentile.

2009; Sparkes and Dunning, 2009). Similarly, the *Two Time* and *C Zone* are deemed to be IOCG in nature by the respective investigators (Morgan and Giroux, 2008; Ross, 2008; Sparkes and Kerr, 2008).

Cobequid-Chedabucto Fault Zone

The Cobequid-Chedabucto Fault Zone (CCFZ) in northern Nova Scotia is a polyphase, 300 km long series of *en echelon* faults that mark the boundary between the Avalon and Meguma terranes to the north and south respectively (Fig. 10). The Meguma terrane contains Cambrian to Devonian sediments and minor volcanic rocks, while the Avalon terrane is composed of various Proterozoic rocks and Silurian to Carboniferous sediments. Importantly, the latter terrane also contains abundant 360 to 350 Ma (Devonian to Carboniferous), A-type granites, co-magmatic mafic intrusions and their extrusive equivalents, namely high-Zr rhyolite and basalt (Pe-Piper *et al.*, 1998; Piper *et al.*, 1999; Pe-Piper and Piper, 2002). Ignimbrite forms a major component of the rhyolite, and there is evidence of co-existing mafic and felsic magmas. The igneous rocks of the Avalon terrane are at least superficially similar to those of the Proterozoic Gawler Craton, which hosts to the giant Olympic Dam IOCG deposit in South Australia (Reynolds, 2000). High temperature shearing along the CCFZ occurred in Devonian to Carboniferous times (360 to 350 Ma) and aided in the localisation of syntectonic mafic and felsic intrusions (Pe-Piper and Piper, 2002). Renewed movement took place at 340 Ma, with associated ductile shearing and hydrothermal alteration, including sodic (albite and scapolite), potassic (K feldspar and biotite), potassic-iron (biotite-magnetite) and iron alteration documented in granite and gabbro plutons (Pe-Piper *et al.*, 2004). A radiometric potassic signature (Ford *et al.*, 1989) is interpreted as highlighting potassium-bearing fluid activity along the western section of the Cobequid Fault system (Pe-Piper *et al.*, 2004).

O'Reilly (1996; 2001) first drew attention to the large number of iron-rich hydrothermal breccias and vein systems along the CCFZ, some of which have been mined for iron oxide on a small scale, and to a lesser extent for copper. The most important of these are shown on Fig. 10. These veins and breccias crosscut units deformed at ca. 340 Ma ($^{40}Ar/^{39}Ar$ plateau ages; Reynolds *et al.*, 2004) and part of the mineralisation has been dated at 320 Ma, coeval with both the emplacement of mid-crustal mafic magmas and regional deformation (Kontak *et al.*, 2008b). Iron occurs variably in the form of iron carbonate (ankerite and lesser siderite) and iron oxide (hematite and lesser magnetite). The occurrences typically contain anomalous contents of copper, cobalt, barium and gold. Barite is common, fluorite is locally present, and REE mobility has been recorded in at least one of the mineralised zones (hydrothermal monazite; Kontak *et al.*, 2008b). Copper and hydrothermal iron (iron oxides and ankerite/siderite) occurrences in northern Nova Scotia have a distinct tendency to concentrate along the CCFZ, as do copper and cobalt anomalies in regional stream sediment samples (Fig. 11).

The *Bass River* prospect is a 475 x 60 m area rich in magnetite, which occurs as a replacement of the original siltstone host rock, as fracture fillings, and most notably as cement within a hydrothermal breccia (O'Reilly, 2002). Exploration in the 1950s suggested the prospect might contain in the order of 3 Mt of material grading 40% Fe (O'Reilly, 2002). Fine-grained, cobalt-rich pyrite occurs within the magnetite, with a sulphide concentrate from the prospect assaying 0.9% Co. The prospect is proximal (within 1 km) to the A-type Pleasant Hills granite, and the breccia contains clasts of that pluton (O'Reilly, 2002). Rapakivi texture has been recognised in the pluton close to Bass River (Setterfield, 2004).

In the *Londonderry* district there are three main past-producing iron mines that operated from 1847 to 1906 (O'Reilly, 1996). These mines exploited a series of veins and breccias (Fig. 6E) which collectively have a 16 km strike length along the CCFZ, with individual veins and pods that can be up to 40 m in width. Approximately 2 Mt of iron ore was produced from the upper 100 m of the vein system, which is dominated by limonite-hematite and grades downwards to ankerite/siderite (Wright, 1975). The deposits contain iron, without any significant concentration of other economic metals.

The *Mt Thom* prospect is an intensely faulted area with pyrite, chalcopyrite and hematite present along fractures and in breccias. It was initially discovered by following up geochemical surveys, and was drilled in the early 1970s (O'Reilly, 2001). Alteration is widespread, consisting of siderite in veins and disseminations, pervasive silicification and/or iron carbonate, chlorite and sericite, and local scapolite-phlogopite zones (Kontak, 2006). Alteration and mineralisation are related to northwest-trending faults thought to be splays off the CCFZ. Drill intersections contain several metres of between 0.5 and 2% Cu, with up to 0.3 g/t Au and 0.6% Co (O'Reilly, 2001). Host rocks are Carboniferous sediments, intruded by granite, which also occurs as clasts within the breccia (Kontak, 2006). Based on petrographic features, this granite is interpreted to have been emplaced close to the surface (Kontak, 2006). A showing of hematised granite yielded grab sample assays of up to 3.32% Cu and 0.61 g/t Au (O'Sullivan, 2004).

Copper Lake is a small past-producing copper-gold deposit, from which 1100 tonnes of ore were mined in 1908-09, and 325 t averaging 5.5% Cu were processed (Black, 1996). Grab samples contain up to 10.9% Cu and 0.5 g/t Au, indicating the presence of anomalous gold (Setterfield and Downes, 2005). The ore contains as much as 40% Fe. The deposit comprises a series of east-trending, coarse-grained, epigenetic, siderite-ankerite veins and breccias, with associated chalcopyrite, pyrite, pyrrhotite and lesser hematite (Fig. 6F), emplaced at 320 Ma, after deformation of the host rocks at 340 Ma (Kontak *et al.*, 2008b). The veins are traceable for 300 m and occur along an east-trending fault, subparallel to and 2.5 km distant from the CCFZ, adjacent to a northeast-trending splay off the CCFZ. Pervasive quartz-carbonate-albite alteration, as well as muscovite, chlorite, apatite, rutile and clay, and trace amounts of monazite (hydrothermal and coeval with mineralisation), zircon, xenotime, thorite and rare earth element phases are present (Kontak, 2006; Kontak *et al.*, 2008b). A second copper-iron deposit, *College Grant*, which is 8.5 km southwest of *Copper Lake,* is associated with a northeast splay off the CCFZ. It was mined in the late 1800s, and consists of numerous quartz-ankerite-siderite veins with chalcopyrite, pyrite and hematite (O'Reilly, 1999). The veins are up to 1.8 m thick and averaged approximately 10% Cu.

The *North Ogden* prospect contains a pyrite±chalcopyrite-bearing hydrothermal breccia with clasts of epidotised country rock cemented by a matrix of magnetite-chlorite-hematite (Fig. 6G). The breccia contains more than 50% iron oxides. The rock occurs along the bank of the Salmon River in east-central Nova Scotia. Work prior to 2000 produced reports of outcrops bearing significant copper and gold, and a silt sample containing 6.5 g/t Au (O'Reilly, 2004). However, the river course has since shifted and recent sampling of available outcrops failed to return anomalous metal values. In spite of this, the prospect is still considered as an excellent example of IOCG type mineralisation.

Shebandowan Greenstone Belt

Probable IOCG-style alteration and mineralisation has recently been recognised in the Archaean Shebandowan greenstone belt in Ontario. This greenstone belt consists of mafic to felsic (and minor ultramafic) volcanic rocks, and lesser clastic and chemical sediments that are intruded by mafic sills and several types of felsic plutons (granodiorite, granite, syenite and monzonite; Osmani, 1997). IOCG-style occurrences discovered to date are hosted by various types of volcanic rocks (Fig. 12). A north to northeast trending deformation zone, with intermittent probable IOCG mineralisation, has been defined over a strike length of 15 km, while a subparallel, southern, discontinuous IOCG-bearing zone has a strike length on the order of 10 km (Fig. 12).

The *East Coldstream* gold deposit is presently under investigation (Fig. 12; Schandl, 2006; Tremblay and Koziol, 2007). The deposit has historical resources of 5.1 Mt @ 1.4 g/t Au, and occurs in sheared and brecciated felsic volcanic, volcaniclastic, and minor sedimentary rocks. Drilling in 2006 yielded intersections of up to 68 m @ 1.21 g/t Au (Tremblay and Koziol, 2007). Gold is associated with pyrite and lesser chalcopyrite. Immediate host rocks contain up to 10% low-titanium magnetite, as well as abundant disseminated fine-grained hematite (Schandl, 2006). Alteration minerals include quartz, albite, sericite, ankerite and chlorite. Very fine-grained REE minerals (monazite and xenotime) are present.

The *North Coldstream* copper deposit produced in excess of 46 000 t of Cu, 13.7 t of Ag and 0.685 t of Au (Osmani, 1997). The deposit occurs in a silicified zone at the contact between a gabbro and volcanic rocks. Because of its high TiO_2 content, the silicified zone is thought to be silicified gabbro. Silicification is typically accompanied by a "considerable" increase in magnetite. Chalcopyrite and pyrite are the dominant sulphides, with lesser amounts of pyrrhotite, arsenopyrite, malachite and azurite. The deposit also contains up to 0.4% Co, 0.6% Ni and anomalous bismuth.

Wide zones of anomalous gold, including up to 34 m @ 0.95 g/t Au, were drilled at the *Burchell* occurrence (Alto Ventures website, 2009). As at the *East Coldstream* deposit, gold is associated with pyrite and lesser chalcopyrite, with the highest gold values associated with copper mineralisation (Debicki, 1992). "Intense" hematite alteration, magnetite stringers, and up to 10% disseminated magnetite have been recorded in the drill logs. The main types of alteration noted include: albitisation, silicification, sericitisation and chloritisation (Debicki, 1992). Iron carbonate is also present locally.

The *Moss Lake* gold mineralisation is hosted by sheared diorite and intermediate to felsic volcanic rocks. A resource of 50.9 Mt @ 0.93 g/t Au for a total of 47.3 t Au has been calculated (Sullivan *et al.*, 2006). The deposit appears similar to *East Coldstream* and *Burchell*, with wide intersections of low grade gold (e.g., 60 m @ 1.51 g/t Au). Gold is associated with pyrite and minor chalcopyrite, and alteration includes hematite and sericite (Sullivan *et al.*, 2006).

The *Hamlin-Deaty* zone comprises an iron oxide-bearing breccia which occurs discontinuously over 10 km and contains variable amounts of copper, gold, silver and molybdenum. Mineralisation is associated with pyrite, magnetite, chlorite, epidote and hematite (East West Resources Corp. website, 2009). The best intersection was 72 m @ 0.42% Cu, 0.11 g/t Au, 2.9 g/t Ag and 0.016% Mo. The mineralisation has been dated at 2690 Ma (East West Resources Corp. website, 2009). A recently discovered extension or subparallel zone occurs south of *Hamlin* (not shown on Fig. 12). The breccia contains "locally appreciable chalcopyrite and heavy magnetite as breccia filling, with clasts characterised by moderate to intense sodic, hematitic, potassic and calcic alteration" (Freewest Resources Canada Inc. website, 2009). Grab samples have returned up to 6.3% Cu, 1.5 g/t Au and 187 ppm U.

The interpretation that some or all of the mineralisation described above is IOCG-style is relatively recent, and

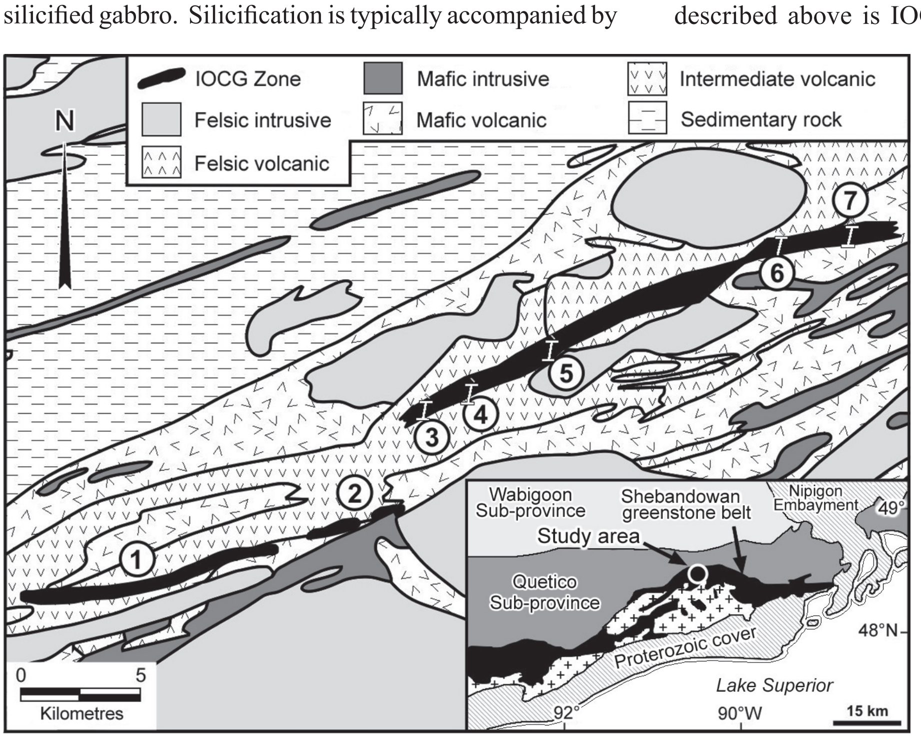

Figure 12: Location of IOCG prospects in the Shebandowan greenstone belt, modified from Tremblay and Koziol (2007). **(1)** Hamlin zone; **(2)** Deaty zone; **(3)** Moss Lake main zone; **(4)** Moss Lake QES zone; **(5)** Burchell occurrence; **(6)** North Coldstream copper; **(7)** East Coldstream gold. The lower-right inset shows the location of the Archaean Shebandowan granite (crosses) - greenstone (dark) belt, which is part of the Wawa Sub-province, fault bounded to the north by the metasediments and felsic intrusive rocks of the Quetico Sub-province, and unconformably overlain by Palaeoproterozoic metasediments and iron formations of the Animikie Group to the south and Mesoproterozoic, mainly sediments, of the Nipigon Embayment to the northeast.

consequently documentation of pertinent diagnostic features that may be present is probably incomplete. The present evidence for IOCG-style mineralisation is permissive, but not conclusive. Certainly the combination of structural control, localised extensive brecciation, the metal association (Cu-Au±Ag±Mo), and the presence of iron oxides and other common IOCG alteration assemblages support the hypothesis.

Grenville Province IOCG District and Targets

Manitou Lake District

The Manitou Lake district in the central Grenville Province hosts a series of magnetite-group IOCG prospects with minor hematite such as the Kwyjibo deposit, as well as some magnetite±apatite (IOA) prospects in the Lac Marmont region (Fig. 13). These prospects are collectively polymetallic (Ag, Au, Cu, P, REE, U, Y) and are accompanied by a wide range of alteration and breccia types typical of IOCG deposits worldwide (Gauthier *et al.*, 2004; Clark *et al.*, 2005, 2010; Magrina *et al.*, 2005). The IOCG mineralisation at the *Kwyjibo* deposit, in the northern part of the district, is hosted within a leucogranite of the metamorphosed 1.17 Ga Canatiche granite suite. The suite intrudes Canatiche complex orthogneisses and enclaved paragneisses, inferred to be part of the 1.5 Ga Pinwarian magmatic arc (Gobeil *et al.*, 2003; Gower *et al.*, 2008a). The Canatiche granites are biotite, hornblende and magnetite-bearing, and have an A-type affinity, although their Ba, La, Ce, Zr and Nb content is greater than that of most A-type granites and is more typical of peralkaline granites (Clark *et al.*, 2010). Peraluminous to meta-aluminous leucogranites of the suite are more uraniferous than the hornblende-biotite granites (up to 35 ppm compared to a maximum of 20 ppm, respectively) and are albitised peripheral to the mineralised zones (Magrina *et al.*, 2005). IOA-type mineralisation characterises the *Lac Marmont* sector to the south, hosted within the Manitou complex, a metasedimentary package with quartzo-feldspathic, pyroxene-hornblende and granitic gneisses, and minor supracrustal rocks with probable mixed Labradorian (~1.65 Ga) and Pinwarian (~1.5 Ga) ages. This complex is also intruded by small, 1.17 Ga magnetite-fluorite-bearing leucogranite intrusions. While the *Lac Marmont* prospect occurs in this assemblage of mostly quartzo-feldspathic and mafic gneisses (Clark *et al.*, 2005, 2010), the *Guido* and *Lac Gad* showings to the north in the *Kwyjibo* area are hosted by leucogranite. All of the above units were metamorphosed to amphibolite facies, and up to granulite facies in the Manitou complex, at 1.08 Ga during the onset of the Grenvillian orogeny (Gobeil *et al.*, 2003). Orogenesis ended by about 1.05 Ga in this area and was followed by intrusion of post-tectonic granites at 1.03 Ga (Gobeil *et al.*, 2003). Late- to post-tectonic, composite, mafic to felsic intrusions and dykes occur in close proximity to the *Kwyjibo* deposit and in the *Lac Marmont* region, and belong to the late- to post-Grenvillian magmatic belt (985 to 950 Ma) of the eastern Grenville Province (Gower *et al.*, 2008a).

At *Kwyjibo*, alteration and mineralisation occur within two parallel bands along a zone of at least 8.0 × 3.5 km that straddles a major deformation zone marked by a strong residual total field magnetic anomaly (Gauthier *et al.*, 2004: Clark *et al.*, 2010). Most of the mineralisation occurs within foliated to gneissic leucocratic alkali feldspar granite or syenite. Clark *et al.* (2005, 2010) interpret the entire zone as hydrothermally altered and brecciated leucogranitic units (Fig. 6H), pointing out that where mineralised, the leucogranites have a marked increase in potassium, iron, and depletion in sodium. Poorly exposed carbonate-bearing calc-silicate rocks occur immediately south of the *Kwyjibo* deposit. Gauthier *et al.* (2004) interpreted these as metasedimentary rocks of the Manitou complex whereas Clark *et al.* (2005) considered them to represent an intense calcic alteration zone within the Canatiche complex. These contrasting conclusions clearly illustrate the difficulty of interpreting protoliths in a high-grade metamorphic terrane.

The mineralised zones are enveloped by potassic alteration along a 1 km corridor, except for the *Andradite* prospect which is surrounded by sodic alteration. Siderite, ankerite, chlorite, epidote, massive andradite, and magnetite alteration with cordierite or barite, and magnetite-K feldspar alteration are proximal to some mineralised zones (Gauthier *et al.*, 2004; Clark *et al.*, 2005; Magrina *et al.*, 2005). Detailed geochemical and petrographic studies of host granites document pervasive sodic (albite) alteration, high variations in Fe_2O_3 contents (3 to 45 wt.%), significant variations in U/Th ratios, very high K_2O content reaching 10 wt.%, and high REE, Zr and Y values. The mineralogy and geochemistry have been variably interpreted as magmatic with some alkaline affinities, and in other cases as hydrothermal (e.g., high iron content; Magrina *et al.*, 2005). Magnetite showings reach 0.96% (La+Ce+Sm) and 1.83% Cu in a 9.4 m long channel sample (*Josette* prospect), and 1.84% (La+Ce+Sm) and 0.69% Cu in a 3 m channel sample (*Fluorine* prospect; Clark *et al.*, 2005). Mineralisation is replacive and multistage. The main polymetallic stage comprises chalcopyrite, pyrite, fluorite, molybdenite, REE-bearing minerals and coarse-grained magnetite in hydrothermal veins and stockworks. They crosscut pre-existing (pre-1.03 Ga metamorphism), locally folded, massive, layered or brecciated tabular bodies or stockworks of fine-grained magnetite ironstone replacing a 1.17 Ga protolith along its fabric. A deformed magnetite-matrix breccia (Fig. 6H) is cut by a co-mingled, mafic-felsic dyke with field characteristics similar to those of the 1.17 Ga dyke suite dated by Wodicka *et al.* (2003), and significantly distinct from those of the non-recrystallised 0.97 Ga co-mingled mafic-felsic dykes. This field interpretation suggests that significant magnetite alteration and breccia in-filling is largely coeval with the Canatiche granite that it crosscuts. The 0.98 to 0.95 Ga intrusions cut the mylonitic fabrics of the deformation zones that host the IOCG and IOA mineralisation but are coeval with U/Pb allanite, titanite and perovskite ages of 972 and 951 Ma from mineralised veins at the *Josette* and *Grabuge* prospects respectively (Gauthier *et al.*, 2004; Clark *et al.*, 2005). These field and geochronological data indicate that alteration and mineralisation are coeval with the two main phases of granitic magmatism and mafic-felsic dyke swarms in the area (see Gauthier *et al.*, 2004 and Clark *et al.*, 2005, 2010 for discussions of age constraints and various alternatives for alteration and mineralisation ages that illustrate complexities in determining the timing of key events in polyphase build up of IOCG deposits in orogenic terranes).

Both the IOCG *Kwyjibo* deposit and the IOA prospects and showings in the *Lac Marmont* region occur on the lower decks of a series of major thrust faults across which contrasting styles of mineralisation occur. Magmatic nickel-copper sulphides of 1.35 Ga age hosted within the infolded 1.37 Ga Matamec mafic-silicic layered intrusion occur to the southwest of the Kwyjibo deposit and titanium-rich iron oxide deposits within the Havre St-Pierre anorthosite massif occur to the southeast (Clark *et al*., 2003; Saint-Germain and Corriveau, 2003). None of these mineralisation styles are coeval, and the age of the main IOCG build-up of the Kwyjibo deposit remains to be dated. Nevertheless the spatial distribution of hydrothermal low-titanium iron oxide and magmatic high-titanium iron oxide deposits, and magmatic nickel-copper sulphides mineralisation is worthy of mention in light of two models. Tornos *et al*. (2005, 2006) have highlighted that calc-alkaline magmatic arcs can be host to magmatic nickel-copper and hydrothermal IOCG ores (e.g., Ossa Morena Zone in Spain). These two distinct styles of mineral deposits formed at local extensional zones along crustal-scale strike-slip and thrust faults that played a major role in magma emplacement and hydrothermal circulation. They highlighted the importance of mantle to crust dynamics in the generation of mafic magmatism as thermal catalysts for IOCG mineralisation following their discussion of large mid-crustal mafic sills in the area. In parallel, Gauthier *et al*. (2004) revisited the Grove hypothesis and emphasised that the Kwyjibo and other IOCG showings and prospects in the Grenville Province all lie at the southern end of known sub-surface Archaean crust.

The Bondy Gneiss Complex

The Bondy gneiss complex is one of a series of 1.4 to 1.35 Ga quartzo-feldspathic gneiss complexes, metamorphosed to granulite facies between 1.2 and 1.18 Ga, that outcrop as structural windows within the Central Metasedimentary Belt in the southwestern Grenville province, Quebec (Fig. 1; Blein *et al*., 2003; Corriveau *et al*., 2007). The 30 × 15 km gneiss complex is composed of granitic to tonalitic orthogneiss intercalated with 10 to 500 m wide units of layered metabasite, laminated felsic gneiss, and one fragmental polymictic unit interpreted as volcaniclastic in origin. These gneiss complexes are interpreted to be parts of a juvenile arc built over a thin Laurentian continental substrate in the southern part of the Central Metasedimentary Belt (Blein *et al*., 2003). They are interpreted to form the substrate of a failed back-arc into which the supracrustal rocks of the Central Metasedimentary Belt were deposited (Dickin and McNutt, 2008). Due to multiple episodes of deformation and high grade metamorphism, the Bondy gneiss complex represents an even more challenging mapping and exploration environment than the Manitou Lake district discussed above.

In its northern part, the Bondy gneiss complex hosts a large-scale iron oxide-, copper- and gold-bearing

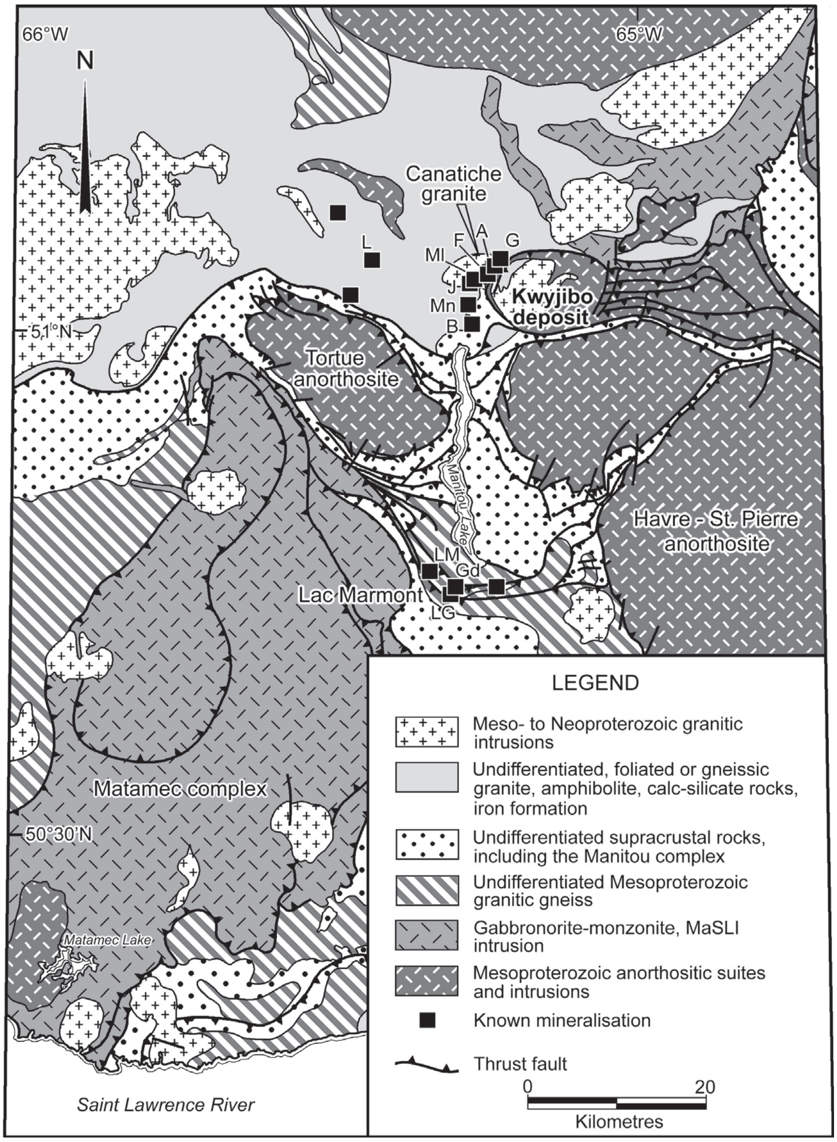

Figure 13: Manitou Lake district, Quebec; prospects and showings: Grabuge (G), Andradite (A), Fluorine (F), Lavaivre (L), Malachite (Ml), Josette (J), Manitou (Mn), Bottine (B), Guido (Gd), Lac Marmont (LM), Lac Gad (LG) (after Gobeil *et al*., 2003; Clark *et al*., 2010).

hydrothermal system metamorphosed to granulite facies (Corriveau *et al.*, 2007 and reference therein). Geological indicators of polymetallic mineralisation abound along a 12 km by >100 m zone transposed concordantly and folded. From north to south, the hydrothermal system comprises: (1) a 200 m long granoblastic tourmaline-rich unit, hosted by phlogopite-sillimanite-bearing aluminous gneiss, interpreted as potential argillic or sericitic alteration; (2) a variety of felsic orthogneiss; (3) a cordierite-orthopyroxene-plagioclase-bearing white gneiss, interpreted as a severely choritised unit; (4) a series of aluminous gneisses rich in biotite, cordierite, garnet, orthopyroxene and/or sillimanite, locally with relict lapilli-sized mafic and felsic fragments, and interpreted as argillic or sericitic alteration of a volcaniclastic unit; (5) laminated quartzo-feldspathic gneiss with rhythmic layering; (6) a series of magnetite-rich, garnet-bearing rock, biotite-orthopyroxene gneiss and amphibolite, locally containing chalcopyrite and interpreted as magnetite altered and, in the case of the garnet rock, as severe leaching of felsic and mafic hosts; (7) a hyperaluminous sillimanite-quartz gneiss with pyrrhotite, interpreted as an advanced argillic or phyllic alteration zone; (8) a biotite-rich garnet rock among biotite-garnet gneiss, interpreted as a potassic-altered amphibolite; and (9) a diverse array of layered, garnet-bearing amphibolites, interpreted as leached mafic rocks. Outside the main zone, several concentrations of interlayered garnet-bearing calc-silicate rock, garnet-bearing and garnet-free amphibolite, magnetite-rich rock, and Cu showings are also found. Disseminated to massive magnetite and schlieren, and anastomosing veinlets of magnetite occur intermittently over a 6 × 9 km zone. Magnetite-rich units form with garnet-rich and calc-silicate rocks, and are the main hosts to copper mineralisation and associated anomalous gold values. As in the *Kwyjibo* area, this mineralisation is independent of the magnetite content and occurs in close association with HREE, Zr, and Hf enrichments. The behaviour of trace elements implies rock interaction with reducing hydrothermal solutions, and large amounts of fluorine-rich fluids that are not associated with the major element signature, suggesting that IOCG-type hydrothermal activity in this 1.4 to 1.35 Ga volcano-plutonic setting occurred prior to the 1.2 Ga metamorphism (Fu *et al*., 2003).

The recognition of volcanic textures and metamorphosed hydrothermal alteration in the Grenville Province is a vindication of mapping strategies developed to explore for volcanic-hosted oxide or sulphide deposits and epithermal mineralisation in frontier gneiss terranes (Bonnet and Corriveau, 2007). Some units resembling metasedimentary rocks, in particular metapelite, may be first order targets for metamorphosed hydrothermal deposits in 'frontier terranes', but in the case of IOCG deposits, metamorphosed 'iron formation' and former iron mines in metamorphic terranes may be another target (Corriveau, 2007), such as the Hilton and Marmoraton iron mines in the Central Metasedimentary Belt of the southwestern Grenville Province (Fig. 1). Where magnetite, hematite, pyrite and pyrrhotite ore, associated K feldspar, amphibole, and/or magnetite 'skarn' alteration, veins and lenses of massive magnetite, and biotite-rich schists are closely related to biotite-granite, they may represent metamorphosed iron oxide, calcic-iron, potassic-iron and potassic alteration zones. Another example is the arc-related Palaeoproterozoic granulite-facies Disappointment Lake unit in the Wilson Lake terrane of Labrador. It occurs southwest of the Central Mineral Belt, is coincident with a very high positive aeromagnetic anomaly, due to iron oxide lenses and abundant iron oxides in mafic dykes that crosscut the iron-rich gneisses. Conceptually the area may also constitute an exploration target for IOCG deposits (Corriveau, 2007).

Trans-Hudson Orogen

Of the little-explored 'frontier terranes' in Canada, the Palaeoproterozoic Trans-Hudson Orogen (THO) of northern Manitoba and Saskatchewan stands out as one of the largest (~300 000 km^2) and most promising prospective regions for IOCG-related mineralisation. The Trans-Hudson constitutes a Palaeo- to Mesoproterozoic tectonic collage of early island-arc terranes, accretionary complexes, continental orogenic belts, arc- and continental-rift environments, collisional suture zones, and granitoid and gneiss belts favourable for and hosting a variety of igneous and hydrothermal styles of mineralisation (Corrigan *et al.*, 2007). In spite of the attractive geotectonic setting, the camouflaging effects of high-grade metamorphism, scarcity of outcrop, remoteness, and limited access to much of the Trans-Hudson Orogen have left most of it virtually unexplored.

In 2002, a scoping study for IOCG deposit potential was initiated in the province of Manitoba, focusing on the Trans-Hudson Orogen (Mumin and Perrin, 2005). Using a combination of 1960s vintage 5 km line spaced regional government radiometric surveys, 800 m spaced regional magnetic surveys, extant Manitoba Geological Survey geological map sheets, and only occasionally more detailed local geological information, 144 IOCG potential prospective sites were identified. Of these, only 13 received ground follow-up visits because the remainder were too remote to access except by fixed wing aircraft or helicopter. Despite the simplicity of the methodology, it was successful in identifying magmatic-hydrothermal systems, some in very difficult to interpret migmatite terranes. The first carbonatite complex discovered in Manitoba was located in this manner at Eden Lake at a site of coincident potassium and uranium radiometric and magnetic anomalies superimposed on alkaline intrusions. The complex is very interesting due to the presence of britholite, allanite, apatite, albite and pyroxene veins with very high LREE concentrations, as well as abundant carbonatite veins, dykes and pods containing LREE enriched (~ 25 000 ppm) apatite (Mumin and Perrin, 2005). The complex is situated at the western end of the ~10 × >80 km Eden deformation corridor (Mumin and Corriveau, 2004). The deformation corridor is also host to other forms of magmatic-hydrothermal mineral showings, including Ni-Cu-PGE. Deep-crustal seismic profiles indicate that the corridor overlies a major crustal-scale ramp and offset in the Moho, similar to deep crustal structures underlying Olympic Dam (Corriveau, 2007).

Other interesting results of the study derived from regional field and geophysical data include recognition of a unique style of mineralisation referred to as iron-sulphide copper-graphite (ISCG) deposits (Mumin and Perrin, 2005). They comprise a series of hydrothermal pyrrhotite-dominant showings with minor copper and silver, and abundant quartz and graphite. The ISCG showings occur in abundance in metapelites of the northern Kisseynew terrane, in spatial association with felsic intrusions. They resemble, at least in part, metapelite-hosted pyrrhotite-rich, low iron-oxide deposits classified as the "Low Fe Oxide Cu-Au (in pelites)" sub-class in the IOCG classification scheme of Williams (2010a). Other examples from this class include Pahtohavare, Sweden (Carlson, 1991), Khetri, India (Haynes, 2000; Knight *et al.*, 2002) and Greenmount, Mount Dore, Lady Clayre and Victoria, Cloncurry district, Australia (Krcmarov and Stewart, 1998; Sleigh, 2002). The ISCG showings of the Kisseynew remain unexplored for their economic potential, and further work is required to fully understand the origin of these showings.

Exploration Techniques

In glaciated terranes such as in Canada, where IOCG targets are commonly exposed or only thinly and partially covered, geophysical exploration complements but does not replace detailed geological mapping and systematic application of geological criteria in exploration (Goad *et al.*, 2000; Setterfield, 2006; Mumin *et al.*, 2007). In the Great Bear Magmatic Zone, the *Sue-Dianne* Cu-U-Au deposit was first discovered by prospectors allegedly looking in areas of regional magnetic highs from government-flown airborne surveys. The prospect was then optioned and first drilled by Noranda Exploration (ca. 1976), and later further explored by Fortune Minerals Limited (Goad *et al.*, 2000). Similarly, mineralisation at *NICO* was first detected by prospecting in areas of regional magnetic high signatures. A small part of a marginal lens was drilled with 21 holes, ca 1960s. However, the major exploration at NICO using the "Olympic Dam" model was inspired largely by the presence of a >16 km^2 radiometric eTh/eK (equivalent thorium divided by equivalent potassium) anomaly coincident with a magnetic anomaly, revealed in the 1994 Geological Survey of Canada multiparameter airborne radiometric and magnetic survey (Hetu *et al.*, 1994). eTh/eK low and eU/eTh high ratios are good indicators of hydrothermal enrichment of potassium and uranium respectively, because of the relative immobility of thorium in hydrothermal solution (Shives *et al.*, 1997). The area was mapped and sampled in great detail in 1995. Even though sub-cropping, the mineralisation is so finely disseminated and weathered at surface that it is rendered completely cryptic. Hence, only very detailed mapping enabled recognition of the economically mineralised zone within large, regional hydrothermal alteration and airborne geophysical anomalies. Detailed ground geophysical surveys showed excellent coincident magnetic and gravity highs and a resistivity low at both *NICO* and *Sue-Dianne*, although IP proved ineffectual and gave misleading results at *NICO*. The 1994 Geological Survey of Canada airborne survey also shows small but discrete uranium-radiometric anomalies in a distal peripheral halo to the *NICO* deposit.

Another case example in integration of geology, mineral occurrences, geochemistry, magnetic, IP, gravity, and EM data for IOCG exploration is the exploration programs along the Cobequid-Chedabucto Fault Zone (CCFZ) and the concerted effort by government (O'Reilly, 1999, 2001, 2002, 2004; Setterfield and Downes, 2005). The fault zone was initially recognised as prospective because it: (1) is a crustal-scale fault zone with abundant iron-rich (oxide and carbonate) hydrothermal breccias and iron-copper showings (and small deposits); (2) has an associated regional copper-cobalt anomaly; (3) has coeval intrusive and volcanic activity; and (4) is proximal to A-type granites. Reconnaissance exploration included targeting regional gravity highs interpreted from government data, local and detailed- to regional-scale (3600 km^2) ground gravity surveys (Belperio, 2008), airborne and ground magnetic and electromagnetic surveys, induced polarisation, soil and water geochemistry, mapping, prospecting and diamond drilling (O'Sullivan, 2004; Hudgins, 2005; Setterfield and Downes, 2005). Radiometric data has provided complementary information in well exposed areas, and EM and IP chargeability anomalies have allowed refinement of zones of interest within magnetic and gravity derived target areas. Over the past six years, these exploration programs have validated the overall prospectivity of the fault zone, but have not yet located an economic deposit.

In the Wernecke Breccia, regional geophysical datasets generated by the Geological Survey of Canada have proven useful. Property-scale airborne magnetic and radiometric surveys have been flown, and a regional airborne gravity survey has been undertaken in the Wernecke Mountains. Ground geophysical methods employed include magnetic, gravity, radiometric and IP surveys. Various geochemical methods have also been applied as described above, and the Wernecke Breccia has been extensively mapped and prospected (e.g., Thorkelson, 2000).

Serious IOCG exploration within the CMB, which commenced in 2003, included ground and airborne gravity surveys, and focussed on copper-gold-silver (Setterfield and Tykajlo, 2003b; Smith *et al.*, 2004). This initial IOCG exploration was not immediately successful, but it set the stage for more successful uranium-related IOCG exploration starting in 2005. With the change in focus to uranium exploration, radiometric surveying became very common, and is used by all the companies presently exploring in the CMB (*Michelin, Jacques Lake, Gear, Nash, Inda* and *Rainbow* all have radiometric hydrothermal uranium signatures; Cunningham-Dunlop and Lee, 2008). Magnetic and radiometric data are typically collected concurrently, in order to obtain structural information. Induced Polarisation (IP) surveys have also been undertaken by some companies, as much of the mineralisation found to date has associated sulphides (pyrite, chalcopyrite or pyrrhotite). Geochemical data is used extensively, particularly the government lake sediment database (Davenport *et al.*, 1999). Individual companies have conducted lake sediment, water, soil and various types of radon surveys.

Hydrothermal Alteration

Geological mapping and prospecting in areas of regional airborne magnetic and radiometric anomalies led to the discovery of the *NICO* and *Sue-Dianne* IOCG deposits (Goad *et al.*, 2000). Delineation was by follow-up, systematic drilling. However, in areas with a high percentage of outcrop exposure, such as the GBMZ, hydrothermal alteration mapping has emerged as the single most effective means of identifying prospective areas for IOCG mineralisation. This holds true on a regional scale during early exploration programs and regional government mapping, as well as locally during detailed mapping for specific drill-target selection. This is possible because of the regional-scale footprint (sometimes exceeding 100 km^2) of alteration, and the progressive inward changes in mineralogy, alteration intensity and textural features.

Zoning of Hydrothermal Mineral Assemblages

Hydrothermal alteration zoning has long been known in IOCG systems. The early model of Hitztman *et al.* (1992) has stood the test of time and remains valid. Additional alteration zoning criteria is provided by Smith (2002) and Nisbet *et al.* (2002). However, hydrothermal alteration shows variations from system to system within a district, and between districts within a metallogenic belt, with even greater possible variations between metallogenic belts worldwide. Nevertheless, commonalities exist and are the principal criteria upon which the IOCG classification is built (Williams 2010a). It is these commonalities that are brought into an alteration mapping framework and zoning model that can guide regional mappers and explorationists during fieldwork and facilitate the discrimination of a potentially fertile area in spite of the commonly cryptic nature of mineralisation (Corriveau *et al.*, 2010). In this section we discuss the well-exposed hydrothermal alteration zoning of the GBMZ IOCG system. The GBMZ alteration is so clearly manifested that it presents an excellent case study to help interpret the hydrothermal effects associated with magmatic-hydrothermal IOCG systems elsewhere in non- or poorly-exposed regions. Although alteration assemblages and patterns vary somewhat from site to site throughout the GBMZ, a surprisingly consistent pattern is observed.

Hydrothermal alteration zoning for the various documented systems in the GBMZ as a whole, follows the systematic pattern given in Mumin *et al.* (2010). As an aid to field mapping or core logging, specific hydrothermal alteration assemblages (zones) are subdivided and discussed according to recognisable field characteristics, with each distinctively mappable zone named after its dominant characteristic mineral(s); these are then classified within the larger scheme of the zoning model in Fig. 3. As not all zones are necessarily present at any one location, the specific mineral species may vary somewhat without changing the mineral group. Intermediate assemblages are common (e.g., magnetite-amphibole alteration is manifested as magnetite-hornblende at *NICO* vs magnetite actinolite±apatite at *Port Radium* vs albite-magnetite amphibole-apatite at *Mag Hill*), and accessory hydrothermal species will vary. Significant overlap and overprinting of mineral assemblages is common, resulting from both prograde and retrograde alteration, multiple superimposed hydrothermal events over short or long periods of time, and partially overlapping stability fields for associated minerals.

Alteration Mapping as a Guide to Exploration

The simple, diagnostic and signature alteration that defines the core areas of all known productive and potential IOCG systems in the GBMZ is alkali-iron metasomatism. This is manifested as variable hydrothermal sodic (albite), calcic (amphibole), potassic (biotite, K feldspar), and/or iron (magnetite) enrichments with respect to the composition of precursor rocks. Characteristic distal alteration and common overprints on earlier assemblages include variably lower temperature potassic (K feldspar, sericite), iron (hematite, carbonate), silicic, calcic (epidote, carbonate) and manganese enrichments. Alteration and associated changes in whole-rock composition vary from subtle to extreme (e.g., K_2O can increase by 1 to 5 or 8 wt.%) and can give way to significant changes in mineral assemblages and mineral modal composition that can be mapped in the field. Overprint relationships can be documented through alteration mapping and the chemical addition or substraction associated with overprints characterized through selective sampling and subsequent whole-rock analysis, or measured directly in the field with portable hand-held gamma ray spectrometers (potassium, thorium and uranium) or XRF. In the case of severe leaching prior to overprinting, the chemical addition of a studied elements may not be perceptible if a comparison is made with the composition of the original protolith instead of the leached precursor alteration. Mineral assemblages, textures, zoning patterns and other effects associated with alteration are summarised below. Fig. 3 highlights commonalities in IOCG system development that can be used as a simplified guide while mapping. The alteration zoning model has proven useful to rapidly identify potentially fertile parts of IOCG systems in virgin territories and to assess whether specific mineralised zones belong to an IOCG system or not. Ultimately, final mapping of the systems will undoubtely provide as many variations on the theme as observed worldwide, but in the meantime, using these simple criteria as vectors to ore can prevent geologists from being overwhelmed by IOCG complexities while working in uncharted terranes. Ultimately, it is the alteration style that best defines the IOCG deposit model and allows framing of the extraordinary range of IOCG and affiliated deposits into a conceptual evolutionary iron oxide-apatite to magnetite-group and hematite-group IOCG±U deposit model (Fig. 34 in Corriveau *et al.*, 2010).

Albite (sodic) alteration is laterally significant locally, and most intense within or proximal to major heat sources, such as the contact of syn-volcanic intrusions with a volcanic pile and/or as zones within the intrusion. Sodic alteration generally occurs distal to and at deeper levels with respect to known mineralisation and sulphide occurrences, unless fertile lower temperature alteration is superimposed upon it. Albitisation is largely through replacement, can be pervasive close to or within the heat source, and grades to variegated patches and bands distal to massive zones of replacive albite (e.g., Contact Lake belt; Mumin *et al.*, 2007; Corriveau *et al.*, 2010). Host rock textures are preserved where alteration is mild, but are totally destroyed through severe leaching, significant sodium gain, and albite grain coarsening where alteration is intense. In the latter case, hypidiomorphic equigranular textures may develop in albitites, which form rocks with field characteristics more typical of syenite or massive grey-white anorthosite.

Magnetite-amphibole±apatite±biotite±epidote (calcic-ferrous) alteration is superimposed on or peripheral to sodic and/or early, spatially extensive, mild to intense potassic alteration. Various iron-rich minerals with or without calcium alteration form disseminations, veins, stockwork and breccia matrix, or occur as replacement of host rocks. Brecciation is very common, but tends to be best developed when preceded by or coeval with K feldspar alteration. Magnetite-rich zones are the most easily field recognisable and detectable expression of high-temperature core zones of IOCG alteration systems (e.g., magnetic, gravity and electromagnetic surveys). The hydrothermal magnetite is typically low in titanium, but in some localities, such as *Echo Bay*, is distinctly enriched in vanadium where it averages about 0.70 wt.% V_2O_5 in pure magnetite concentrate (Breen and Mumin, 2008). Magnetite-rich zones range from barren, where they are monomineralic or associated with amphibole±apatite±epidote, to fertile with associated chalcopyrite and pyrite±gold and silver (e.g., *Sue-Dianne* and minor parts of *NICO*). In the fertile zones, magnetite is associated with K feldspar or biotite, and may have late overprinting by cobalt- and bismuth-bearing arsenides and Au-Bi-tellurides (e.g., *NICO*), or by Ag-Cu-Co-Bi-Ni arsenides and sulphides (e.g., some epithermal veins at *Port Radium* and *Conjuror Bay*).

Biotite, with or without amphibole alteration, is commonly associated with magnetite (potassic-ferrous alteration), although it also occurs as a peripheral halo that extends further outward from the hydrothermal centre than magnetite. As such, it can form its own distinctly mappable zone, and typically is a harbinger of the nearby presence of magnetite. It occurs as massive to pervasive replacement bodies, and as veins and stockworks. In some areas (e.g., *Port Radium*), amphibole-biotite may grade into chlorite-rich alteration, and at *NICO* proximal green annite (Fe-rich biotite) grades to distal Fe-Mg biotite. K feldspar, hematite, sericite and pyrite may also accompany amphibole-biotite. Amphibole is dominantly ferro-hornblende in the *NICO* region and ferro-actinolite in the *Echo Bay* area.

Development of breccia and the presence of sulphides are common at the stage of abundant biotite and/or K feldspar with magnetite. Significant Cu-Au-Co-Bi mineralisation occurs within such alteration zones during repeated influx of potassium-iron minerals with or without amphibole (*NICO*). An intense K feldspar zone with associated brecciation may develop over tens to hundreds of metres where systems evolved from magnetite- to hematite-bearing, and grade to, or are overprinted by, potassic-ferric alteration with hematite and sericite or K feldspar, chlorite and carbonate. The transition between potassic alteration with magnetite and potassic alteration with hematite, in some cases is associated with focussed (e.g., *Echo Bay*), to extensive (e.g., *NICO*) development of felsites (a few to tens of metres to hundreds of metres in extent, respectively).

Hematite alteration is highly variable, ranging from massive replacement bodies to veins, stockwork and breccia fill, to pervasive finely dispersed hematitic dusting impregnating silicates and other hydrothermal minerals. It occurs both as specularite and as earthy varieties, and has been observed in every alteration zone except albitites. Hematite is commonly associated with one or more of: magnetite, K feldspar, chlorite, tourmaline, epidote, quartz, carbonate, sericite and pyrite. In high-temperature reduced cores of hydrothermal systems, magnetite is the principal iron oxide, whereas peripherally in oxidised and cooler areas hematite dominates. Intense hematite overprinting on magnetite-bearing breccia has been observed at several prospects in the Echo Bay area of the northern GBMZ. Rhythmic growth banding of magnetite-hematite grains is observed in some areas, such as the *Sue-Dianne* deposit, reflecting alternating stability between magnetite and hematite. In a number of cases, the best mineralisation occurs where a change in the stability between magnetite and hematite fields is observed (i.e., a change in redox state and/or temperature; *NICO* and *Sue-Dianne*). In the massive and semi-massive magnetite ironstones of the southern GBMZ (e.g., *Ron, Hump Lake, Mar* and *Peanut Lake;* Fig. 4), a few modal percent of specularite occurs with magnetite. Mineralisation associated with hematite alteration is variable, but tends to be polymetallic and may include uranium. It ranges from chalcopyrite-bornite-chalcocite at *Sue-Dianne*, to the polymetallic quartz-carbonate-hematite sulphide and arsenide rich epithermal veins of the northern GBMZ, to pitchblende-rich quartz-carbonate-hematite veins (*Port Radium*), to copper only (chalcopyrite-bornite-chalcocite) in some giant quartz vein complexes (e.g., *Mariner* and *Sloan* deposits in the northern GBMZ).

Potassium feldspar hydrothermal alteration is the most characteristic and diagnostic alteration after iron oxides in IOCG systems of the GBMZ. Alteration intensity ranges from mild to near massive and commonly extensive felsite with greater than 80% K feldspar (e.g., altered rhyodacite capping at the *NICO* deposit). Potassic alteration (K feldspar) originates within source intrusions and emanates outwards in a major flooding event that grades to phyllic or sericitic assemblages in its most distal expression. Extensive K feldspar development is part of the prograding and outwardly expanding alteration signature, and precedes the onset of significant iron-oxides and subsequent mineralisation. In the *Echo Bay* district, over many tens of km^2, it occurs as patchy alteration ranging from slight modification of plagioclase, to felsites. In many mineralised breccias (e.g., *NICO, Sue-Dianne, K2*) clasts cemented in an iron oxide matrix are strongly potassic-altered, and fine breccia matrix typically contains abundant finely comminuted potassic-altered fragments of the original host rock. Potassic alteration in association with some iron oxide is a common feature of all the known mineral deposits and significant showings of the GBMZ. Alteration is intense in the *NICO, Sue-Dianne, K2, Summit Peak* Cu (1 km northwest of *NICO*), *Mile Lake* skarn, *Stevens Island* copper and many other deposits and showings (Figs. 4, 5A, 6B). Weaker potassic alteration is found within, or in spatial association with, epithermal vein deposits such as at the *Port Radium, Echo Bay, Contact Lake* and *El Bonanza* mines, the large weakly mineralised phyllic gossans thoughout the northern GBMZ, and in the giant quartz vein complexes known throughout the GBMZ including the *Mariner* and *Sloan* copper deposits.

Phyllic alteration (sericite, quartz, pyrite) occurs peripheral to, and is gradational with, potassium feldspar. It is the most distal and lowest temperature expression of hydrothermal potassium enrichment. Phyllic alteration is common in the northern GBMZ along the eastern shore of Great Bear Lake, forming intense but commonly texture pseudomorphing alteration. It occurs over tens of metres to kilometres in extent, and where exposed at surface forms dramatic surface gossans of limited depth due to sulphuric acid burn from weathering pyrite. A less intense variation of phyllic alteration manifests as distal sericite in both the *NICO* and *Sue-Dianne* areas, generally not prominent until several hundred metres to several kilometres distant from mineralisation.

Chlorite, epidote, carbonate±albite, sericite, quartz ('propylitic') alteration is widespread in the *Echo Bay* region. It is the most distal alteration from the hydrothermal centre. In almost all cases original rock textures are well preserved, giving the field impression of unaltered rocks, even though alteration is thoroughly pervasive and almost completely replaces primary mineralogy of host andesites. Propylitic alteration may be overprinted by other hydrothermal assemblages, and may itself be a late feature overprinting earlier alteration.

Carbonate alteration is a distal feature in the GBMZ, and is generally accompanied by one or more of: quartz, hematite, pyrite, sulphides and arsenides. Notwithstanding its minor to modest presence in propylitic±other zones, it occurs primarily as veins, stockworks and breccia fill. At *Echo Bay*, it occurs as epithermal quartz-carbonate-hematite veins that contain Cu, Ag, ±Co, Ni, Bi, Pb and Zn sulphide and arsenide mineralisation and/or pitchblende. This type of polymetallic epithermal veining accounts for all past mine production in the area. In the *Echo Bay-Port Radium* district, mixed carbonates, including calcite and Fe-Mn varieties, are typical of those associated with polymetallic mineralisation. Elsewhere, calcite dominates where sulpharsenide mineralisation is not present. In certain restricted areas, such as the *Mile Lake* district, mineralised skarn assemblages were preceded by barren hydrothermal carbonate veining and alteration of host rocks.

Quartz and/or silicification is the most distal form of alteration in the GBMZ. It occurs as part of the mineral assemblage in potassic, phyllic and epidote-chlorite-carbonate alteration, and as barren or mineralised quartz-carbonate-hematite veins. However, quartz/silicification is most evident as giant quartz vein complexes found throughout the GBMZ in various orientations, typically, but not universally aligned with the major geotectonic lineaments. The complexes comprise veins, stockworks and breccias exposed for up to 10 km in length and 500 m in width. Immediate host rocks and breccia fragments within the giant quartz complexes are typically silicified and mildly K feldspar altered. Locally they may also be associated with minor epidote, hematite and sericite. In some locations, the giant quartz complexes are mineralised with copper (chalcopyrite±bornite±chalcocite; e.g., the *Mariner* and *Sloan* deposits), or pitchblende and hematite (e.g., the past-producing *Ray Rock* mine).

Hydrothermal Textures

The textures of hydrothermally altered rocks are highly variable throughout the GBMZ. Mild pervasive alteration and some types of complete recrystallisation perfectly psuedomorph and preserve primary rock textures. Elsewhere, the alteration is texture destructive, leaving a fine-grained hydrothermally altered or brecciated rock. In some cases, alteration results in grain coarsening, up to and including pseudo-igneous and pegmatoidal textured rock. Iron alteration is generally intense and leads to massive replacement lenses. If replacement is after a sedimentary unit, the resulting alteration may take the aspect of an iron formation (e.g., *NICO* and *Port Radium*). In all cases it is essential to recognise these alteration textures and assemblages for what they are, and not confuse them with magmatic and metamorphic textures, or with iron-rich sedimentary rocks. Interpreting alteration as unusual igneous rocks or pegmatites, or fine-grained replacive alteration as meta-amphibolites and meta-sedimentary rocks, may lead to IOCG systems remaining unrecognised during regional mapping.

Remaining Frontiers and Conclusions

Research on understanding alteration and brecciation processes, sources of fluids, metal reservoirs, crustal architecture, fluid flow and timing of events in reference IOCG deposit environments is advancing deposit models (Jackson and Günther, 2003; Wijns *et al.*, 2003; Betts and Giles, 2006; Drummond *et al.*, 2006; Pelleter *et al.*, 2007; Austin and Blenkinsop, 2008; Baker *et al.*, 2008; Mumin *et al.*, 2009; Jébrak, 2010; Skirrow, 2010; Williams, 2010b). Combined with the development of practical exploration tools such as remote predictive mapping, mineral potential maps, refined alteration vectors, palaeomagnetic application and indicator minerals (Schetselaar *et al.*, 2007; Beaudoin and Dupuis, 2010; Corriveau *et al.*, 2010; De Kock and Evans, 2008; McMartin *et al.*, 2009), these metallogenic models provide a framework to increase effectiveness of exploration strategies in Canada's glaciated terranes and analogs worldwide. However, exploration for IOCG deposits beyond known districts and prospects is a significant challenge in the remote under-explored and under-mapped geological terranes that characterise large parts of the Canadian landmass (Corriveau and Mumin, 2010). In these virgin territories, many of which are felsic to intermediate volcano-plutonic terranes with abundant granites and their metamorphic derivatives, challenges to exploration include the common lack of modern geoscience and high-resolution regional geophysical data. The former and current portrayal of felsic rocks as undifferentiated plutonic or gneissic units, even where high level porphyries, volcanic rocks and hydrothermal alteration zones occur, and the lack of government mapping and exploration with respect to diagnostic IOCG attributes severely hinders recognition of IOCG systems (Corriveau, 2007; Corriveau *et al.*, 2007; Jackson, 2008). Recognising that many of these terranes are key to diversifying mineral exploration in Canada, significant efforts are being directed to acquiring new airborne geophysical and geochemical data across Canada, and to conducting remote predictive mapping within government framework bedrock mapping projects to support grassroots and advanced exploration. Moreover, governments have renewed their large mapping programs outside Canada's large mining districts and undertaken scoping studies for new ore-types including IOCG deposits. Such mapping programs have taken place in the Manitou Lake district and in the Wernecke Breccia in the 1990s and the 2000s (Thorkelson, 2000; Gobeil *et al.*, 2003), Great Bear Magmatic Zone (Jackson, 2005, 2008; Mumin *et al.*, 2007; Ootes *et al.*, 2008, in press), Iron Range region (Staples *et al.*, 2008), Central Mineral Belt (Sparkes and Kerr, 2008; Hinchey and LaFlamme, 2009), Archaean greenstone belts (Kontak *et al.*, 2008a) and Trans-Hudson Orogen (Mumin and Perrin, 2005).

Prospective geological environments for IOCG deposits in Canada are most common in Proterozoic settings, but Phanerozoic examples occur within the Appalachian Orogen and the Cordillera, and Archaean examples are emerging. The Palaeoproterozoic GBMZ displays superb glacially-polished, cross-sectional exposures of polymetallic magnetite-group and hematite-group IOCG deposits, including the Au-Co-Bi-Cu *NICO* and Cu-Au-Ag *Sue-Dianne* deposits. Giant hydrothermal alteration systems in the GBMZ record many of the processes required to form large uranium-rich IOCG deposits, including: (1) significant regional- to deposit-scale element mobility driven by magmatic intrusions in a tectonically active environment; (2) superposition of extensive prograde and retrograde alteration and brecciation within large coalescing hydrothermal cells; and (3) repeated and focussed precipitation of metals within structural and lithological traps. The physico-chemical conditions of hydrothermal fluids were constantly evolving and fluid-rock interactions were particularly intense, leading to an extraordinary range of IOCG and associated deposit types with varied commodities and with a well-exposed continuum to porphyry and epithermal systems. The GBMZ case studies discussed in this paper are unambiguous IOCG magmatic-hydrothermal systems. In contrast, the Mesoproterozoic Wernecke Breccia in the Yukon is frought with uncertainties, starting with the origin of the breccias and the extent of magmatic input. 3D exposures, current and upcoming government and academic research on the Wernecke Breccia and mafic dyke swarms are bound to break new ground in coming years. The Archaean to Mesoproterozoic geological environments of the Central Mineral Belt contain some key geological traits of IOCG settings, including continental arc/back-arc volcanism and plutonism with uranium-rich A-type granites and crustal-scale fault zones. All currently known alteration and mineralisation systems are uranium-rich and have not developed the alteration footprint typical of IOCGs, but non-debatable examples of IOCG systems are emerging. To illustrate crustal-scale fault control on the developement of IOCG systems, this paper has discussed in detail the Phanerozoic Cobequid-Chedabucto Fault Zone in the Appalachian orogen. Another case example could have been chosen from the Cordilleran Iron Range fault zone in British Columbia (Fig. 1; Staples *et al.*, 2008). The imprint of metamorphism and the buildup of IOCGs through orogenic processes, a trademark of many IOCG systems, is illustrated by the Mesoproterozoic Manitou Lake district of the Grenville Province in Quebec. Finally, emerging Archaean IOCGs such as those of the Shebandowan greenstone belt represent a significant potential for new exploration targets around traditional greenstone belt-hosted mining districts.

Well-exposed examples from the GBMZ and other Canadian settings show commonalities in alteration zoning patterns at various scales that provide a useful framework for IOCG exploration in virgin territories during early, regional-scale exploration, as well as for advanced exploration at the deposit scale. Geological and alteration mapping through academic-government-industry partnerships was a key element in the discovery of the *NICO* deposit. These partnerships continue in the investigation of under-appreciated areas of the GBMZ. In Canada, like global analogs, IOCG deposits commonly occur in clusters and form mineral districts along entire geological belts, and hence districts have a high potential for being recognised during regional mapping of glaciated terranes where exposures tend to be present. Structural control on deposits and their spatial distribution is crustal in scale and understanding the 3D architectural framework of a targeted area helps to articulate deposit models at the scale required to understand processes involved in their formation. From a more pragmatic perspective, exploration is most effective by combining geological and geophysical methods at the regional to deposit scale. That *Sue-Dianne* and *NICO* have gone from curiosities to economic deposits owes a lot to a strong focus on geology, including detailed mapping of cryptic alteration and mineralised zones.

As is observed in the Andes (Tornos *et al*., 2010), some Canadian IOCG districts display a continuum to porphyry and epithermal systems that significantly broadens the potential impact of exploring Canada's largely virgin volcanoplutonic settings of felsic to intermediate composition (Mumin *et al.*, 2010). Skarns, once considered a lower priority for IOCG exploration (Nisbet *et al.*, 2000), are in some cases part of IOCG alteration sequences. Considering that skarns were recognised and mapped in the past, some iron-rich skarns may be potential markers for IOCG systems. Collectively, the Canadian systems described in this paper present a coherent scheme for the vast array of deposits that can be brought under the IOCG umbrella and most importantly, the continuum between iron-oxide rich deposits that include both Cu and Au as main commodities and others that do not. They further demonstrate that hydrothermal alteration and process, rather than commodities, are the best criteria to assess if a deposit is part of the IOCG family.

Nowhere are the knowledge gaps more pronounced than in the sea of undifferentiated gneisses that characterise many parts of the Canadian landmass. An essential step in identifying metamorphosed hydrothermal systems is the recognition of the remains of primary volcanic and sedimentary rocks and the metamorphosed overprint of hydrothermal alteration. As metamorphism is largely isochemical, mineral exploration in high-grade metamorphic terranes can rely to some degree on lithogeochemical studies, which require careful fieldwork to recognise and sample the key lithologies for geochemical and geochronological studies (Bonnet and Corriveau, 2007). Recognition of former hydrothermal effects is further hindered by the varied and unusual aspects the rocks can take once metamorphosed above mid-amphibolite facies. Altered rocks (commonly aluminous in felsic terranes) can look like metapelite and restite, but in some cases have proven to be hydrothermally altered volcanic rocks through the recognition of primary fragmental units, U-Pb geochronology of zircon and mass balance calculations that supported field interpretations based on anormal mineralogy, mineral content and assemblages (Bonnet and Corriveau, 2007). Carbonate veins and carbonate alteration zones may take the appearance of a normal marble and calc-silicate rock unit, as exemplified by the contentious origin of calc-silicate layers at *Kwyjibo*.

Collectively, Canadian IOCG settings and their intense hydrothermal systems contribute a new dimension to IOCG deposit modelling and exploration. In Canada, it is now recognised that IOCG deposits will play a major role in sustaining the country's mineral resource needs for a long time into the future.

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