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A Paleoproterozoic Andean-type iron oxide copper-gold environment, the Great Bear magmatic zone, Northwest Canada

Luke Ootes [a,*], David Snyder [b], William J. Davis [b], Pedro Acosta-Góngora [b,c], Louise Corriveau [d], A.Hamid Mumin [e], Sarah A. Gleeson [c,f], Iain M. Samson [g], Jean-François Montreuil [h], Eric Potter [b], Valerie A. Jackson [a,1]

[a] *Northwest Territories Geological Survey, Box 1320, Yellowknife, Northwest Territories X1A 2L9, Canada*
[b] *Geological Survey of Canada, 601 Booth Street, Ottawa, ON K1A 0E8, Canada*
[c] *Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta T6G 2E3, Canada*
[d] *Geological Survey of Canada, 490 rue de la Couronne, Québec, QC G1K9A9, Canada*
[e] *Department of Geology, Brandon University, Brandon, Manitoba, R7A 6A9, Canada*
[f] *Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Section 3.1: Inorganic and Isotope Geochemistry, Telegrafenberg B121, 14473 Potsdam, Germany*
[g] *Department of Earth and Environmental Sciences, University of Windsor, Windsor, Ontario N9B 3P4, Canada*
[h] *Red Pine Exploration, 141 Adelaide Street West, Suite 520, Toronto, ON M5H 3L5, Canada*

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ABSTRACT

Iron oxide copper-gold (IOCG) and associated iron-oxide apatite (IOA) styles of metallic mineralization are recognized throughout the Paleoproterozoic Great Bear magmatic zone of the northwest Canadian Shield. The Great Bear magmatic zone was constructed between ca. 1876 and 1855 Ma on top of the older Hottah terrane, which preserves continental arc magmatism that began around ca. 2.0 to 1.97 Ga and continued between ca. 1.93 and 1.89 Ga. The Great Bear represents the final stages of ca. 150 million years of intermittent and pulsed magmatism related to an evolving continental orogenic belt. The preserved geology supports a dramatic geodynamic change in the subduction zone process at ca. 1875 Ma, a key driving mechanism for magma and metal mobilization, and was rapidly followed by a large-scale introduction of felsic-intermediate plutons. The overall tectonic setting is partially constrained from new and previously published geochemical data that show that the volcanic and plutonic rocks are high-K calc-alkaline to shoshonitic in nature (e.g., high K_2O, Th/Yb, and Ce/P_2O_5). They also have suprasubduction-zone geochemical signatures, including primitive mantle normalized positive Th and negative Nb, P, and Ti anomalies. The data support the primary melts were derived from a GLOSS-modified mantle wedge. Three-dimensional rendering of geophysical datasets suggest that two (of four) preserved surfaces within the upper mantle lithosphere, at 70 to 120 km depths, represent frozen, subducted oceanic slabs, and likely were the drivers for the bulk of Hottah and Great Bear arc magmatism. The older slab is northwest-striking and dips 12° to 15° northeast, whereas the younger is deeper and north-striking, dipping 13° east. The geometry of the surfaces are comparable with 4D modeling, where a subduction zone is temporarily shut down due to plateau collision, and then steps oceanward and re-initiates; there is no need for polarity reversal of the subduction system. This new geometry and the related inferences about process should be the focus of future research in the region, but for the time-being it can be stated that these subduction and collisional processes were the first order control on lithospheric evolution, and therefore metallic mineralization. Overall, the Great Bear magmatic zone IOCG and related mineralization is not comparable to other Proterozoic IOCG belts, such as those in Australia. However, the complexity of mineralization styles, the spatial-temporal relationship between IOA and IOCG mineralization, the suprasubduction zone environment, and a major change in tectonic regime are features similar to Andean-type IOCG mineralization, as well as Cordilleran alkali porphyry Cu-Au deposits. This further establishes the linkages between subduction zone processes and IOCG formation, as well as relationships in the IOCG-porphyry deposit continuum model.

1. Introduction

The iron oxide copper-gold (IOCG) deposit model was initiated to help explain a series of somewhat disparate hydrothermal iron-oxide

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[*] Corresponding author at: British Columbia Geological Survey, Box 9333 Stn Prov Govt, Victoria, BC V8W 9N3, Canada.
E-mail address: Luke.ootes@gov.bc.ca (L. Ootes).
[1] 3126 Westridge Pl, Victoria, BC, V9E 1C8

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rich mineralization types (Hitzman et al., 1992). This has since been updated to be both inclusive and exclusive of a variety of mineralization styles (Williams et al., 2005; Corriveau, 2007; Groves et al. 2010; Chen, 2013). The original IOCG definition of Hitzman et al. (1992), followed by Williams et al. (2005), has been streamlined in some recent classifications that have removed iron-oxide-apatite (IOA) from the IOCG model (Groves et al. 2010; Chen, 2013), while others continue to show a possible relationship between magmatic-hydrothermal IOCG and IOA deposits (e.g., Mumin et al., 2010; Smith et al., 2012; Richards and Mumin, 2013a). Groves et al. (2010) suggest that the only examples where IOA-type and IOCG deposits are related to one another are in Mesozoic and Cenozoic Andean-like convergent margin-settings (ie. the Mesozoic deposits in Chile and Peru; Sillitoe, 2003; Barton et al., 2013; Chen et al., 2013).

The ca. 1875 to 1850 Ma Great Bear magmatic zone has long been considered a Paleoproterozoic example of a convergent margin volcano-plutonic complex. As early as 1973, it was shown to contain predominantly K-rich, calc-alkaline igneous rocks, interpreted to be consistent with a trench-distal subduction origin (Badham, 1973). That work has since been extensively built upon and a continental arc environment, with similarities to many continental volcanic arcs, was further substantiated for Great Bear magmatism (Hildebrand, 1981; Hildebrand et al., 1987; Gandhi et al., 2001). It was hypothesized that Great Bear magmatism was driven by eastward-directed subduction and was built upon the older crust of the Hottah terrane and western Slave craton (Hildebrand, 1981; Hildebrand et al., 1987, 2010a; Ootes et al., 2015). Uranium-lead zircon dating of volcanic and intrusive phases has pinned this magmatism between ca. 1876 and 1855 Ma (Bowring, 1984; Gandhi et al., 2001; Bennett and Rivers, 2006a; Davis et al., 2011; Ootes et al., 2015). The Slave-Northern Cordillera Lithospheric Evolution (SNORCLE) geophysical transect yielded a seismic profile that imaged east-dipping reflections interpreted to be a frozen, subducted oceanic slab under the Great Bear magmatic zone and western Slave craton, and independently validated the subduction-related hypothesis for the evolution of the Great Bear magmatic zone (Cook et al., 1999). This frozen slab was further defined by related datasets utilizing magnetotelluric, teleseismic, and wide-angle refraction data (Bostock, 1998; Cook and Erdmer, 2005; Clowes et al., 2005; Wu et al., 2005, Oueity and Clowes, 2010).

Iron oxide copper-gold styles of mineralization and IOA ± actinolite mineralization are recognized throughout the Great Bear magmatic zone, where they are spatially and temporally related to one another and extensive magmatism (Badham and Morton, 1976; Hildebrand, 1986; Gandhi, 1994; Goad et al., 2000; Mumin et al., 2007, 2010; Corriveau et al., 2010a, 2010b; Ootes et al., 2010; Potter et al., 2013; Somarin and Mumin, 2014; Acosta-Góngora et al., 2014, 2015a, 2015b; Mumin, 2015). We present a large-scale overview of the Great Bear magmatic zone and its geodynamic setting. The IOCG and IOA deposits fit in a tight time-window, and we link the deposits and the associated magmatism with a convergent margin-like subduction origin, albeit during an extensional relapse (Mumin et al., 2014). The results also provide new insights into the geometry and petrologic evolution of the region. This study supports the suggestion that this Paleoproterozoic metallogenic zone is not directly comparable to many other Precambrian IOCG examples (Groves et al., 2010), but rather we show it is comparable to the Andean styles of IOCG mineralization preserved in Chile and Peru (e.g., Sillitoe, 2003; Groves et al., 2010; Chen et al., 2013), as well as alkaline porphyry Cu-Au deposits that occur during episodes of extensional rifting within greater Cordilleran -type orogenic events (Mumin et al., 2007, 2010; Richards and Mumin, 2013a, 2013b; Logan and Mihalynuk, 2014; Richards et al., in press).

2. IOCG and IOA deposits

Polymetallic, IOCG deposits are a favorable exploration target because of their potential to host large tonnages of ore metals, particularly Cu, Fe, Au, and U, as well as accessory Ag, Bi, Co, and rare earth-elements. In addition, IOA deposits can host significant Fe and P resources. Common characteristics of IOCG deposit are structurally controlled mineralization with hydrothermal magnetite and/or specular hematite as a major constituent, less abundant chalcopyrite + bornite and precious metals, and extensive K ± Si ± Ca-metasomatic haloes (e.g., Hitzman et al., 1992; Sillitoe, 2003; Barton and Johnson, 2004; Dreher et al., 2008; Richards and Mumin, 2013a). Commonly, the parental mineralizing fluids are highly saline (up to 60 wt.% NaCl equiv.) + CO_2-rich fluids (e.g., Oreskes and Einaudi, 1992; Huston et al., 1993; Perring et al., 2000; Baker et al., 2008; Somarin and Mumin, 2014). Despite these commonalities, individual deposits are varied in terms of metal budgets, mineralization style, alteration, tectonic setting, age, and nature of the host rocks. The origin of the oxidizing fluids is poorly understood, and as such region-derived models are common for the genesis of these deposits (Fig. 1; Barton and Johnson, 1996; Pollard, 2000; Corriveau et al., 2010b; Groves et al., 2010; Mumin et al., 2010; Smith et al., 2012; Chen et al., 2013; Richards and Mumin, 2013a, 2013b; Acosta-Góngora et al., 2015a, 2015b).

The stable isotope character ($\delta^{18}O$, $\delta^{34}S$, and $\delta^{37}Cl$) of IOCG mineralizing fluids has been used to suggest that they originated as magmatic, evaporitic, formation, metamorphic, and sea-water derived, or as mixtures of some of these end-members (e.g., Oreskes and Einaudi, 1992; Williams, 1994; Pollard, 2000, 2006; Chiaradia et al., 2006; Benavides et al., 2007; Hunt et al., 2007; de Haller and Fontboté, 2009; Gleeson and Smith, 2009). The presence of apparently evaporite-derived fluids in some deposits has been postulated as a key factor for the development of the extensive Ca and Na alteration and complexation of metals in some IOA and IOCG systems (Barton and Johnson, 1996, 2004; Baker et al., 2008; Xavier et al., 2008; Gleeson and Smith, 2009; Barton, 2014). Halogen and noble gas studies from selected IOCGs and IOAs have reinforced the presence of non-magmatic fluid sources in the mineralizing system and the importance of magmatic-derived fluids mixing with non-magmatic fluids, for metal deposition (Chiaradia et al., 2006; Fisher and Kendrick, 2008; Smith et al., 2012). Alternatively, a number of investigators suggest that the alteration and ore minerals in IOCG systems have a magmatic, or dominantly magmatic source, derived from calc-alkaline to moderately alkaline suites similar to the ones responsible for Cu-Au porphyry deposits (Pollard, 2000, 2006; Mumin et al., 2010; Richards and Mumin, 2013a, 2013b). Pollard (2001) further suggests that high levels of CO_2 promote the separation of ore fluids from the crystallizing magma at a wide range of pressures that are compatible with the depths inferred for these systems. Furthermore, CO_2 may also influence the Ca-Na partitioning between silicate melts and fluids, potentially generating brines with high Na/K ratios that might be responsible for the widespread sodic alteration present in many IOCG settings. The generation of iron oxide-dominated systems and the corresponding sodic alteration for some deposits, has also been explained as having been formed by metamorphic processes involving high temperature saline fluids (500 to 600 °C; up to 40 wt.% NaCl equiv.; Williams, 1994). The salinity of these fluids is interpreted to have been acquired from older Cl-rich rocks, and the introduction of metals is the epigenetic with respect to iron-enrichment processes (Williams, 1994).

The Sue-Dianne and the Damp prospects in the Great Bear magmatic zone (Table 1) contain breccias that were recognized to be similar in nature to Olympic Dam breccias (Fig. 2C–D; Gandhi, 1994) and henceforth were considered as IOCG deposits (Goad et al., 2000). In the Echo Bay region the IOCG model has been used in exploration and to reclassify previously known mineralization and alteration (Corriveau, 2007; Mumin et al., 2007, 2010; Somarin and Mumin, 2014; Mumin et al., 2014). The NICO deposit in the southern Great Bear was recognized by Goad et al. (2000) as an IOCG-like deposit, and this has been supported by detailed mineral deposit and regional alteration studies (Table 1; Acosta-Góngora et al., 2015a, 2015b; Montreuil et al., 2013, 2015). The Fab Lake Cu-U prospect is another example of an IOCG system in the