Petrological Mapping and Chemical Discrimination of Alteration Facies as Vectors to IOA, IOCG, and Affiliated Deposits within Laurentia and Beyond

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Abstract. Recent research on iron oxide and alkali-calcic alteration systems of the Great Bear magmatic zone, Romanet Horst, Central Mineral Belt, Bondy Gneiss Complex (Canada) and southeast Missouri (USA) districts highlights the potential for Laurentia to host undiscovered iron oxide-apatite (IOA), iron oxide copper–gold (IOCG), and affiliated deposits. The metasomatic footprints are vertically zoned from deeper Na (albite), through Ca-Fe (amphibole-magnetite-apatite), K-Fe (magnetite-biotite-K-feldspar to shallower hematite-sericite-chlorite-carbonate), and epithermal alteration facies. The facies can be discriminated by Na-Ca-Fe-K-Mg mineral assemblages and cation proportions, and from other ore systems by cation contents and Al-Si proportions. Each facies has distinct paragenetic, chemical, and geophysical characteristics and their metasomatic reaction paths vector to specific deposit types (IOA, IOCG, skarn, albitite-hosted U or Au-Co-U, and polymetallic vein deposits). Exploration in Laurentia can be focused by considering: (1) distribution of IOA, IOCG, and affiliated deposits in mineral belts up to 1500 km long; (2) pan-Laurentia distribution of fertile Paleoproterozoic and Mesoproterozoic terranes; and (3) diagnostic metasomatic signatures that can be used as vectors to ore.

Keywords. Iron oxide and alkali-calcic alteration facies, IOA, IOCG, albitites, mapping, discriminants, Laurentia.

1 Introduction

Exposed prograde, retrograde, telescoped, and cyclical metasomatic reaction paths of mineralized iron oxide and alkali-calcic alteration systems in the Great Bear magmatic zone (Canada)—as well as those from southeast Missouri (USA), Romanet Horst (Canada), and Central Mineral Belt (Canada)—provide evidences of genetic links among iron oxide copper–gold ± Co- and Bi-rich variants (IOCG), iron oxide–apatite ± REE-rich variants (IOA), albitite-hosted U or Au-Co-U, skarn, and polymetallic vein deposits. Recognition of such linkages emphasizes the potential in Laurentia to host additional deposits including high-grade metamorphic terranes (e.g., Kwyjibo, Bondy; Corriveau et al. 2007; Fig. 1). However, most prospective terranes of Laurentia remain under-explored, under-mapped, and under-valued, as are those of many terranes worldwide, (e.g., Bamble and Kangdian districts; Engvik et al. 2017; Zhao et al. 2013; Fig. 1). Herein we highlight the diagnostic geological and chemical attributes of iron oxide and alkali-calcic alteration facies, provide case examples, and describe alteration mapping protocols and chemical discrimination plots useful in exploring these ore systems.

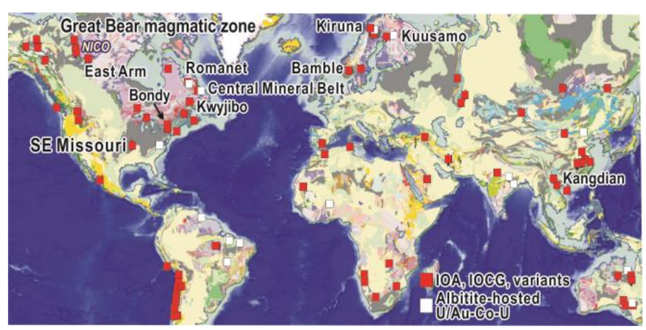

Figure 1. Location of districts and deposits discussed in text.

2 Regional Geological Contexts

The studied ore systems are spatially and temporally associated with, or developed within, mafic to felsic extrusive and intrusive rocks in the southeast Missouri district (~1.49–1.44 Ma), Great Bear magmatic zone (1.87–1.85 Ga), Central Mineral Belt (~1.88–1.85 Ga) and Bondy Gneiss complex (1.4–1.35 Ga). Some of these terranes have juvenile sources. In some examples, the regional-scale, iron oxide and alkali-calcic metasomatism was coeval with caldera formation; batholith emplacement followed a few million years later (Day et al. 2016; Montreuil et al. 2016). In another example, alkaline magmas intruded a carbonate-dominant sedimentary basin (Romanet Horst; Corriveau et al. 2014).

Mineral-resource-bearing metasomatic systems linked to voluminous granitic magmatism can extend a thousand km as part of continental magmatic arcs. Many of the associated magmatic systems are compositionally bimodal and many of the mafic end members have tholeiitic affinities. The felsic (and intermediate rocks where exposed or recognised) are dominantly calcalkaline to shoshonitic and A-type compositions (e.g., 1.87 Ga Great Bear magmatic zone; 1.47 Ga Missouri district and Pinwarian arc of Grenville Province; 1.16 Ga intrusive suites hosting Kwyjibo deposit; Corriveau et al. 2007; Montreuil et al. 2016; Day et al. 2017).

3 Alteration Attributes and Field Mapping

A great variety of mineral assemblages and contents, grain sizes, textures, structures, and space-time relationships of metasomatic rocks occurs at the deposit- to regional-scale and poses major challenges to alteration mapping. The morphology (replacements, veins, breccias) and extreme differences in paragenetic sets of altered rocks enable the documentation of a series of distinct alteration facies and their space-time relationships with magmatism and tectonics.

Intervening metasomatites between least- and most-altered sequences are used as proxies for the incremental progress of alteration. Alteration intensity is classified as subtle, weak, moderate, intense, or megascopically complete depending on the degree to which precursor minerals and textures are preserved, grain sizes of metasomatites, and spatial extent of the alteration zone (Fig. 2). Ultimately, paragenetic sets, rock physical properties, and compositions of each alteration facies are diagnostic due to the distinct cations of the dominant mineral phases in the paragenetic sets (Corriveau et al. 2010, 2016; Montreuil et al. 2013; Enkin et al. 2016). The predominant visible grain size of the metasomatites enables the use of a field-based compositional alteration nomenclature (i.e., Na, high temperature (HT) Ca-Fe, HT K-Fe, and low temperature (LT) K-Fe facies; Fig. 2).

Field mapping complexities are largely resolved by (1) focusing description on paragenetic sets and related metasomatic facies, (2) qualifying alteration intensity, reporting mineral assemblages and modes, standardizing terminology for veins, replacements and breccias, mapping crosscutting and overprinting relationships among alteration facies, and documenting alteration facies paragenetic affinities of mineralisation assemblages.

4 Alteration Facies as Vectors to Ore

4.1 Prograde metasomatic paths

The metasomatites and linked deposit types are zoned vertically and laterally, recording a regular sequence of fluid-rock reactions that led to prograde paths with Facies 1 Na (albite) transitioning to high temperature (HT) Na-Ca-Fe (albite, amphibole, magnetite, apatite); Facies 2 HT Ca-Fe (amphibole, magnetite, apatite) and IOA deposits; Facies 3 HT K-Fe (magnetite, biotite, K-feldspar) and magnetite group IOCG deposits; Facies 4 K-felsite (K-feldspar), K-skarn (clinopyroxene, garnet, K-feldspar), and polymetallic Pb-Zn-bearing deposits; Facies 5 low-temperature (LT) K-Fe (hematite, K-feldspar, sericite, chlorite, carbonates), hematite-group IOCG deposits and light REE-rich variants within LT Ca-Fe-Mg (chlorite, carbonates); and Facies 6 epithermal including vein-type mineral deposits. K-feldspar felsite breccias, not large-scale K-feldspar haloes, vector to IOCG mineralisation.

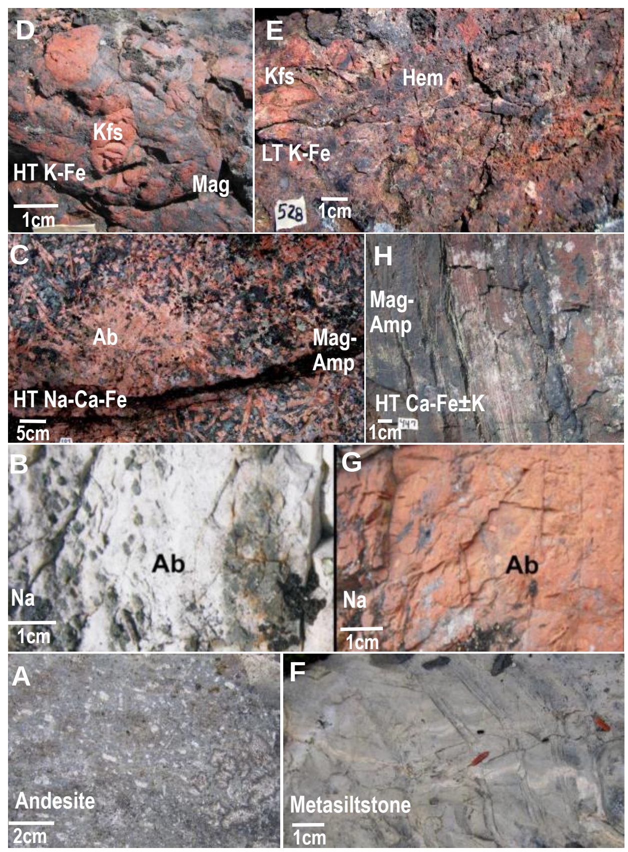

Figure 2. Great Bear ore systems. A-E. Altered andesite sequence. F-H. Altered sedimentary sequence at NICO deposit. Pink and white varieties of albitites (B and G) independent of protolith types. Ab, albite; Amp, amphibole; Hem, hematite; Kfs, K-feldspar; Mag, magnetite.

In carbonate-rich host rocks, skarns (typically clinopyroxene and garnet) form coevally with or slightly after albitites and are locally replaced by HT Ca-Fe alteration mineral assemblages. These skarns, as well as the presence of carbonate alteration zones provide evidence that fluids in these systems can generate their own skarn mineral assemblages without a proximal intrusion. A regular spatial and temporal progression is also observed among brecciation, polymetallic mineralization, and the appearance and increasing intensity of K-Fe alteration facies. Co-crystallisation of iron oxide minerals and K-feldspar is, however, megascopically decoupled. Iron oxide minerals are concentrated within the matrix and K-feldspar replaces host protolith and derived fragments in breccias (Fig. 2D, E). Rocks of the HT Ca-Fe alteration facies commonly undergo ductile deformation during metasomatism; other alteration facies experience brittle to brittle-ductile deformation.

4.2 Telescoped, cyclical, and retrograde paths

Where exposed (e.g., Great Bear), the IOA deposits are deeper expressions of cogenetic IOCG mineralisation, but fluidised-type IOA breccias also point to the ability of magnetite-apatite mush to ascend to higher structural levels. Fluidisation of HT K-Fe metasomatites also occurs. Faulting can telescope albitites into levels where fluids precipitates U (HT and LT K-Fe fields) (Corriveau et al. 2014; Montreuil et al. 2015); younger REE-rich breccias can form through remobilisation of IOA deposits (Harlov et al. 2016). Epithermal veins also form within earlier alteration facies during retrograde alteration. Cyclical development of a fertile alteration facies can increase local metal endowment (e.g., 33 Mt Au-Co-Bi NICO deposit; Fig. 1). Collectively, metal enrichment in these ore systems includes ferrous, base (Fe, Cu, Pb, Zn, Ni), precious (Au, Ag, PGE), specialized (Bi, Co, Mo, V, Nb, Ta, W, HREE, LREE), and actinide (U, Th) metals.

4.3 Exploration and mapping challenges

Metasomatised rocks can resemble common rocks; this can hamper recognition of ore systems. Exemples include: (1) albitites for hornfels, K-feldspar- and hematite-altered or silicified zones, anorthosites, rhyolites, and syenites (Fig. 2B, G); (2) Na-Ca-Fe facies for igneous pegmatites (Fig. 2C); (3) un-metamorphosed HT Ca-Fe or LT K-Fe metasomatites for iron formations, metasedimentary rocks, marls, iron oxide lavas, and amphibolites (Fig. 2H); and (4) K-feldspar alteration for rhyolites or albitites, commonly masking the andesite protoliths (Montreuil et al. 2016). Syn-alteration ductile deformation of HT Ca-Fe metasomatites increases their resemblance with metamorphic rocks, and may lead to misinterpretation of syn- or post-metasomatic regional orogenic metamorphism. Selective K-feldspar or magnetite replacement of breccia fragments can mask the timing of brecciation versus alteration and obscure the nature of protoliths (Fig. 2D, E).

Another challenge is the non-recognition of IOA-IOCG systems and metasomatic linkages among deposits, which can result in the deposits being misclassified, such as: (1) iron formation; (2) VMS; (3) SEDEX; (4) intrusion-related skarns and polymetallic mineralization; (5) diagenetic, metasomatic-metamorphic, sedimentary, magmatic, hydrothermal, shear-hosted, unconformity-type, and stratiform U; (6) polymetallic veins; and (7) syngenetic/diagenetic stratiform Cu, red bed Cu, etc. (e.g., Potter et al. 2013; Slack 2013; Corriveau et al. 2014; Engvik et al. 2017; Sparkes 2017 and references therein).

4.4 Chemical mapping

By recognizing metasomatites and recording their mineral assemblages, paragenesis, and spatial distribution, it is possible to map the principal cation mobility across ore environments, from fluid and metal sources to deposits (Corriveau et al. 2016). Geochemical data refine the major-element mobility interpreted megascopically. Efficient whole-rock molar proportions allow mapping alteration footprints from the regional to the drill core scale. Such maps can efficiently guide exploration (Fig. 3).

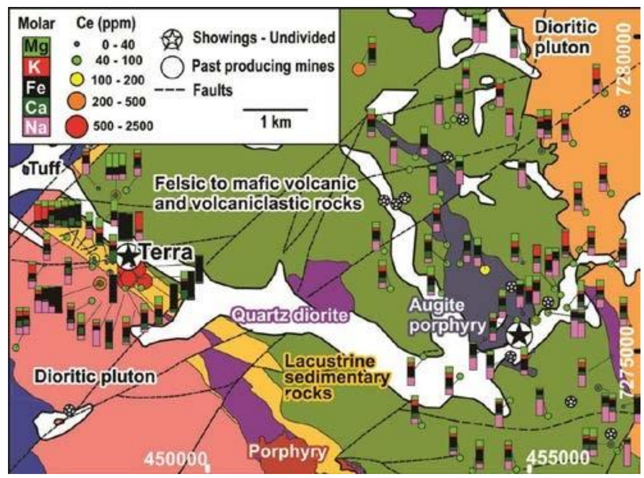

Figure 3. Chemical alteration map at Terra, northern Great Bear magmatic zone. Chemical data from Corriveau et al. (2015).

5 Chemical Discriminants of Prograde and Telescoped Reaction Paths

The chemical evolution of these systems can be visualised by plotting the element bar codes on the IOCG geochemical alteration discrimination diagram of Montreuil et al. (2013) (Fig. 4A) and those of Large et al. (2001) and Williams and Davidson (2004). The bar code signatures of megascopically and chemically least-altered igneous and sedimentary rocks (Fig. 4B) can also be discriminated from the mixed signatures induced by superposition of alteration types (Fig. 4C) during prograde, telescoped, and/or retrograde metasomatic paths.

Prograde metasomatism results in a counter-clockwise trend (Fig. 4A). These metasomatites with a single alteration type display bar codes dominated by one or two elements; least-altered bar codes have more even cation proportions. Replacement of early metasomatites by other alteration facies (e.g., telescoped or retrograde paths) recombines elements and leads to compositions that occupy the least-altered field (Fig. 4C). Bar codes are however distinct from those of the least-altered rocks (Fig. 4B versus C).

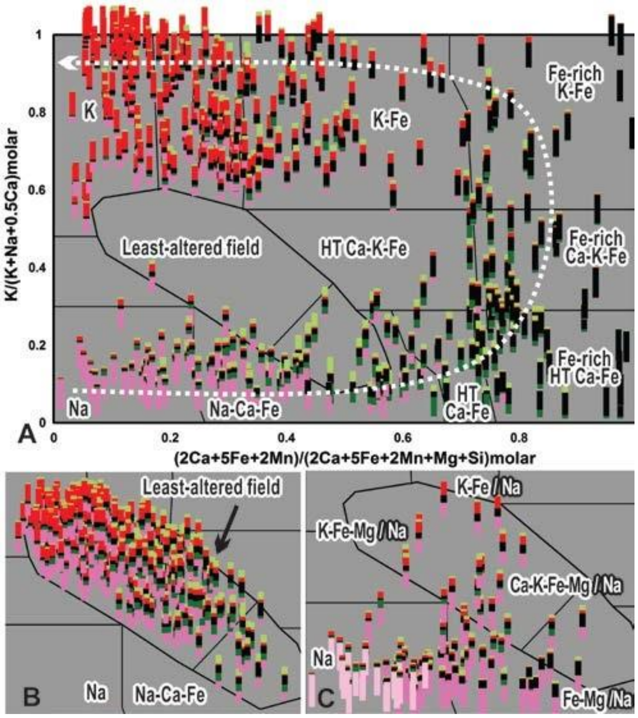

Figure 4. Plot of Na-Ca-Fe-K-Mg bar codes on IOCG discriminant diagram of Montreuil et al. (2013) for Great Bear magmatic zone; chemical data from Corriveau et al. (2015). A. Prograde path of alteration facies. B. Felsic to mafic protoliths. C. Replacement of original albitites (light pink) by other alteration facies leading to alteration trends toward least-altered field.

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