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Alteration vectoring to IOCG(U) deposits in frontier volcano-plutonic terrains, Canada

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ABSTRACT

Iron Oxide Copper-Gold (±U-Ag-Co-Bi) deposits (IOCG) and the uranium-rich ones (IOCG(U)) provide a relatively new and exciting exploration opportunity in Canada. They are, however, challenging as most prospective Canadian settings are frontier felsic-to-intermediate volcano-plutonic terrains mapped prior to the recognition of the IOCG deposit-type in the 1990's. On-going research on stunning exposures of IOCG(U) alteration patterns in the Great Bear magmatic zone (NWT) demonstrates that the hydrothermal alteration footprint related to IOCG(U) mineralization demarcates prospective regions and, within these regions, can point to mineralization. Non-mineralized, but regionally significant alteration types include: 1) early and intensive sodic alteration distal to mineralization and most proximal to intrusive heat sources; 2) in their periphery and away from intrusions, extensive calcic-iron (magnetite-actinolite-apatite) alteration that is commonly texture-destructive and coarse-grained, and; 3) subordinate vein-type overprint or laterally-extensive mild potassic alteration. Alteration types proximal to mineralization start where intensive replacement-type K-feldspar or biotite alteration, with magnetite at first, develops. In these zones, brecciation and polymetallic sulphide enrichments are coeval to, or slightly post-date the potassic alteration. Such zones can also be affected by skarn-like calc-silicate alteration, late-stage K-feldspar overprint and hematite alteration with their associated mineralization. Porphyry copper alteration systems and some types of epithermal mineralization are also clearly associated with the significant IOCG systems. The intensive iron oxide and potassic footprints, the striking recrystallization associated with certain alteration types, and the systematic evolution of alteration enable the development of strategic exploration tools at the regional- to deposit-scale. Our goals are to refine key alteration zoning models, better define timing relationships for IOCG(U) deposits and alteration, adapt alteration and geochemical vectors to frontier terrains, provide reference rock and mineral indicator databases for till geochemical and mineral indicator fingerprinting, and develop predictive hyperspectral airborne or spaceborne capabilities. Collectively, these efforts will increase our ability to target potential mineral resources in frontier volcano-plutonic terrains of Canada.

INTRODUCTION

Iron oxide copper-gold (±U-Ag-Co-Bi) (IOCG) deposits and the uranium-rich ones (IOCG(U)) are economically and strategically attractive exploration targets for Canada. They have significant polymetallic and nuclear energy resources, both of which are seen as nation builders. For example, the 4.43 billion tonne Olympic Dam deposit in Australia, ranks 1st in world Uranium resources, 4th in gold, and 4th in copper (BHP-Billiton, 2006). These IOCG(U) deposits tend to be hosted in modern or ancestral continental margins, as illustrated by the Andean IOCG deposits and current interpretation for the tectonic setting of the Olympic Dam deposit (Sillitoe, 2003; Betts and Giles, 2006). Considering IOCG(U) deposit generation in continental margin settings, rather than focussing on the former anorogenic paradigm, opens many Canadian frontier granitic volcano-plutonic terrains and their metamorphic derivatives to IOCG(U) exploration (Corriveau, 2007).

IOCG(U) deposits are currently viewed as the most challenging field of research in contemporary economic geology

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(Williams et al., 2005). They are "non-traditional" metallic deposits in that they have oxide-rich rather than sulphide-rich ore zones that can be cryptically disseminated in barren iron oxide and alkali-altered host rocks over kilometres. They occur within 'pinkstone' belts instead of the greenstone belts typical of most Canadian base and precious metal mining camps. Composition of ore varies significantly from one deposit to the other. To date, genetic model(s), origin of fluids and processes of metal recharge and discharge during the alteration, brecciation and ore deposition processes that lead to IOCG(U) deposits remain poorly understood. Knowledge gaps can be partially attributed to the recent recognition of this deposit-type (Hitzman et al., 1992) and the importance of pre-enrichment of their hosts to generate uranium-rich deposits (Hitzman and Valenta, 2005), the non systematic geometry and the diversity of known deposits, the complexity of possible ore-forming processes, and the non-exposed nature of many IOCG(U) deposits (e.g., Olympic Dam).

Mineralization in IOCG(U) deposits have significant lateral extent and their associated zoned alteration patterns are diagnostic and extensive. Targeting of these regional systems can thus rely on alteration mapping, geochemistry, IOCG(U)-type indicator mineral signatures, and remote predictive mapping. Two major impediments exist for Canadian settings. 1) Prospective settings are still largely uncharted, or were mapped prior to the 1990's hence key alteration zones are missing in available records. 2) Many of the above tools remain to be developed or to be refined for their application to under-mapped terrains. The joint government-industry-academia research partnership described in this paper aims to advance IOCG(U) knowledge along many fronts: 1) IOCG(U) case examples onto which anchor exploration in Canada, 2) practical vectoring protocols and predictive mapping capabilities tailored for exploration in frontier terrains, and 3) new targets.

THE GREAT BEAR MAGMATIC ZONE

Located at the western edge of the Canadian Shield, the Great Bear magmatic zone (GBmz) in the Wopmay orogen (NWT; Figure 1) is currently the most prospective IOCG(U) setting in Canada. It hosts the NICO deposit with total reserves of 21.8 Mt at 1.08 g/t Au, 0.16 % Bi, and 0.13 % Co; the Sue-Dianne deposit with 17 Mt resources at 0.72% Cu, 2.7g/t Ag; and the Port Radium and Echo Bay district with past production of 15,000,000 lbs U_3O_8 and ~32,000,000 Oz Ag (Goad et al., 2000; Fortune Minerals, 2006; Mumin et al., in press). Stunning cross-sectional exposures of alteration patterns associated with these deposits provide means to refine zoning models and vectors to ores. Lesser explored systems such as DeVries and Fab lakes provide testing ground for the defined vectors. The remainder of this 450 km long magmatic belt is still a largely uncharted geological terrain.

The GBmz is a 1.88–1.85 Ga volcano-plutonic domain interpreted as a continental magmatic arc on the western margin of the Archean Slave craton (Gandhi et al., 2001). Andean-type, calc-alkaline basaltic to rhyolitic caldera fill complexes and stratovolcanoes, diatremes, hypabyssal porphyries, and older underlying Treasure Lake Group metasedimentary rocks form dispersed windows among GBmz felsic to intermediate epizonal plutons (Hildebrand, 1986; Gandhi and van Breemen, 2005). The GBmz is bounded to the east by the Wopmay Fault Zone; minor coeval intrusions also occur into the mixed Archean and Proterozoic rocks of the eastern Wopmay orogen (Jackson, 2006).

Regional government mapping

The South Wopmay bedrock-mapping project is a multi-year study undertaken by the NWT Geoscience Office, part of which includes the first systematic, regional-scale transect across the central portion of the GBmz since the mapping by Kidd (1936). Collaborative research projects, including B.Sc. and M.Sc. thesis projects and a Post-doctoral study, are helping to further unravel the tectonic and metallogenic evolution of the area, as briefly outlined below.

Crustal-scale geophysical studies along east-west transects across the Wopmay orogen include magnetotelluric, teleseismic and airborne magnetics surveys. The magnetotelluric investigation consists of 21 stations spaced 10 to 15 kilometres apart and stretched across from the central Slave craton to the east and over the Phanerozoic Platform to the west (Spratt et al., 2004). The teleseismic study consists of four stations placed 40 to 100 kilometres apart from the central Slave craton across to the most western exposure of the GBmz, near the community of Gameti (Snyder and Bruneton, 2006). Both of these geophysical studies are aimed at defining and better understanding crustal- to mantle-scale features in the study area and neighbouring geologic terrains. A regional airborne magnetics survey was flown over the Phanerozoic Platform to the southwest of the study area to investigate the extent and nature of the GBmz 'basement' beneath the platformal rocks. Currently, a 400 metre line-spacing regional airborne magnetic and radiometric study is being planned to cover the area to the north of the south Wopmay project area and will extend across the GBmz to the north. This study is aimed at investigating the duality of magnetic and radiometric anomalies that are characteristic of alteration patterns discussed below. This study will be further complimented with follow-up bedrock-mapping and geochemical investigations.

Bedrock-studies complimentary to the mapping investigations include U-Pb geochronology (e.g., Bennett and Rivers, 2006a, b), geochemical and tracer-isotope investigations, and studies of mineral occurrences and alteration patterns (Goff and Ootes, 2005; Landry et al., 2005; Bennett and Rivers, 2006a, b; Landry, 2006). These sub-projects, combined with previous research and ongoing studies in other parts of the GBmz, will help further unravel the tectonic evolution of the area and highlight key features and associations of mineralization and host-rocks. Apart from this mapping project, the GBmz has not been subject to regional-scale, non-proprietary mapping since the definition of the IOCG deposit-type in 1992. Planning has begun, in partnership with the Geological Survey of Canada, for another multi-year project north of the current study area; this will complete mapping of the GBmz between 64° and 65° north.

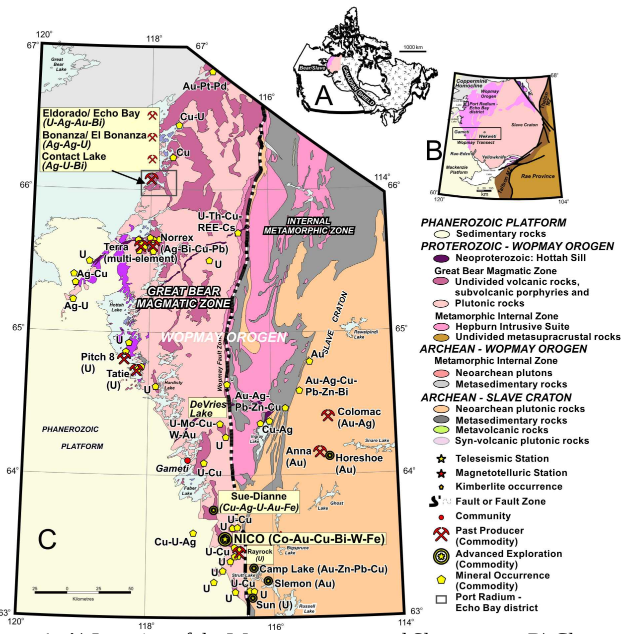

Figure 1: A) Location of the Wopmay orogen and Slave craton. B) Close up view of A. C) Known mineralization in the Wopmay orogen. Geology is modified after Hoffman and Hall, 1993; Jackson, 2006; Pierce and Turner, 2004; Stubley, 2005. Mineral Showings from NORMIN.db (www.nwtgeoscience.ca/normin)

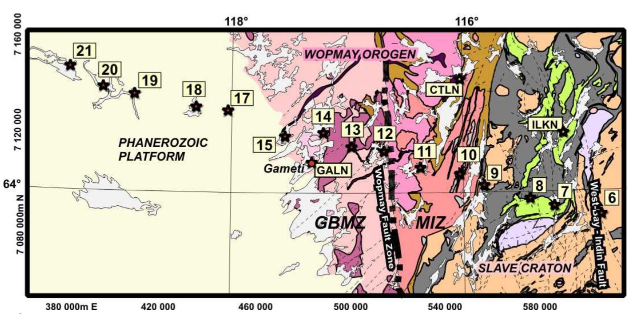

Figure 2: Details of geology and location of some teleseismic and magnetotelluric stations along the Wopmay Transect of Figure 1b. Teleseismic section: GALN = Gameti; CTLN = Castor Lake; ILKN = Indin Lake. Legend as in Figure 1.

Pre-GBmz IOCG(U) events

Early 'fluxing' of pre-existing crust prior to the voluminous ~1.87–1.86 Ga GBmz magmatism is documented by 1878 to 1871 Ma LAM ICP-MS zircon ages of intrusive bodies that crosscut pre-, syn- and post-deformation IOCG(U)-type alteration in folded and foliated metasedimentary rocks of the Treasure Lake Group (1.88 Ga maximum LAM ICP-MS detrital zircon age) in the De Vries Lake area (Bennett and Rivers, 2006b). Early alteration types include 1) lit-par-lit albite, amphibole and magnetite alteration, 2) K-feldspar lit-par-lit overprint, and 3) magnetite-bearing breccia, granitic veins, and sulphide mineralization in metasedimentary rocks. A late-stage potassic vein network overprints all early alteration as well as a 1877±3 Ma foliated pink porphyry unit. A suite of ca. 1866±5 Ma aplite dykes postdates all major magmatic and most alteration events in the area apart from pervasive late stage potassic alteration. Finally an extensive body of 1860±4 Ma rapakivi granite intrudes altered metasedimentary rocks of the Treasure Lake Group north of De Vries Lake.

The Port Radium – Echo Bay district

A GBmz-related andesite stratovolcano complex within the Port Radium–Echo Bay district contains exceptionally widespread and well-exposed hydrothermal alteration in multiple coalescing systems attributable to a continuum between IOCG, Porphyry Copper and Epithermal type systems. Host rocks are regionally altered by the effects of a series of linear monzodiorite to diorite subvolcanic intrusions. Distal to intrusion are propyllitic assemblage of chlorite-carbonate-epidote±sericite±albite superimposed by mild potassic (K-feldspar) alteration in patchy to extensive zones. Phyllic alteration (quartz-sericite-pyrite) precedes and is often overprinted by potassic assemblages in many zones of up to 1 km in extent. Where potassic alteration is particularly intense, it may be associated with abundant sulphides and one or more potentially economic metals, most commonly Cu, Ag, Co and Au. Locally superimposed on potassic, phyllic and/or propyllitic zones are extensive areas (up to km-scale) of pervasive hematite dusting that can grade into hematite and/or specularite veining and stockwork to massive hematite replacement beds. Tourmaline and quartz-tourmaline veins, stockwork and/or disseminated clots can be superimposed on the phyllic, potassic and hematite alterations. Where associated with intense potassic, phyllic or hematite alteration, tourmaline zones tend to be accompanied by Cu-Ag-Au-Co-Bi bearing sulphides and arsenides. In other zones, intense skarn alteration hosts mineralization.

Closer to the core of hydrothermal centres amphibole (actinolite) appears first as veins and then pervasively in the host rock. This zone quickly grades inward to intense magnetite-actinolite-apatite veining and stockwork and then to massive and veined pegmatitic bodies with spherulitic albite crystals and magnetite-actinolite-apatite interstices. These zones reach 100s of meters in extent, form the most recrystallized parts of the systems and appear to be the deepest-seated alteration style in the region. Such alteration is also reported in the Rainy Lake area to the South (Hildebrand, 1986). K-feldspar overprints are observed in the form of rims around albite crystals. These zones can contain from trace to ~25% sulphides (mostly pyrite ± pyrrhotite) with local patches to more extensive zones with trace to minor retrograde sulphides and arsenides of Cu, Ag, Co, Bi, Ni, Au, Pb and Zn. Within the spherulitic alteration, evidence of the precursor rock is generally lacking. However, structurally above, this alteration type replaces in situ the andesite host, overprinting an early set of albite and amphibole±magnetite veins. Peripheral to these cores zones are more leucocratic albitite that grades from texture-destructive (e.g., anorthosite-looking rocks) to texture-pseudomorphing (cross-bedding textures preserved). Massive albitite with or without actinolite±magnetite occurs within the causative intrusions and as bona fide enclaves within them. These field relationships indicate that alteration started prior to final emplacement of the intrusion and concluded after its crystallization. Subordinate vein-type potassic alteration is common within albitite, pegmatitic alteration and all the variants in Na and Na-Ca-Fe alteration.

Potential economic mineralization is hosted by any of the alteration zones discussed, either as part of the alteration, or as later superimposed or retrograde phases of alteration and mineralization. Propyllitic and albitite alterations appear to be the only phases that are not associated with some type of primary potential economic mineralization, and are only mineralized if affected by later, retrograde or superimposed events. Late stage to retrograde veins and vein breccia of quartz-carbonate-hematite are superimposed on any of the other alteration zones, and host high-grade polymetallic mineralization with various sulphides and arsenides of Cu, Ag, U, Co, Ni, Au, Bi, Pb and Zn. The previously unrecognized continuum of alteration and mineralization between IOCG, Porphyry Cu and Epithermal deposits is the subject of ongoing investigations in the Great Bear Magmatic Zone (Mumin et al., in press).

Indicator mineral research and geochemical exploration

In Canada, drift prospecting is an integral part of kimberlite and gold exploration (Klassen, 1997, 2001; McClenaghan et al., 2000; McClenaghan, 2005) on the premise that lithological, mineralogical, or geochemical indicators of mineralization can be traced in Quaternary glacial cover to locate their bedrock source. However, the application of indicator mineral methods to IOCG(U) exploration is nearly non-existent. Potential indicator minerals include oxide (hematite, magnetite, rutile, spinel, uraninite), silicate (allanite, amphibole, epidote, garnet, titanite, tourmaline, vesuvianite, zircon), phosphate (apatite, monazite, xenotime) and sulphide (bismuthinite, cobaltite) minerals (Corriveau, 2007). To this effect, the mineral chemistry of iron oxides (magnetite and hematite) from a variety of deposit type environments has been characterized and an efficient and optimized electron microprobe analytical method that allows routine analysis of iron oxides has been developed (Gosselin et al., 2006). Discriminant diagrams such as the Ti/V vs Ti or the (Ni+Ca)/(Cr+Mn) vs Ti/V are efficient to distinguish iron oxides formed in polymetallic IOCG(U) deposits from those formed in Kiruna, porphyry Cu-Au, and Fe-Ti deposits. Similar investigations will be attempted on zircon following the outcomes of research on hydrothermal zircon by Bonnet et al. and Pelleter et al. (personal communications, 2007). Concurrently, we have initiated an orientation study around two known IOCG(U) deposits in the GBmz to characterize their indicator mineral and alteration geochemical signatures. Detailed sampling and chemical analysis of mineralization, host rocks and alteration zones was carried out to typify their mineral and whole-rock signatures and provide baseline data. In turn, these baseline data will be used to identify and characterize indicator minerals recovered from till samples collected around each deposit test site, to interpret regional geochemical surveys and to identify areas for more detailed drift sampling.

Geochemical profiling across alteration types

The ITRAX™ core scanner is a cutting-edge XRF instrument that provides in situ millimetre to micrometre-scale optical, radiographic and chemical mapping of major, trace, rare-earth (REE), platinum group (PGE) and high-field strength (HFSE) elements along rock cores and slabs. As a case study, we have obtained chemical concentration profiles every 500 microns with 30 seconds of analysis time, across pervasive hydrothermal alteration zones and veins from the Port Radium, Echo Bay, Fab and DeVries areas and the NICO deposit. Many elements analysed were abundant enough for their profile to be significant without detailed reprocessing. These include Si, S, Cl, K, Ca, Ti, Mn, Fe, Cu, Se, Rb, Sr, Zr, and Y. Checking of individual analysis confirmed the presence of Au, Pt, Bi and U where profiles display significant peaks. Reprocessing development to increase ability to analyze U is in progress. In contrast, Ni, Cr, V, As, Ba, Hg, Pb could not be distinguished easily from background. Finally, the abundance of K precluded the detection of Ag, though none of the samples could be shown to have any in the first place. This is the first application of the ITRAX™ core scanner for such complex material and already the potential in exploration is clear. Integrated to field relationships, the spatially detailed geochemical fingerprinting across alteration will provide a means of tracing chemical evolution of many detectable elements involved in IOCG(U) systems (excluding Na and F) from least to intensively altered rocks. Knowledge of when and where significant Cu, Au, U, PGE and other commodities appear in a system will enhance our ability to refine exploration criteria and metallogenic models for IOCG(U) deposits.

Hyperspectral signatures of alteration zones

Weathered surfaces of outcrops were sampled within each alteration zone and reflectance measurements collected between 400-2500nm with an Analytical Spectral Devices radiometer at a nominal spectral resolution of 3nm at 700nm, 10 nm at 1500 and 2100 nm. Though displaying variable amplitude, the spectra of each alteration type present common absorption features suggesting that each type can be represented by a unique signature. The potassic and sodic alteration show similar overall profiles but can be distinguished on the basis of the location of an hydroxyl feature (OH^-) near 2200nm. These results suggest a potential to remotely map the distribution of these alteration types using hyperspectral airborne or spaceborne imaging given sufficient spatial resolution. Hyperspectral imaging offers unique capability to identify and map surface minerals, potentially offering a means to map exposed alteration zones, gaussans, and bedrock geology over large expanses of the GBmz.

PRACTICAL FIELD GUIDES

The Port Radium – Echo Bay IOCG district offers cross-sectional exposures of IOCG(U) alteration across basal intrusions and overlying volcanic and sedimentary packages. An

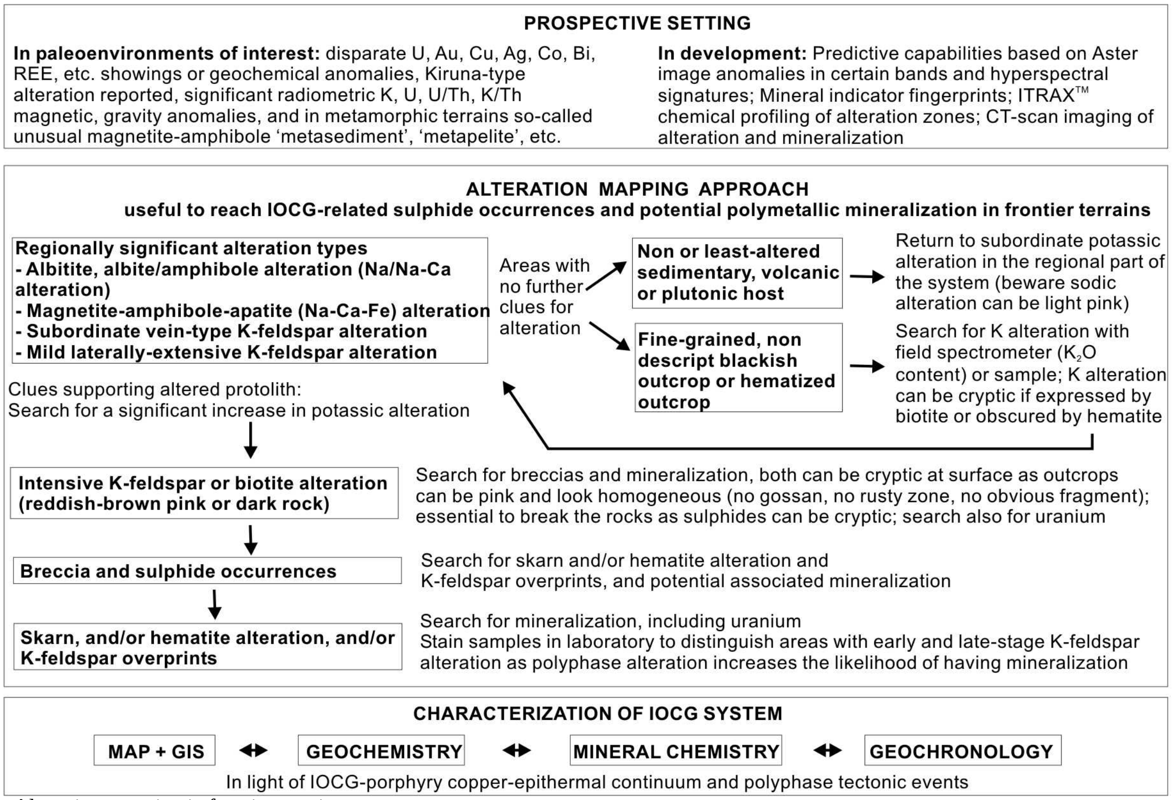

Figure 3: Alteration mapping in frontier terrains.

underground ramp at NICO provides an opportunity to "map processes" proximal to ore continuously. The DeVries Lake area provides insights on the importance of regional-scale fluid activities during the crustal and tectonic build up of the Wopmay orogen and, with the volcanic setting at Fab Lake, provide testing ground for the vectors developed from IOCG(U) deposits (Williams et al., 2005; Corriveau, 2007) and adapted for frontier terrains (Figure 3).

At regional scale, sodic and sodic-calcic-iron alteration zones (including albitites) develop distal to mineralization and most proximal to associated intrusive heat sources. Some also develop along fault zones (e.g., De Vries Lake SE). Subordinate vein-type or mild replacive-type potassic alteration is a common overprint. Where K-feldspar (or biotite) alteration becomes intensive (with magnetite and amphibole at first), brecciation and polymetallic sulphide enrichments generally follow. Such intense K alteration is in general peripheral to previous alteration. Locally, skarn-like, calc-silicate alteration may overprint early potassic alteration and is associated with several variations of igneous-hydrothermal mineralization. K-feldspar-bearing overprint may occur and can be particularly difficult to distinguish from early potassic alteration. Staining of rock slabs has proven a key tool in deciphering the presence, timing and overprinting relationships of K-feldspar alteration. Hematite alteration is late stage, either pervasive, disseminated or in veins. Alteration types that host uranium are characterized by distal hematite and/or quartz-carbonate-hematite, ± potassic-rich zones, however, the occurrence of uranium oxide minerals is not as predictable in the field as the sulphide ones.

CONCLUSION

Continuous and laterally extensive exposures across IOCG(U) deposit systems are required to refine vectors to mineralization at regional to deposit scale. Several reference, world-class, IOCG(U) deposits are hidden deposits where regional and deposit-scale knowledge is derived from drill core, open pits and underground workings. In the GBmz, IOCG(U)-related alteration is diagnostic and varied in types, laterally extensive to intensive, and texture-pseudomorphing to texture-destructive. Being widespread, well exposed from the deepest to the upper parts of the systems, it is an exceptional setting for study of the geochemical fingerprints and systematic evolution of IOCG(U) systems that lead to coherent overprinting relationships, lateral zonation, intense brecciation and mineralization. It is also a key area to establish a practical guide to geochemical and mineralogical exploration for IOCG(U) deposits in glaciated terrain through reference rock and mineral indicator databases, and geochemical criteria that contribute vectors to mineralization. These studies combined with the chemical profiling and hyperspectral analysis of the diagnostic alteration will catalyze the interpretation of archived till samples and geochemical surveys from potentially fertile granitic terrains and support the development of predictive capability in chemical vectoring to IOCG(U) mineralization for field and remote-predictive mapping and grass roots exploration. GIS analysis of existing till datasets, re-analyses of archived till samples, and targeted till sampling over known anomalies or potential

IOCG(U) prospects, using an integrated multi-disciplinary approach, has high potential for finding new prospects/deposits.

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