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GEOLOGICAL SURVEY OF CANADA
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Targeted Geoscience Initiative
2016 Report of Activities

N. Rogers (ed.)

2017

Celebrating 175 yrs

Canada



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Targeted Geoscience Initiative
2016 Report of Activities

Edited and compiled by
Neil Rogers

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Targeted Geoscience Initiative: 2016 Report of Activities – An Overview

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Introduction

The Targeted Geoscience Initiative (TGI) is a Government of Canada led, collaborative geoscience research program directed towards providing next generation knowledge and methods that will facilitate more effective targeting of buried mineral deposits (Fig. 1). The objective of the program is to improve the effectiveness of exploration for Canada's major mineral systems by resolving foundational geoscience problems to constrain the geological processes that liberate metals from their source region, transport these ore metals and control their eventual deposition. In the course of this research TGI will mentor and assist in the training of students who will become the next generation of highly qualified personnel available to the mineral exploration industry.

TGI uses a thematic, ore system approach (Fig. 2). In this context, an "ore system" is defined as: "A mineralized system, across a range of scales, which culminates in a group of related deposits that share common genetic and geologic characteristics. At the large scale, the ore system is defined by the geodynamic and tectonic setting that created the set of conditions which, at the smaller scale, resulted in ore deposition. Ore deposits comprising an ore system can differ in style, position in the crust and timing, but share common causative ore-forming processes and controlling parameters." This definition varies to some extent from Wyborn et al.'s (1994) original definition of "mineral systems", as it considers the entire process chain (Fig. 2). It is worth noting the correspondence to the older, but largely overlapping concept of metallogeny that is defined in Neuendorf et al. (2005) as: "the study of the genesis of mineral deposits, with emphasis on their relationship in space and time to regional petrographic and tectonic features of the Earth's crust."

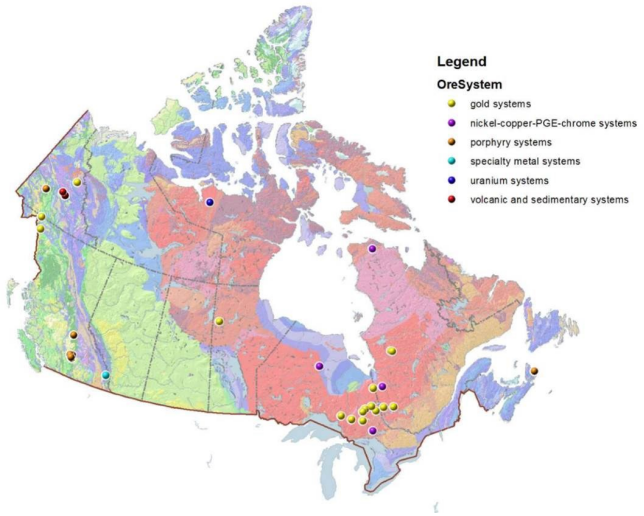


Figure 1 – Distribution of field studies undertaken in 2016. Geology after Barton et al. (2003).

For the TGI program, four aspects of the the ore system concept are more specifically addressed, namely: what terrane, region or geological/tectonic setting to look in; where to look in a specific terrane, region or geological/tectonic setting; how to vector towards mineralized rocks; and detection methods.

The principal questions when determining what terrane to look in are related to tectonic setting and temporal extent, and may include:

- What are the optimal tectonic settings for a particular deposit type?
- How do we recognize these settings?
- Is this deposit type unique to one location and/or time period?

For the second part of where in a terrane to look, then questions are based around lithologic and structural controls, such as:

- Are there optimal rock associations for a particular ore environment?
- Are there regional-scale structural controls that focus the ore system?

The third part of the ore system concept in the TGI context is related to vectoring towards ore, which breaks down the individual component parts of how an ore deposit is formed. These components are examined to determine whether there are distinctive features that can characterize the potential of, or

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TGI 5 (2015-2020)

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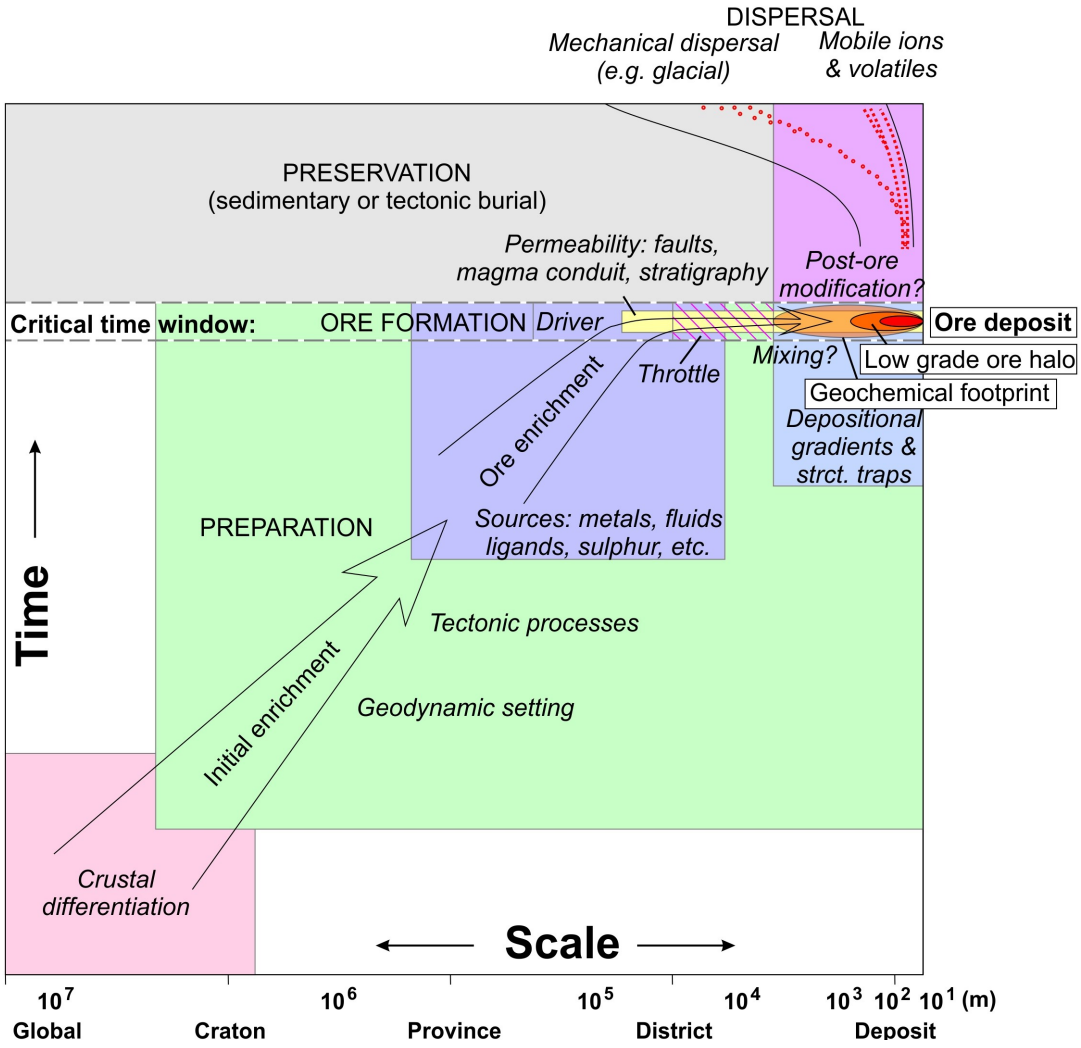


Figure 2 – Time vs. scale diagram illustrating the concept of complex mineral systems culminating in an economic ore deposit (small red ellipse). The existence of an ore deposit accessible to mining typically involves initial preparatory processes, several critically linked ore formation processes, and finally preservation. These linked processes occur across a vast range of scales. Initially, large-scale geodynamic and tectonic processes concentrate elements of interest into a regional- to district-scale source region, from which they are stripped by hydrothermal fluids or magmas. Faults or other permeable zones then focus fluids or magmas into depositional environments where chemical, physical or thermal gradients cause ore deposition. After passing through the depositional environment, spent fluids disperse into the environment. Many of these processes leave forensic evidence, such as hydrothermal alteration, that can be used to locate mineral deposits and their larger geochemical "footprints". Post-depositional dispersal of ore constituents or "pathfinder" elements, whether by chemical or mechanical means, may enlarge the scale of the exploration target. Modified from Huston et al. (2012).

provide directional information to ore. In general the component parts for ore development are as follows:

- Extraction from source – What is the energy driving the system? What are the sources of metals, fluids and ligands?
- Migration to trap – How are fluids focussed? What is the nature and extent of fluid pathways?
- Formation of trap – What is the trapping mechanism for metal-bearing fluids/magmas? Under what conditions do these traps form?
- Deposition of metal – What conditions are necessary for metal precipitation? Are multiple events required to develop ore grade materials?
- Secondary processes – Is post-deposition remobilization of ore essential in forming economically significant deposits?

The final part of the ore system concept relates to detection methods and techniques, which looks at how improved knowledge on ore-forming processes can be adapted into enhanced exploration tools and models.

The thematic, ore systems approach to research program design enables TGI to conduct its research on the best-suited areas, districts and deposits from across Canada (Fig. 1) to support, develop and test next generational geoscience knowledge. TGI supports projects on gold, Ni-Cr-PGE, porphyry-style

mineralization, uranium and volcanic- and sedimentary-hosted base metal mineralization ore systems, with each project divided into subprojects focussed on resolving specific knowledge gaps by integrating data and studies from multiple sites across Canada.

Gold project

Several gold discoveries were recently made in Canada, both in mature and emerging districts. The detailed documentation of many of these discoveries has categorised them as geologically atypical or unique. This has broadened the diversity of auriferous ore styles and highlights a previously underestimated potential for certain areas or geological settings. However, even within established Canadian gold districts, many knowledge gaps remain, particularly in relation to the source of gold, ore transportation mechanisms, concentration processes and the overall distribution of gold deposits. The objective of the Gold project is to identify factors that control or influence the heterogeneous distribution of gold resources through space and time, allowing us to tackle fundamental aspects of ore genesis and optimise exploration models by improving their predictive capacity. Solving crucial issues in understanding ore-forming processes at the ore system scale necessitates a multi-scale (craton to ore zone), multi-disciplinary and collaborative approach.

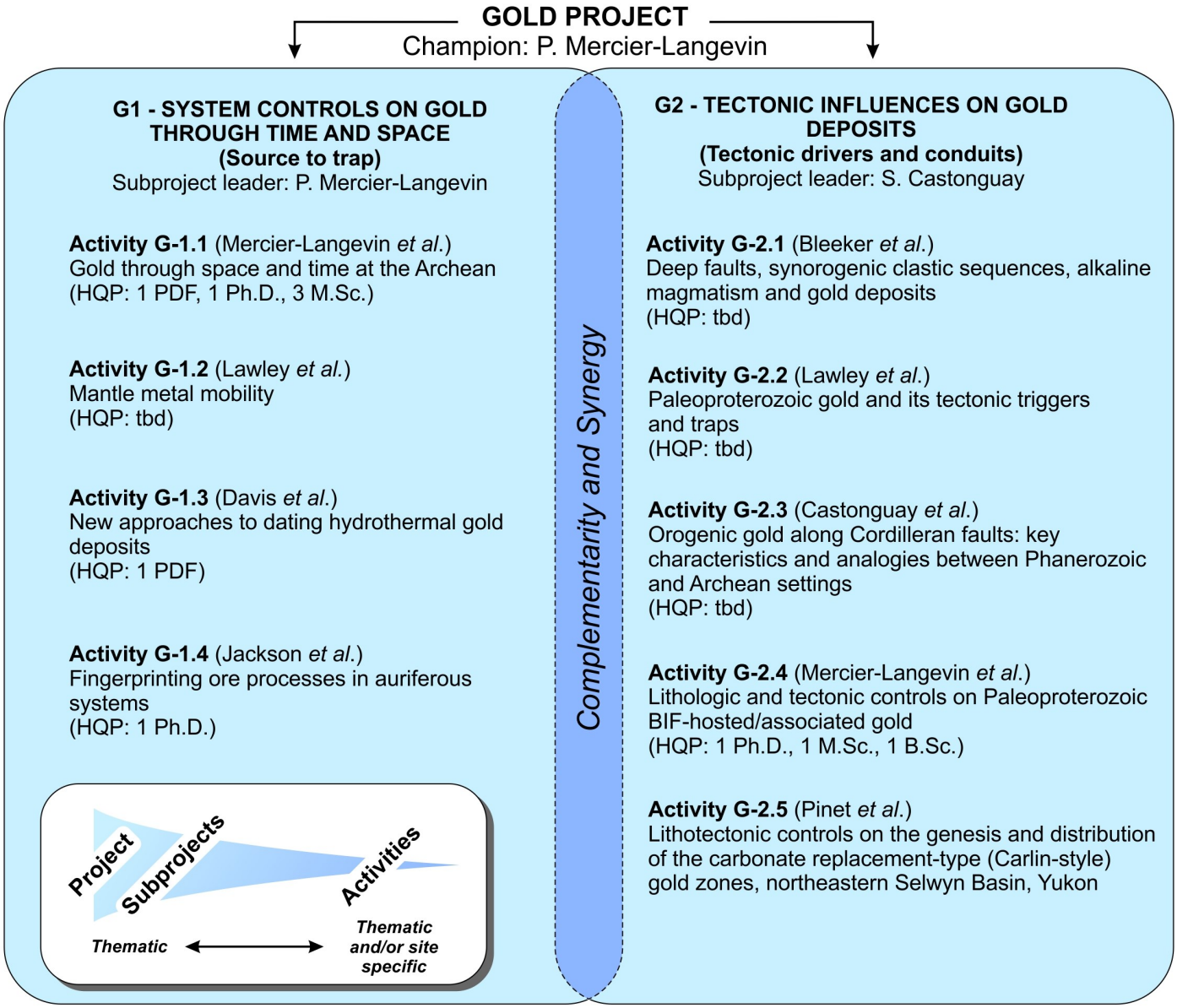


Figure 3 – Schematic diagram showing the structure of the Gold project with its two subprojects and nine activities. HQP = Highly qualified personnel, tbd = to be determined. Reported HQP as of December 2016, more will be added in 2017. Modified from Mercier-Langevin et al. (2016).

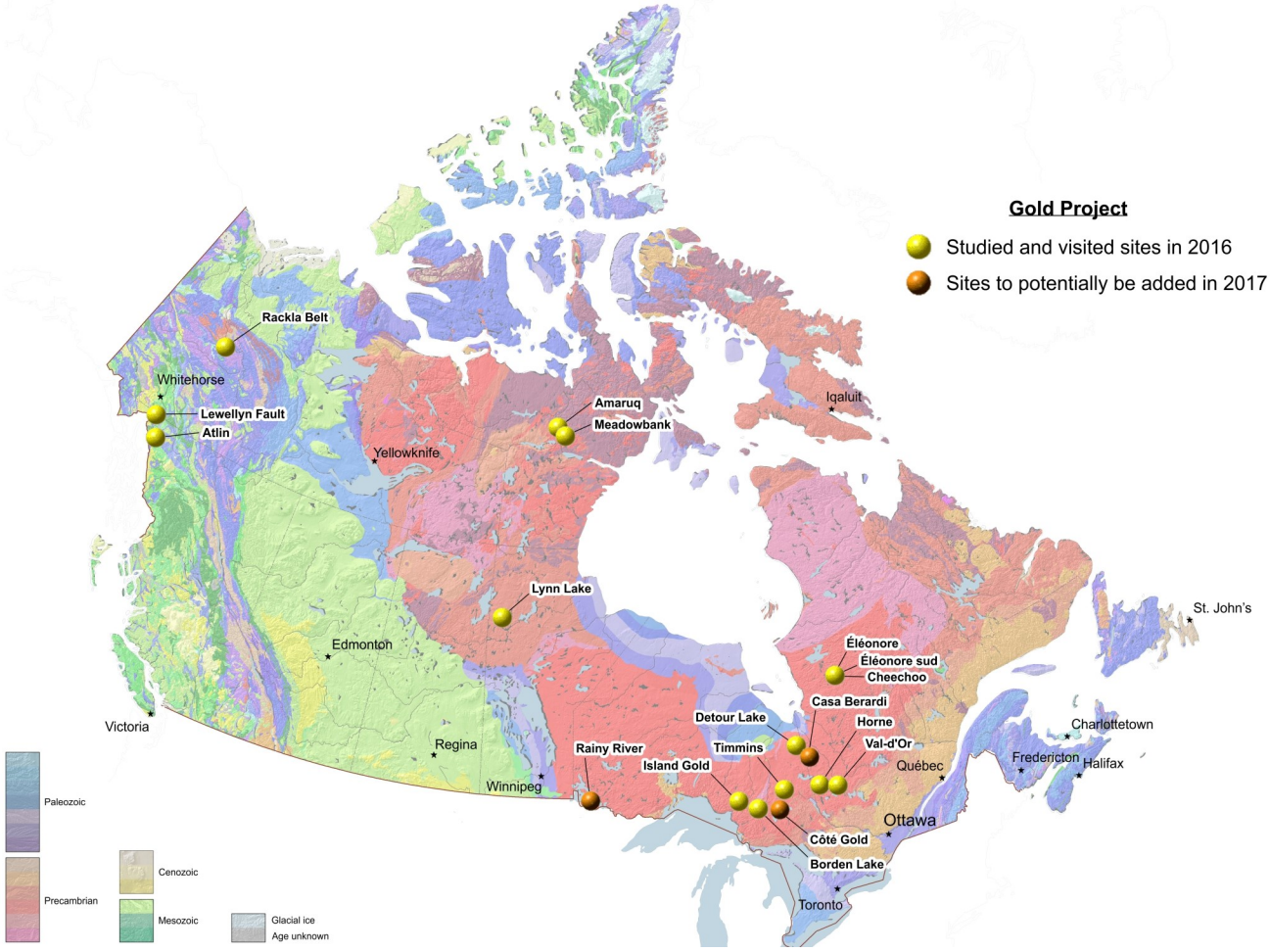


Figure 4 – Location map of the principal study sites of the Gold project for 2016, and preliminary sites to be added in 2017. Geology after Barton et al. (2003).

Two complementary research themes define the Gold project: 1) System controls on gold through space and time (source to trap); and 2) Tectonic influences on gold (tectonic drivers and conduits). These two subprojects are complementary and divided into a series of thematic and/or regional activities (Fig. 3) in many of the gold-bearing Canadian geological provinces (Fig. 4).

Subproject 1: System controls on gold through space and time (source to trap)

Summary

The formation and localization of major gold deposits and districts are linked to the secular evolution of the Earth through time and space and/or supercontinents cycles (Barley and Groves, 1992). In Canada, the Archean, particularly the Neoarchean, is spectacularly endowed in gold. Numerous giant orogenic gold deposits and districts were formed during that period, in addition to a number of major gold deposits of varying types that, in some cases, resulted from polyphase mineralization (see Dubé and Mercier-Langevin, 2015, and references therein). The precise reasons for such a major endowment remain largely enigmatic and proposed explanations are, for the most part, speculative. Among the proposed controls of gold in the Neoarchean are fertile upper mantle-lower crustal source (s), enriched upper crustal units, and the presence of crustal-scale faults and/or terrane boundaries as favourable conduits allowing for repeated tapping of the same enriched source regions (e.g., Barley and Groves, 1992; Sillitoe, 2008; Dubé and Mercier-Langevin, 2015). To balance data and conceptual aspects, activities forming this subproject aim at establishing the mechanism that control the endowment of a district and/or orebody, largely based on an appraisal of the multi-scale geologic characteristics of gold mineralization in regions known to be gold-rich and comparing those with regions with similar characteristics but lesser known gold endowment.

The southern Superior craton represents a key, data- and knowledge-rich area that allows us to tackle such fundamental aspects of gold metallogenesis, and permits a comparison between areas known to be extremely fertile and other areas in the Superior craton and elsewhere that are apparently less fertile. Importantly, comparative/correlative studies in other geological provinces across Canada are being conducted as part of the broader Gold project. Many of these research activities

emphasize district-scale features since this represents an important knowledge gap for the mineral exploration industry. Subproject 1 comprises four activities that are summarized in Davis et al. (2017), Jackson et al. (2017), Lawley et al. (2017a), and Mercier-Langevin et al. (2017b).

Rationale

Activities in this subproject aim at defining controls of ore formation mainly based on: 1) the characterization of unusual, important and/or newly discovered mineralization styles that are fundamental to finding or expanding ore bodies and to continuously improving exploration and geological models at various scales; and 2) a review of the multiscale geologic characteristics of gold mineralization in well-endowed regions and/or areas that represent exceptional opportunities to study processes relevant to gold deposit genesis in poorly endowed terranes. The focus is on potential source(s) and processes at depositional sites (the conduits will be more specifically studied in the second subproject). Whether the largest gold districts are related to particularly enriched source region, unusual gold-rich hydrothermal fluids and/or favourable host rocks/successions remains unclear. Synthetizing available data and comparing established and emerging districts will provide basic, but critical, information on the geologic setting and evolution of the most prolific periods/areas for gold mineralization. Much of the necessary information is already available, especially for the Superior Province and adjoining areas, providing an opportunity to integrate it into a comprehensive, multidisciplinary framework and re-analyze it in the perspective of understanding metallogenic provinces and revise/update key metallotects. These data must be distilled into knowledge that the industry can use to improve predictive models and detection techniques for district-scale exploration. Finding the next generation of gold deposits is a priority, but also a great geological challenge for industry. Therefore a special emphasis is put on ore-associated features that are relevant at district scale to help fill that knowledge gap and thus aid exploration.

Subproject 2: Tectonic influences on gold (tectonic drivers and conduits)

Summary

The lack of multi-disciplinary understanding of the major fault zones, terrane boundaries and tectono-metamorphic discontinuities in the best endowed metallogenic provinces of Canada hinders efficient large-scale mineral deposit targeting. A number of such ore-associated, long-lived structures have been studied in detail, but many still need to be investigated to better map out their extent, their kinematic history and critical role in the formation (and preservation) of ore deposits. For example, there are apparent predictable relationships between deep-reaching (first-order) faults with an early extensional history, preserved panels of synorogenic clastic sequences, synorogenic (alkaline) magmatism, and orogenic gold deposits in a number of major Precambrian gold districts (Bleeker, 2015). Crustal-scale faults may also be characterized by thermal signatures that are potentially related to the metal budget or fertility. A proper characterization of thermal signatures of major faults and their timing can provide new vectoring and fertility assessment tools for exploration.

This subproject on the tectonic influences on gold consists of an analysis of the nature and evolution of major ore-associated structures in selected districts. The subproject includes thematic and targeted studies on the overall evolution of major gold-bearing fault/structures and how they relate to gold systems. The proposed subproject directly contributes to the project objectives, primarily through the study of the nature and geometry of the conduits and traps, and of the tectonic drivers essential to forming major gold deposits and districts. Subproject 2 comprises five activities that are summarized in Bleeker et al. (2017), Castonguay et al. (2017), Lawley et al. (2017b), Mercier-Langevin et al. (2017b), and Pinet et al. (2017).

Rationale

This subproject specifically tackles fertile faults and/or terrane boundaries by documenting their evolution and significance in the genesis and preservation of gold deposits, primarily through the synthesis and analysis of data and information related to their evolution, age, and kinematics, with an emphasis on the southern Superior Province. Comparison of such features with those of similar gold districts in other tectonic domains (e.g., Trans-Hudson orogen, Canadian Cordillera, Appalachians, etc.) will allow us to draw analogies and test the importance ore-forming processes. Such studies on the geometry and evolution of ore-associated structures are essential for establishing predictive criteria and defining better detection methods.

Ni-Cr-PGE systems project

Magmatic ore deposits of Ni-Cu-PGEs, Cr, and Fe-Ti-V represent an important class of mineral deposits across Canada, forming the backbone to a number of established and emerging mining camps (e.g., Thompson, Raglan, Sudbury, Voisey's Bay, Mid-Continent Rift (MCR) and Ring of Fire). They are the product of magmatic ore systems, ultimately fuelled by large volumes of deep-seated magma derived from Earth's mantle. Thus, they are an integral component of larger magmatic systems, also known as "igneous provinces", or at the largest scale "large igneous provinces" (LIPs). Within these larger magmatic systems, the majority of mineral deposits form near the magmatic centre of the system, often in clusters, where magma fluxes are highest and more focussed, and the geological conditions are more dynamic (e.g., rifting, upwelling mantle, trans-lithospheric faults, active magma conduits). The final character of the mineral deposits, enrichment of specific metals, grade and size depend on magma composition, magma flux, nature of the wall rock and efficiency of the trapping mechanism, along with numerous other local variables and conditions. Sudbury is both exceptional and unique, in the sense that the large magma pool and the conditions for efficient metal segregation were created not by endogenic processes, but by a large meteorite impact and a superheated melt-sheet.

An in-depth understanding of this class of deposits, and improved, accurate and more predictive models for their formation and localization require a system-wide comprehension of the magmatic systems at the true system scale. Areas of study include: the magma source and its composition (source and its fertility); melting processes; what was the magmatic

plumbing system (conduits); where were the highest fluxes; where and how were metals concentrated (traps); sulphur sources and timing of sulphide saturation; local and regional stratigraphic controls; and which specific magmatic pulses were most productive, and what were their specific tectonic drivers or triggers?

This project significantly advances the knowledge of this ore system, by integrating data from the deposit scale to the full magmatic system scale. Numerous incremental advances have been made in recent years, but rarely have they been fully integrated. Only a national project of the scope of TGI, and executed by collaborative teams, is able to make this critical advance in established and emerging camps and across the country.

Subproject 1: System scale and deposit scale controls on Ni-Cu-PGE mineralization in cratonic areas and their margins

This subproject aims to develop integrated models of key magmatic provinces across Canada, from the magmatic conduit and deposit scale to the full system scale, allowing for more efficient and accurate regional targeting of areas with the highest mineral potential (e.g., Circum-Superior, i.e. Thompson and Raglan, Trans-Hudson Orogen; Ring of Fire, Superior craton; MCR; Cordillera). A lot of relevant data already exists and is being integrated with new data (e.g., high-precision geochronology, new sequence stratigraphy, detailed cross-sections through deposits) into complete system-scale models. This directly addresses the localization and evolution of key magmatic sources, conduits and traps. At a more local scale, but within the context of a system-wide understanding, this subproject investigates models of magma conduits and ore traps, with the intention of predicting deeper extensions to known ore bodies (e.g., Sudbury, Thompson, Raglan, Ring of Fire).

Subproject 2: Magmatic architecture of Cr-bearing ore systems

The discovery of world-class Cr-(PGE) deposits, a major Ni-Cu-(PGE) deposit, and numerous significant Fe-Ti-(V) occurrences in the McFaulds Lake greenstone belt (MLGB; also known as the "Ring of Fire") of northern Ontario has greatly renewed interest in orthomagmatic mineralization associated with mafic-ultramafic intrusions in the Superior craton, and in particular a new metallogenic province referred to as the BUOGE (Bird River – Uchi – Oxford – Stull – LaGrande – Eastmain: Houlé et al., 2015). This metallogenic province is characterized by the presence of major Cr-(PGE) with Ni-Cu-(PGE) and Fe-Ti-(V) metal associations which appear to be fundamentally different from other parts of the craton, such as the Abitibi greenstone belt. However, the main geological criteria that control these variations in metal endowment at various scales (regional- to district-, and to deposit-scale) are poorly understood. This subproject primarily addresses the secular and episodic evolution that led to clustering of beneficial conditions within these metallogenic provinces, but also identifies the most favourable conditions throughout the magmatic architecture (intrusive-subvolcanic-extrusive) of these mafic-ultramafic ore systems, from the magma conduits to the depositional sites (traps), to host significant Cr-(PGE), Ni-Cu-(PGE), and Fe-Ti-V orthomagmatic deposits.

Fully integrated with the Ni-Cu-(PGE) subproject, this more Cr-focused subproject aims at developing an integrated model of a key magmatic province across the northern Superior craton. Key question are: what localised the ore-bearing intrusions from Manitoba's Bird River belt, to the Ring of Fire of northern Ontario, and the La Grande domain of northern Québec?; and do these intrusions form a single metallogenic domain or province (i.e., BUOGE)? At a more local scale, subproject activities will develop detailed models of magma conduits and ore traps.

Porphyry-style mineral systems project

Within porphyry systems, the two extremities of the ore-forming process are the focus of the greatest current knowledge gaps. How, when and why do parental magmas gain sufficient metals to produce world-class, supergiant metal deposits, and how, when and where are metals deposited into economic ore concentrations?

Porphyry-related mineralization dominantly occurs at convergent plate margins, either during active subduction and accretionary orogenesis, or as a consequence of post-orogenic plutonic magmatism. Magmatism within convergent margins is inherently evolutionary and episodic in nature. Consequently, regional metal distribution is heterogeneous in both space and time. Work conducted under this project will strive to elucidate porphyry-related processes at all scales which determine the fertility of primary magmas, and that concentrate metals within the mid- to-upper crust.

The mineral markers subproject's focus is on unlocking information stored within the chemistry and mineralogy of silicate and sulphide minerals to study questions pertinent to specific processes operating at discrete points within the evolution of porphyry ore-forming systems. In contrast, the arc-related porphyry and post-orogenic porphyry' subprojects seek to interrogate the secular evolution and fundamental systemic controls on the location and characteristics of porphyry-related mineralization within accretionary orogenic and post-orogenic settings, utilizing Canada's Cordilleran and Appalachian type locations as ideal natural laboratories to study fundamental processes.

Although the immediate sources of metals within any porphyry-related deposit are widely recognized as being the parent magmas, the mechanisms by which the magma itself becomes enriched (if they are) are uncertain. By better constraining the critical processes that localise metal enrichment within an evolving arc or post- orogenic magmatic system, those critical periods in space and time can be preferentially targeted during future exploration, reducing the time and expense lost in the investigation of unprospective systems.

Subproject 1: Arc-related porphyry mineralization in space and time

Magmatism within convergent margins is inherently evolutionary and episodic in nature. Consequently, regional metal distribution is heterogeneous in both space and time. Work conducted in this subproject elucidates porphyry-related processes at all scales which determine the fertility of primary magmas, and that concentrate metals within the mid- to-upper

crust, as a function of the secular and spatial evolution of an actively subducting margin and an active ore-forming environment. Steady-state subduction magmatism does not produce significant porphyry-related mineralization. Recent models suggest instead that localised and/or transient modification, disruption and evolution of the subduction process are essential to form giant metal concentrations. Understanding these perturbations and preconditioning processes will allow future exploration to be targeted toward districts that display characteristics consistent with favourable tectonomagmatic conditions for significant economic porphyry mineralization. Within a porphyry system, these macro-scale controls may be manifest as a sequence of overprinting events, which evolve through space and time. Although much is understood about the major phase of mineralization within stockwork systems, earlier phases and phases occurring at deeper levels within a system, that may be subject to ductile deformation regimes and substantially contrasting physicochemical conditions, are not well understood at the present.

This subproject encompasses a variety of activities that collectively allow detailed investigation of the four-dimensional evolution of mineralization within the Canadian Cordillera. The backbone of the subproject will be a porphyry deposit databases that can be manipulated and queried to test deposit models and genetic hypotheses. Key geodynamic genetic controls are being investigated at an orogen-wide scale through symbiotic activities that will probe the underlying lithospheric mantle, effusive magmatic systems, and depositional controls active before and during the key porphyry forming events.

Given the episodic and evolutionary nature of magmatism at convergent plate margins, and consequent spatial and temporal heterogeneity of regional metal endowment, identification of patterns in distribution and recognition of the primary controls on the location and mechanisms for mineral deposit formation are key to successful exploration in both brownfield and greenfield settings. This subproject will identify localised and/or transient modification, disruption and evolution of the subduction and resultant magmatic-hydrothermal processes essential to form giant metal concentrations. A more fulsome appreciation of how these perturbations and preconditioning processes have influenced the formation of known deposits will allow future exploration to be targeted more accurately toward those districts that display characteristics consistent with favourable tectonomagmatic conditions for significant economic porphyry mineralization.

Subproject 2: Post-orogenic porphyry systems in space and time

Granitoid magmatism is a common occurrence within the post-orogenic phase of an accretionary orogenic system. Within orogenic belts having protracted histories and multiple accretionary episodes, granitoid bodies can be generated in several distinct pulses. However, despite sharing compositional characteristics and genetic models, only select temporal and spatial subsets are associated with significant polymetallic, porphyry-style mineralization. This subproject is centred on the development of an integrated model for observed spatial and temporal metallogenic events within the overall orogenic framework, with the objective of isolating which characteristics are predictive of ore distribution.

Coupled studies of ore mineral chemistry and geochronology, integrated with petrogenetic studies of the fundamental crustal and mantle affinities of parental igneous bodies, will constrain the critical processes that localise metal enrichment within post-orogenic magmatic systems. Results will include detailed age constraints on major accretionary structures, magmatic events and associated polymetallic mineralization, as well as an evaluation of whether reactivation of terrane bounding structures influences the timing of mineralization. These data are intended to enable predictive model development by resolving which large-scale tectonic events are the drivers behind polymetallic porphyry-style mineralization, as opposed to the more common barren granitoid intrusions. Such knowledge should enable more efficient exploration through targeting of prospective temporal and spatial windows within an orogen.

Subproject 3: Mineral markers of porphyry processes

The intension of this subproject is to unlock the information stored within the chemistry and mineralogy of silicate, oxide and sulphide minerals as a means to interrogate specific processes operating at discrete points within the evolution of porphyry ore-forming systems. By studying a broad suite of porphyry-related mineral species (sulphide, silicate and non-silicate) sampled at all stages within an ore-forming system, both upstream and downstream of the metal trap, compositional and geochemical gradients will be identified that reflect the influence of critical processes that governed source fertility, fluid transport, trapping efficiency and localization of economic mineralization. Knowledge, characterization and classification of these markers will enable future exploration to be conducted even in those areas where mineralized bodies are blind, will permit rapid identification of prospective and barren systems, and will help to improve the effectiveness and efficiency of exploration in identified mineral systems.

Uranium-rich ore systems project

Canada is the world's second largest uranium producer and with demand projected to increase, new exploration models are required to facilitate growth. To this end, the uranium project will focus on: 1) the main unresolved factors controlling high grade, large tonnage unconformity-related ore bodies, such as the Athabasca Basin as these deposits represent Canada's main focus for exploration; and 2) sources and processes of uranium enrichment in iron oxide-copper-gold (IOCG) deposits and iron oxide-alkali altered (IOAA) systems, as little is known about these processes despite potentially large recoverable resources in these deposits.

Unconformity-related uranium deposits are spatially associated with structural trends and/or intersections of crustal-scale faults considered as the main fluid conduits during uranium deposit formation. Identifying novel indicators for fertile faults that host unconformity-related uranium deposits using non-traditional isotopes and geophysics to evaluate geochemical, isotopic and mineralogical signatures, to examine the role of long-lived reactivation of crustal-scale faults, and to quantify ore-related demagnetization and alteration along these faults is the focus of the uranium fluid pathways subproject. The sub-

project will also evaluate the role of marine brines in the formation of uranium deposits, as recent studies suggest that marine brines play a critical role in the scavenging metals from source rocks and their efficient transport to form giant uranium deposits (e.g., Athabasca Basin; Olympic Dam IOCG).

A second subproject, uranium-rich deep metasomatic processes, is designed to address the sources and processes of uranium enrichment in IOCG deposits and the broader IOAA systems that host these deposits, by evaluating the spatial and temporal fluid-metal evolution of these metasomatic systems. An examination of a spectrum of mineral occurrences and alteration from deep high-temperature to shallower low-temperature environments in a system is required to track the evolution, with a goal of refining the genetic model for metal/fluid sources, fluid pathways and ore formation through primary to remobilised ores.

Subproject 1: Uranium Fluid Pathways

This subproject focus is on developing innovative indicators to target faults that host unconformity-related uranium deposits using non-traditional isotopes, geochronology, structural studies and geophysical data to evaluate geochemical, isotopic and mineralogical signatures, constraining the timing of reactivation-alteration to evaluate the role of long-lived crustal-scale shear zones, and quantifying ore-related demagnetization/alteration. Previous fluid flow modelling has highlighted the role of basement fault systems in controlling the location of regional-scale hydrothermal cells during formation of the unconformity-related deposits. The highest fluid flux occurs along these faults, indicating the importance of fault-controlled fluid flow. The critical knowledge gap for exploration is to recognize fertile alteration along faults, particularly in basins previously considered unprospective. Also under investigation within this subproject is the role of marine brines in the formation of uranium deposits, as recent research suggests that marine brines play a critical role in the scavenging of metals from source rocks and their efficient transport to form a deposit.

Subproject 2: Uranium-rich deep metasomatic processes

This subproject addresses the sources and processes of uranium enrichment in iron oxide-copper-gold (IOCG) deposits and the broader iron oxide-alkali alteration (IOAA) systems that host these deposits. Previous studies of IOAA and IOCG occurrences in the Great Bear magmatic zone have shown that they were systematically enriched in uranium at key stages during the evolution of these large, metasomatic systems. The spectrum of mineral occurrences and alteration within the Central Mineral Belt of Labrador provides an excellent opportunity to track the spatial and temporal fluid-metal evolution of these systems from deep, high-temperature sodic alteration to shallower, low temperature, potassic-iron alteration and brecciation. The goal is to refine the genetic model for metal/fluid sources, fluid pathways and ore formation through primary to remobilized (secondary) ores. Objectives include defining potential metal and fluid sources of the proposed IOAA systems and the physical conditions of the metasomatic gradients that result in mineralogical, geochemical/isotopic and geophysical indicators of mineralization.

Volcanic- and sedimentary-hosted base metal mineralization project

Volcanic- and sedimentary-hosted mineralization encompasses a diverse array of deposit types (e.g., volcanic massive sulphide (VMS), sedimentary exhalative (SEDEX) and Mississippi Valley type (MVT)), but fit within the ore system concept as the deposit types share common genetic processes, and in some cases, spatial and temporal linkages. Aspects under investigation include: metallogenic ties between SEDEX and MVT deposits; the potential role of magmatism in SEDEX formation; ore-fluid properties and metal complexation, transport, and fluid pathways; the role of ambient conditions such as anoxia and euxinia; and the hydrogenous origin of metals in highly-enriched black shales (HEBS). Collectively, the results will advance knowledge of the respective roles of metal sources, fluid migration and ultimately deposition in space and time. This research will provide the basis for enhanced genetic and exploration models, particularly for deeply buried or concealed deposits.

The seafloor ore deposition subproject will: determine sources of metals, ligands and other components in VMS, SEDEX, and HEBS deposits; elucidate transport pathways; and clarify the role of ambient conditions (e.g., anoxia, euxinia) in at or near seafloor ore deposit formation.

The base metal sources and mineralizing processes subproject will investigate the primary genetic connections between sedimentary deposits and magmatic systems, identify key physico-chemical/isotopic features of ore fluids and identify the depositional controls by placing mineralizing events in temporal and spatial context.

Subproject 1: Seafloor ore deposition through space and time

The objective of this subproject is to determine the sources of metals, ligands and other constituent elements in VMS, SEDEX, and black shale-hosted (i.e., HEBS) deposit types, and determine the role of ambient conditions such as anoxia (no oxygen in the water column) and euxinia (H_2S in the water column) in the formation of these deposits which formed at or near the seafloor. The results will be used to develop predictive genetic and exploration models. This will be done by combining established analytical methods with state-of-the-art techniques (i.e., non-traditional metal isotopes (Mo, Ni, Re-Os, etc.) in pyrite and other sulphides and non-sulphides by LA-ICPMS). Collectively, the results could impact genetic and predictive exploration models for several deposit types, for example by linking oceanic redox state to ore deposition.

Subproject 2: Base metal sources and mineralizing processes

Through research focussed on the genetic connections between various sedimentary and/or magmatic ore-bearing systems, this subproject seeks to improve predictive models by placing mineralizing events in temporal and spatial context. Also by identifying the key chemical and isotopic features of ore fluids it will define the controlling processes for deposition that in turn will help discriminate between potentially mineralized and barren regions. The unusual configuration in north-

east British Columbia of parallel deposit rich carbonate (MacKenzie and MacDonald platforms) and shale (Kechika Trough) "corridors" provides an ideal testbed for resolving possible genetic and temporal links between MVT and SEDEX deposits. Spatial and temporal relationships may exist between magmatic rocks and sediment-hosted Zn-Pb in the Selwyn Basin and elsewhere. However, whether this relationship is causal or casual is unknown. Causal and temporal relationships may lead to predictive mineralization models.

The link between genetic ore deposit models and interpretations of the tectonic setting of VMS systems will be investigated by elucidating the contributions of various fluid sources and processes to the metal budget of seafloor hydrothermal ore deposits. Isotopic data will be obtained to constrain the overall role of atmospherically processed sulphur in VMS formation, and by comparison with data for modern deposits will permit analysis of time-independent processes of VMS formation. Mineralizing fluid flow paths in a VMS deposit will be delineated with geological, mineralogical, geochemical and geophysical parameters to refine schematic spatial models of hydrothermal fluid flow on ore system scale and improve the link between genetic ore deposit models and tectonic setting.

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Gold through space and time at the Archean

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Introduction

This activity aims at understanding gold deposits at system scale (from source to ore) by revisiting and "updating" metallogenic models of one of the most fertile period of the Earth, i.e., the Neoarchean. This activity consists of a combination of thematic and site specific research that aim at improving the efficiency of exploration models, with a focus on the southern Superior Province (South of 57th parallel: Fig. 1; dashed line). The southern Superior Province represents an area of both focused geoscientific research by governments and academia and intense exploration by the industry, and is a good example of a data-rich environment with a huge exploration potential where major gaps in our understanding of gold systems remain. Therefore, the area provides the necessary knowledge bases required for the study of multi-scale geologic characteristics and ore-forming mechanisms through space and time by comparing well-documented gold systems of different styles and age and by contributing to the subproject and project objectives, which are given in Mercier-Langevin et al. (2017). Therefore, relevant existing information will be assessed and integrated in support to targeted research (e.g., site specific and/or thematic studies) and analytical work (e.g., lithogeochemistry, geochronology, isotopic analyzes, laser ablation ICP -MS analyzes and quantitative mapping, etc.) aiming at filling knowledge/coverage gaps thus providing a more uniform documentation of key geologic attributes of selected gold districts and deposits.

Targeted field work capturing selected information on key parameters will contribute at establishing a common framework for gold deposits distribution in space and time (mineral belts vs metallogenic epochs). This will directly contribute to, and build on, the other activities of the Gold Project, with the intent of improving geologic and exploration models for both Archean and younger terranes. This will also allow for comparisons between the various Neoarchean gold systems and those of Paleoproterozoic and Phanerozoic age, as well as other well-studied Archean cratons (e.g., Slave, Yilgarn, etc.). This activity also aims at documenting the controls on the quality (i.e., size and grade) of these deposits and districts. It is also the opportunity to tackle the question of "unusual" precious and base metal endowments in specific parts of the crust (e.g., southern Abitibi greenstone belt) and the concept of favourable "pre-concentrations" or "heritage" in some parts of the upper mantle and/or lower crust that may have been tapped by hydrothermal fluids at different times to form different deposits higher in the crust (cf. Sillitoe, 2008). Because of contrasting metamorphic conditions, it is also the opportunity to compare gold deposits at different metamorphic grades.

Activity highlights and preliminary results

This activity is still at an early stage and relatively limited field work was done in the summer 2016 with only part of the activities formally started. However, some site specific research is well underway and only a few selected examples are very briefly summarized here

Island Gold deposit

A M.Sc. project was initiated at the Island Gold Mine in the Michipicoten greenstone belt near Wawa, Ontario, in collaboration with the University of Waterloo, Richmont Mines, and the Ontario Geological Survey. The Island Gold mine was selected as a study site in Activity G-1.1 as renewed mining and exploration activity in this area gives access to a wealth of new information and data in an area that, although clearly fertile, is often seen as a "poor cousin" to the Abitibi greenstone belt, and provides an opportunity to compare gold districts with a number of similarities but different gold endowment. The objective of this Master's project is to better constrain the timing of gold introduction, its relationship with deformation corridors, and to define its hydrothermal signature (Fig. 2). This project will more specifically contribute to this activity by providing information on the Goudreau deformation corridor and its role on the genesis and distribution of orogenic gold deposits in the Michipicoten belt.

Horne deposit

A second M.Sc. project was initiated on the Zone 5 of the Horne deposit, southern Abitibi greenstone belt, Québec, in

This report is a contribution to:
TGI 5 (2015-2020) Gold project
Subproject 1: System controls on gold through time and space (source to trap)
Activity G-1.1

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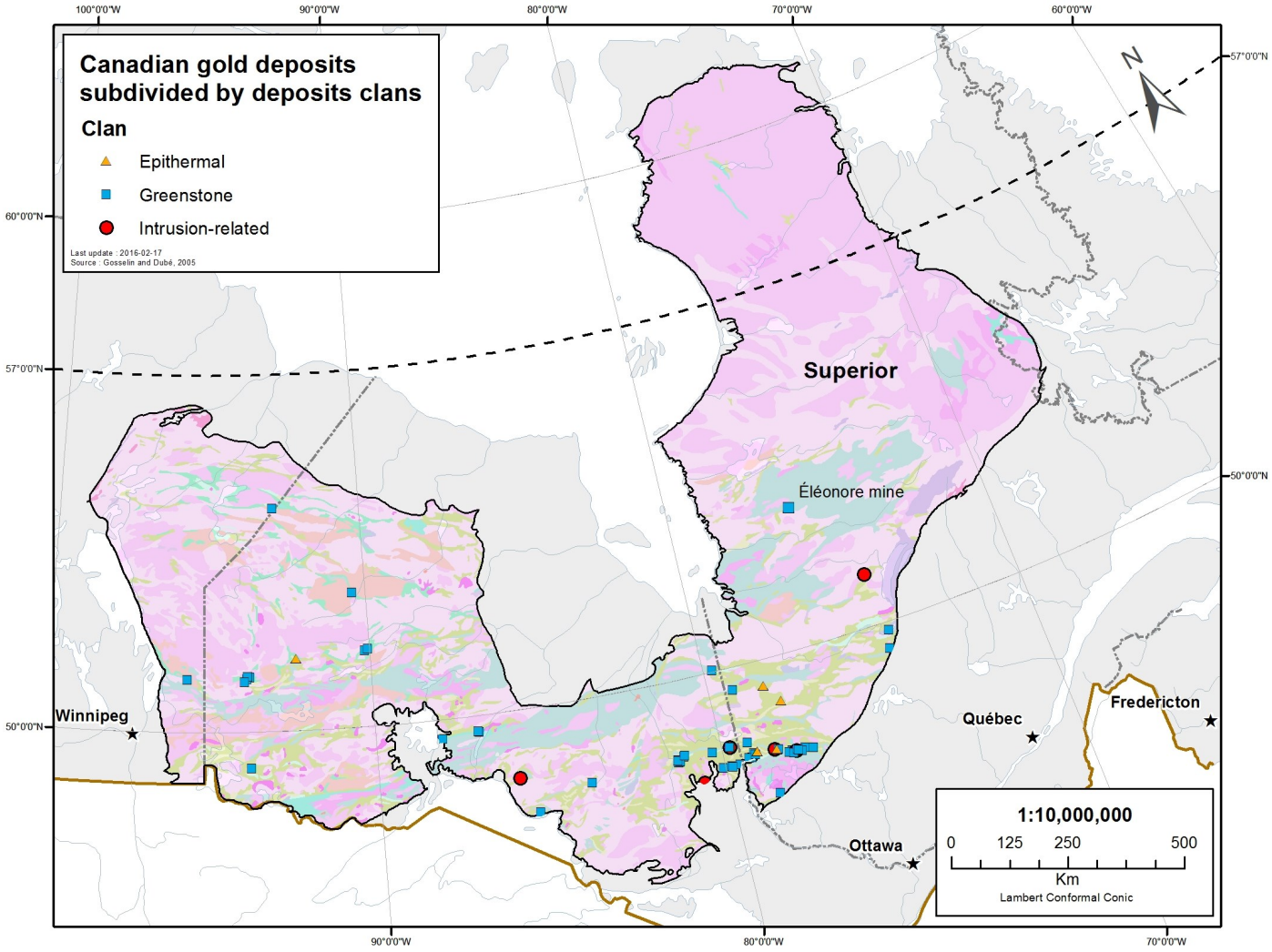


Figure 1 – Simplified geological map of the Superior Province (modified from Wheeler et al., 1996) showing the distribution of the largest gold deposits and districts. Gold deposits from Gosselin and Dubé (2005). Areas in green represent volcanosedimentary greenstone belts, areas in bluish-grey represent metasedimentary domains, pale and dark pink zones represent plutonic and high-grade metamorphic terrains, purple rocks are Proterozoic or younger. The dashed line marks the 57th parallel, the northernmost limit of the studied area for this activity.

collaboration with the Ministère de l'Énergie et des Ressources naturelles, the Institut national de la recherche scientifique – Centre Eau Terre et Environnement, Falco Resources, and the McGill and Laurentian universities. The Horne deposit is considered a key study site as it represents the largest gold-rich volcanogenic massive sulphide deposit of the World, and a type example of a giant Archean synvolcanic gold system. Recent drilling of the Zone 5 gives us access to new material, which hasn't been the case at Horne for decades. The M.Sc. project at Horne aims at providing further constraints on the genesis of giant synvolcanic Archean gold and base metals deposits by studying the nature, composition, and geometry of the ore zones, and by trying to further constrain the age of the host succession and of the mineralization (Fig . 3). This project will help further improve our understanding of synvolcanic gold systems in the southern Superior Province, and of the potential sources and traps of such "early" systems.

LaRonde Penna deposit

A detailed study of pyrite nodules present in argillite lenses of the LaRonde Penna world-class gold-rich volcanogenic massive sulphide deposit, southern Abitibi greenstone belt, Québec, is also well underway. Preliminary results clearly indicate an early, synvolcanic enrichment in gold and precious metals that was later overprinted by barren, syn-main deformation metamorphic metasomatism, overgrowth and recrystallization, providing further evidence for early, synvolcanic major auriferous events in the southern Superior Province (Fig. 4; Mercier-Langevin et al., 2016b, c).

Canadian Malartic deposit

Sampling of outcrops around the Canadian Malartic gold mine for paleomagnetic study was undertaken in collaboration with the Canadian Mining Innovation Council Footprint project with the prime objective of assessing paleomagnetic methods

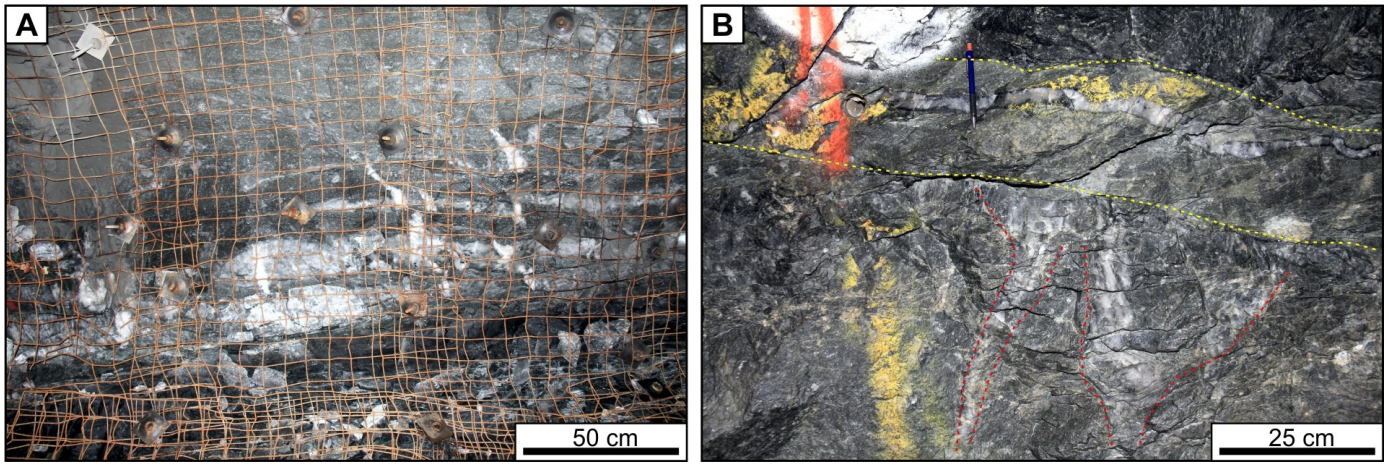


Figure 2 – Photos from the Island Gold mine. A) A mineralized laminated grey quartz vein cut by orthogonal late, white quartz extension veins. View from the back of the stope, level 675, C-zone. B) A mineralized, laminated grey quartz vein (red outline) cut by an amphibole-bearing mafic (lamprophyre?) dyke (yellow outline) itself cut by a late, barren quartz vein. The dyke was sampled for U-Pb geochronology, level 740.

to determine relative timing of deformation stages and mineralization.

Éléonore deposit

Detailed underground mapping, core logging and 3D modelling combined with high-precision U-Pb geochronology help in deciphering the different generations of structures and related metamorphism, clarifying the links with the fertile hydrothermal activity in the Éléonore mine area, James Bay, Québec. Ongoing U-Pb zircon dating of the various generations of pegmatites (ca. 2620-2600 Ma) and of the tonalite/granodiorite (ca. 2612 Ma) at the Cheechoo gold project, approximately 12 km south-southeast of Éléonore indicates several phases of gold mineralization and/or gold remobilization in the region. This work contributes at better delineating a significant (up to 10 km -wide), highly prospective corridor in the La Grande subprovince at the contact with the Opinaca subprovince (Fontaine et al., 2016), a context that differs from other well-endowed gold districts. It also directly contributes at better understanding regional to deposit-scale metamorphic controls on ore.

Science impact

It is premature to present significant impacts that are specifically related to this activity. However, preliminary assessment indicates that some of the ore-associated faults that were considered as potentially major conduits are, based on very preliminary appraisal of the geological context of a few deposits, perhaps only splays of larger but hidden/unrecognized/underestimated structures, which warrants further work (2017-2020) in such areas to locate the first-order fertile fault(s) that control the distribution of the gold deposits at regional scale. By comparing these localities with key districts where we have much greater control on the timing of events (e.g., Timmins-

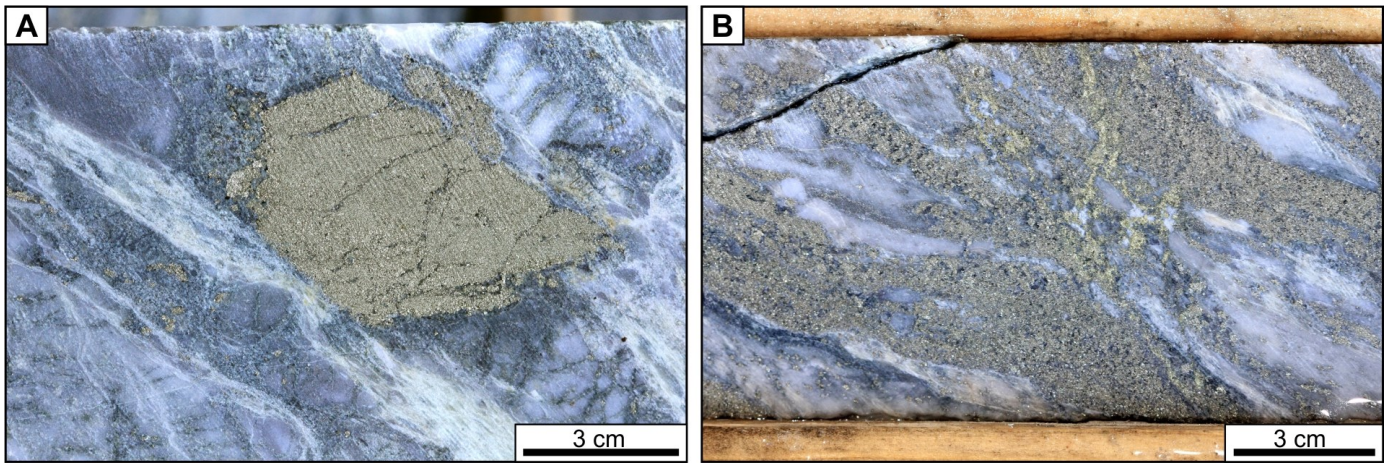


Figure 3 – Photos from the Horne Zone 5. A) Felsic volcaniclastic rock with auriferous massive pyrite clasts indicating auriferous hydrothermal activity, ddh H5-15-05, 1904 m. B) Sericitized felsic volcaniclastic rock cut by partly transposed auriferous sulphide stingers showing the local remobilization of chalcopyrite, ddh H5-15-05, 1873 m.

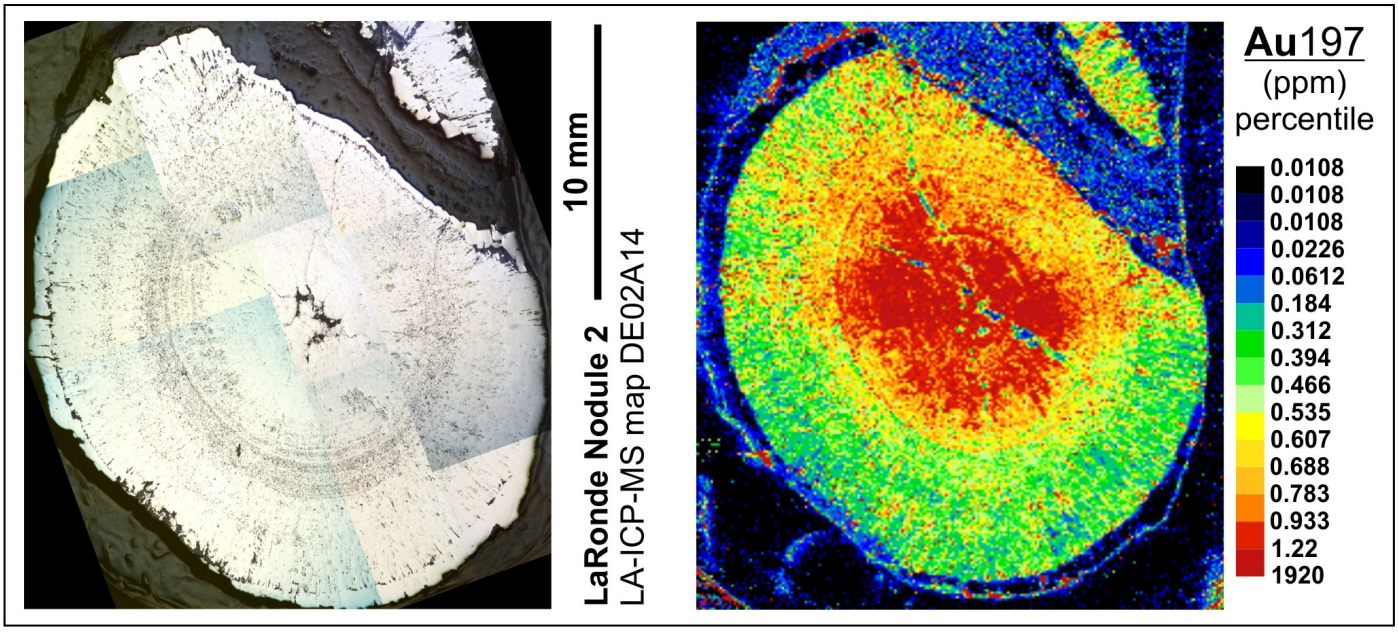


Figure 4 – LA-ICP-MS element maps of a pyrite nodule from the LaRonde Penna Au-rich volcanogenic massive sulphide deposit. Maps use a percentile scaling function with scales in ppm. The nodule was present in an argillite lens present within the principal ore zone at the mine.

Porcupine district: Dubé et al., 2016), we will get a better picture of how and in which specific settings gold deposits form. The combination of research of this activity with that of the other activities of subproject 1 (see Davis et al., 2017; Jackson et al., 2017; and Lawley et al., 2017) will allow to better frame, in space and time, major gold-forming events at the Archean.

The study of the Zone 5 of the Horne deposit, in conjunction with the work done on the pyrite nodules at the LaRonde Penna deposit, will provide more information on the early stage (s) of gold metallogenesis in the southern Superior Province and the controls on the potential source(s) of gold and ore forming processes at the Archean. A similar study of pyrite-marcasite nodules hosted within argillites and conglomerates in the Timmins-Porcupine orogenic gold camp is also underway (see activity G-1.4 summary; Jackson et al., 2017). Results from these studies and those from activity G-1.2 (Lawley et al., 2017) may provide key information on the sources of gold in the prolific Archean period.

Next Steps

The next steps consist in: 1) follow up with ongoing student projects; 2) initiate other site specific studies in key areas where critical information on ore-forming processes from source to trap(s) can be obtained, including areas that are not as well-endowed as the southern Abitibi greenstone belt; 3) further develop the activity by returning to some key areas and gaining first-hand knowledge of other key districts and deposits in the southern Superior Province (e.g., Rice Lake in Manitoba, Red Lake in northwestern Ontario, Rainy River area in western Ontario, etc.) as well as building on the ongoing work and on previous TGI research (Dubé and Mercier-Langevin, 2015 and references therein); 4) link the various projects of Activity G-1.1 to better frame ore-forming processes in time and space at the Archean and develop improved gold deposit and exploration models (e.g., Dubé and Mercier-Langevin, 2015; Mercier-Langevin et al., 2016a); and 5) strengthen the collaboration and synergy with the provincial surveys and other major mineral exploration-related initiatives such as Metal Earth.

Acknowledgements

Through its various projects and study sites, this activity heavily relies on the collaboration of numerous dedicated students and colleagues from the industry, academia, and provincial surveys. We are sincerely grateful to the following individuals for their invaluable help and critical contribution: S. Anderson, F. Aucoin, J. Ayer, C. Bohm, T. Ciufo, R. Creaser, R. Daigneault, A. Fontaine, A. Galley, H. Gibson, K. Jellicoe, A. Krushnisky, B. Lafrance, K. Lauzière, S. Lin, M. Malo, L. Moore, B. Morris, J. Parker, S. Perrouty, H. Poulsen, M. Richer -Laflèche, D. Rhys, P.-S. Ross, J. Styx, and to the following organizations and their personnel for their support and collaboration: the Ministère de l'Énergie et des Ressources naturelles, the Ontario Geological Survey, the Manitoba Geological Survey, Canadian Mining Innovation Council – Footprints Project, Agnico Eagle Mines (LaRonde and Exploration divisions), Detour Gold (Detour mine and Exploration division), Falco Resources, Goldcorp (Timmins-Porcupine district, Éléonore mine), Iamgold (Westwood mine), Lake Shore Gold, Mine Canadian Malartic, Ressources Sirios, Richmont Mines (Island Gold mine), St-Andrew Goldfields, Northern Gold, Alamos Gold (Timmins-Porcupine district), Azimuth and Soquem.

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Mantle metal mobility

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Introduction

The role of some deep-seated, metal-rich source(s) in the formation of mineral deposits hosted within the mid- to upper-crust remains the subject of considerable debate. In the case of orogenic gold deposits, gold and other metals may ultimately be derived from the upper mantle, where basaltic melts scavenge incompatible elements, such as some chalcophile and siderophile elements, and transport them either directly to the upper crust or into transient lower to middle crustal reservoirs. Understanding the processes that mobilize and concentrate such metals requires an in depth knowledge of melting, re-fertilization and metal mobility in the mantle. However, these mantle processes are difficult to investigate directly except by geophysical methods. As such mantle melting, metasomatism and re-fertilization studies are largely restricted to exhumed lithospheric mantle, obducted ophiolites and mantle xenoliths and xenocrysts in volcanic rocks. The absence of well-preserved mantle sections in the ancient rock record means that the behaviour of gold in the Precambrian mantle is difficult to evaluate except through xenolith and xenocrysts studies.

Ophiolite exposures at Atlin (British Columbia) provide an outstanding opportunity to study mantle processes in the field, where clear relationships between igneous and metamorphic processes in the mantle can be established with confidence (Figs. 1 and 2). New advances in ultra-trace determinations of metals within whole rock samples will be combined with conventional lithogeochemistry and in situ micro-analytical methods (LA-ICP-MS) to map the distribution of metals within mantle minerals with clear paragenetic context. Activity results will underpin new process-oriented models for gold deposit genesis and will define the behaviour of gold and other metals during mantle melting and re-fertilization.

Results from this field-study will provide constraints to lab-based mantle xenolith and xenocryst studies where the paragenetic context is lacking due to the disaggregation of these minerals from the host mantle (Figs. 3 and 4). Detailed in situ mi-

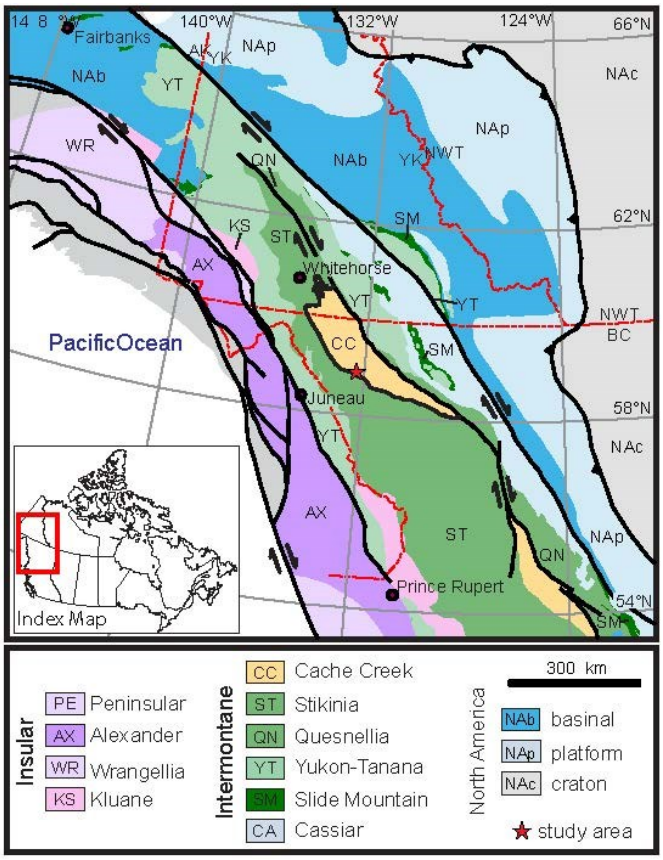


Figure 1 – Terranes of the Northern Cordillera (modified from Colpron and Nelson, 2011).

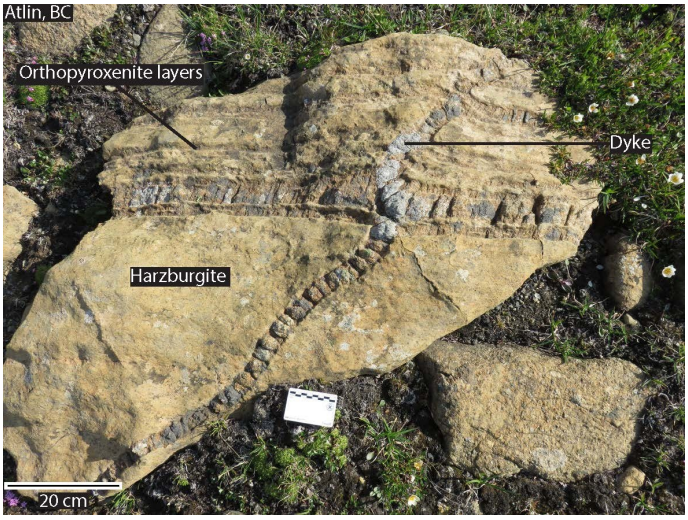


Figure 2 – Orthopyroxenite layers in tectonized harzburgite cut by orthopyroxenite dyke (Zagorevski et al., 2015).

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Lawley, C.J.M., Kjarsgaard, B.A., Zagorevski, A., Jackson, S.E., Yang, Z. and Mercier-Langevin, P., 2017. Mantle metal mobility; *in* Targeted Geoscience Initiative – 2016 Report of Activities, (ed.) N. Rogers; Geological Survey of Canada, Open File 8199, p. 23-25. doi:10.4095/299573

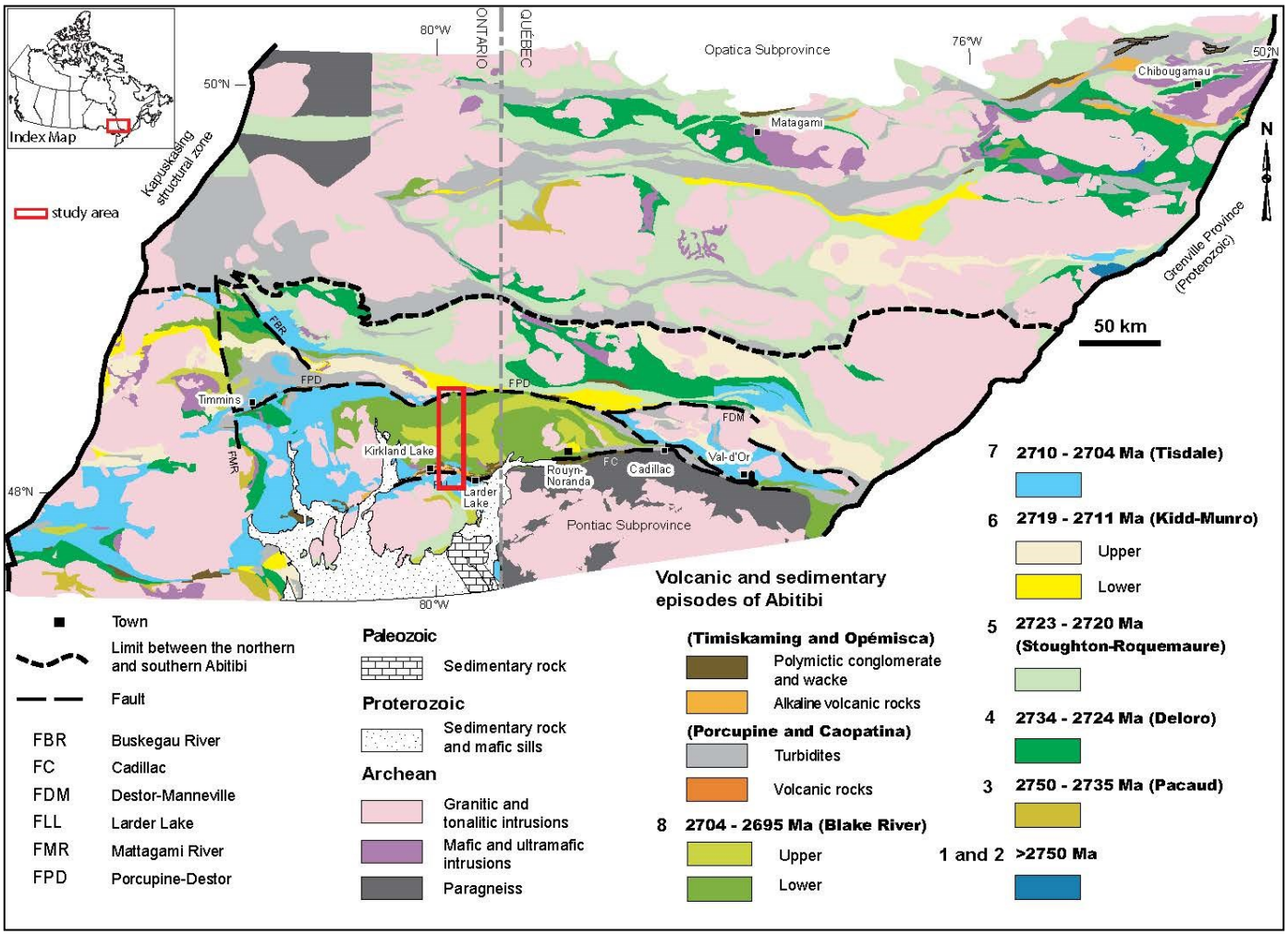


Figure 3 – Simplified geological map of the Abitibi Subprovince (modified from Thurston et al., 2008).

cro-analysis will be conducted on mantle minerals and their sulphide inclusions within kimberlite-hosted xenocrysts from near Kirkland Lake, Ontario (Fig. 3). These sulphides are likely a key mineral host for gold, however, the concentration and micro-scale distribution of gold and other metals within these samples has not previously been reported. Results from this complementary, lab-work will ultimately be used to evaluate the role of mantle metals in the formation of the world-class Abitibi gold province.

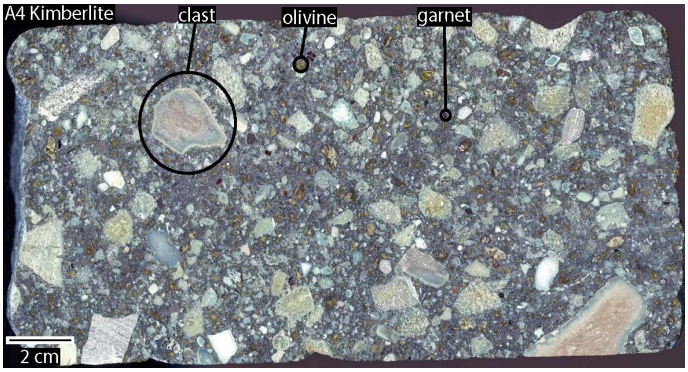


Figure 4 – Kimberlite sample from the Kirkland Lake area, Ontario.

Key Activity highlights

Fieldwork completed in 2016 was predominantly focused on documenting field relationships between mantle lithologies and sampling ophiolitic mantle from the Cache Creek terrane, northern British Columbia (McGoldrick et al., 2016a). This work was able to demonstrate mantle layering comprised of harzburgite, dunite and concordant pyroxenite. Dunite, orthopyroxenite and websterite also formed distinct cross-cutting plugs and dykes establishing a history of melt migration (Fig. 2). Harzburgite in general was clinopyroxene poor, however clinopyroxene was observed in several localities and has previously been reported (McGoldrick et al., 2016b). Thirty-seven samples were collected for conventional lithogeochemistry and ultra-trace PGE+Au analysis. A sub-set of these samples will also be prioritised for geochronology and isotopic analysis. Section blanks will be prepared for each sample to characterize sulphide inclusions within mantle minerals and document mineral paragenesis for the ultramafic rock suite.

Five previously collected kimberlite samples from the Kirkland Lake area have been selected for mineral separation (Fig. 4). Each sample was divided into its mineral constituents following electric pulse disaggregation (EPD). Mineral separates were then prepared from rock powders after heavy liquid and magnetic mineral separation. Sulphide grains and clinopyroxene ± olivine ± garnet ± spinel hosts with sulphide inclusions are to be handpicked and mounted in epoxy prior to imaging and further geochemical analysis.

Next Steps

Sample preparation for petrography, geochemistry and isotopic analysis is currently underway for the Atlin samples. These whole rock geochemical and isotopic results will form the foundation for further in situ and mineral-scale investigations into the concentration and distribution of metals at the micro-scale. A large suite of archived mantle samples (Zagorevski et al., 2015) will be used to complement these field studies.

Sample preparation for the Kirkland Lake kimberlite materials is complete. Sulphide grains and clinopyroxene xenocrysts, and their sulphide inclusions, will be prioritized for analysis. Additional investigations will subsequently be carried out on other mantle xenocrysts present within the kimberlite samples.

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New approaches to dating hydrothermal gold deposits

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Introduction

Establishing the absolute ages of minerals within hydrothermal ore-mineral assemblages, either in ore-bearing veins or intergrown with ore minerals in alteration zones, is critical to quantify the timing of fluid flow events in ore-forming systems. Accurate age information can help discriminate relevant geologic triggers controlling gold-rich hydrothermal systems, at the local and regional scale. For example, it may differentiate between fluids systems driven by plutonic events from tectono-metamorphic fluids driven by regional orogenic processes. Historically, determining accurate ages of mineralizing events has posed both analytical and interpretive challenges, as it is often difficult to establish synchronicity of the dated mineral phases with ore minerals. Dating fluid flow events requires a thorough understanding of the geology and paragenesis of the ore system and dateable phases, coupled with precise analytical data.

This activity aims to integrate improved high-spatial resolution imaging and petrological characterization techniques (such as cathodoluminescence, compositional mapping, Raman spectroscopy, EBSD) with in-situ and high-precision geochronology and geochemistry to advance methods for interpreting the timing of gold-bearing hydrothermal systems, with a focus on hydrothermal phosphate and zircon mineral paragenesis and geochronology. Phosphate minerals such as monazite ($[Ce,La,Nd,Th]PO_4$) and xenotime (YPO_4) are excellent U-Pb chronometers as they occur in a range of alteration assemblages (Fig. 1), typically have high U contents, low common Pb, and have high closure temperatures. The challenge in dating them is that they occur as very small grains (<20 µm) that require in situ analyzes (e.g., Fig. 1; Salier et al., 2005; Vielreicher et al., 2015; Lawley et al., 2015).

The accurate determination of the timing of ore-bearing fluid events (as metal pathways) and evaluation of variations in

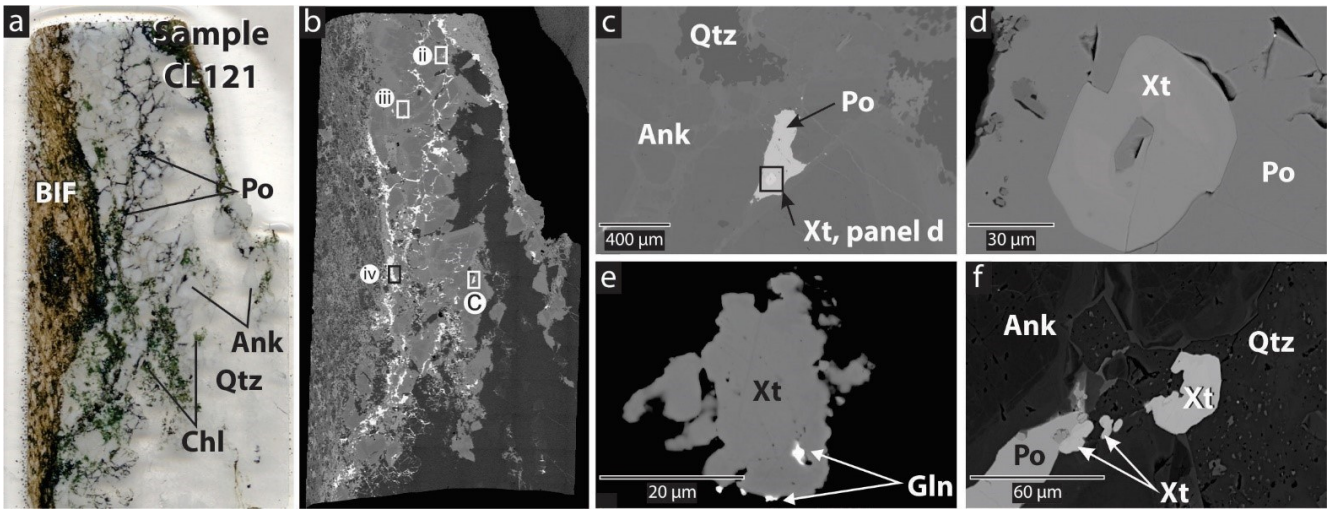


Figure 1 – Example of hydrothermal xenotime occurrence within a sulphide-bearing quartz-ankerite vein from the Tiriganiaq gold deposit, north of Rankin Inlet, Nunavut (modified after Lawley et al., 2015). a) Photograph of polished thin section (~4 x 2 cm) Po=pyrrhotite; Qtz=quartz, Ank=ankerite, Chl=chlorite, BIF = banded iron formation, b) Scanning electron microprobe, back scatter electron (BSE) image of the same field of view as in panel a. c) BSE image of pyrrhotite (Po) within ankerite (Ank)-quartz (Qtz) vein. The pyrrhotite contains a small (<40 µm) xenotime (Xt) inclusion shown in panel d (field of view indicated as box on panel c). Panels e and f are BSE images of xenotime that crystallized at the margins galena (Gln) (e) and of pyrrhotite (f). The xenotime yielded a Proterozoic age of 1858 ± 10 Ma.

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metal endowment will help improve genetic models and exploration tools of major hydrothermal gold systems. Specific test sites, such as the Timmins Porcupine gold camp in Ontario and the Amaruq deposit in Nunavut, are being selected in order to contribute to the overall TGI Gold Project objective to better understand major gold systems through time and space, in addition to enabling methodological development.

Key activity highlights and next steps

Initial work will focus on the Timmins Porcupine gold camp. A preliminary sample suite has been assembled with the participation of several mining and exploration companies. Preliminary work on sample selection and petrological analysis will identify which styles of alteration and host rocks are associated with hydrothermal phosphate minerals (monazite, xenotime, apatite) that are suitable for geochronological analysis. This study will be supported by a post-doctoral research fellow scheduled to start in early 2017.

Subsequent work will expand the study to examine Au systems over a broader area to evaluate regional age differences to see if they may be related to tectonic assembly of the Superior craton, as has been demonstrated for the Yilgarn craton (e.g., Vielreicher et al., 2015).

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Fingerprinting ore processes in auriferous systems

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Introduction

Pyrite is a near-ubiquitous mineral in metalliferous hydrothermal deposits. Moreover, it incorporates and concentrates many important ore and associated elements during precipitation, deformation and associated hydrothermal and/or metamorphic activity. Thus the distribution of elements in pyrite, which can be revealed by laser ablation inductively coupled plasma mass spectroscopy (LA-ICP-MS) element mapping, records the chemical history of its host hydrothermal system. Zoning of key elements (e.g., Co, Ni, As, Se, Te) in ore zone pyrite frequently includes large decoupled variations that may reflect: i) changes in the chemistry of the source fluids; ii) fluid -rock interactions along fluid pathways; iii) changes in precipitation conditions within the metal trap; or iv) post-precipitation modification.

This project will develop advanced approaches to interpreting element contents and zonation in pyrite with a view to identifying quantitative criteria and/or trends that can fingerprint critical geochemical processes conducive to ore formation. The approach will initially be focussed on the study of processes in the source, pathway and trap of gold systems, but should be exportable to other major types of hydrothermal mineralization (e.g., VHMS, SEDEX, orogenic and intrusion-related base and precious metal deposits).

Preliminary investigations to date have followed up on a study initiated in the previous phase of the Targeted Geoscience Initiative on the genesis of, and metal distributions in, large (up to 5 cm) pyrite/marcasite nodules in interflow carbonaceous argillites from the Porcupine (Timmins) mining district, Abitibi greenstone belt (Fig. 1). This study aims to determine the genesis of, and timing of gold introduction into, these gold-rich nodules. The nodules may, if determined to be sedimentary/diagenetic, indicate early introduction of gold in the Timmins area, the significance of which will be evaluated. If determined to have had a later, structurally controlled, hydrothermal origin, the nodules will provide valuable insights into the geochemical evolution of the hydrothermal systems associated with the Porcupine orogenic gold deposits.

Activity highlights

Preliminary results/data analysis

Samples for the project have been collected from the Bell Creek mine (Fig. 1) and the Holloway deposit located approximately 100 km east of the Timmins-Porcupine district mines. The samples include several pyrite settings: a) pyrite nodules and associated bands in carbonaceous argillite, b) adjacent cubic pyrite that the nodules are zoned outward into, and c) disseminated pyrite in the adjacent ore in mafic volcanics. Several samples of pyrite nodules from the Hollinger and Owl Creek mines (Fig. 1) were previously mapped by LA-ICP-MS.

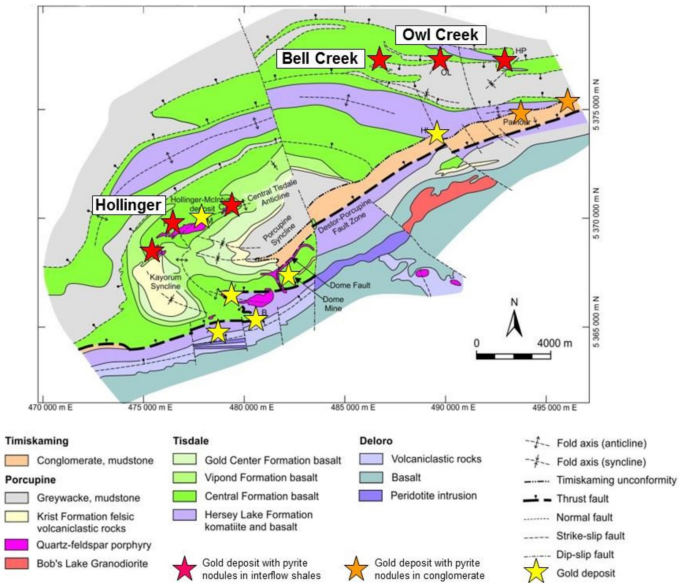


Figure 1 – Geological map of the Porcupine mining district showing major mines and occurrences of pyrite nodules in carbonaceous argillites and within Timiskaming conglomerate (Gray and Hutchinson, 2001, and new data). The Holloway mine is located ca. 100 km east of the map area. Figure modified from Bateman et al. (2008).

Sulphide nodules in interflow carbonaceous argillites of the Tisdale Assemblage, and portions of the Porcupine Assemblage adjacent to Tisdale mafic volcanic rocks from the Porcupine mining district, typically exhibit a pyrite core with concentric zoning of micro-inclusions and a variably developed radially bladed, inclusion-free rim. The nodules commonly record at least one phase of deformation, and often have well developed quartz (± carbonate ± chlorite) pressure shadows and rinds.

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Activity G-1.4

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Jackson, S.E., Dubé, B., Mercier-Langevin, P., and Rhys, D., 2017. Fingerprinting ore processes in auriferous systems; *in* Targeted Geoscience Initiative – 2016 Report of Activities, (ed.) N. Rogers; Geological Survey of Canada, Open File 8199, p. 29-32. doi:10.4095/299573

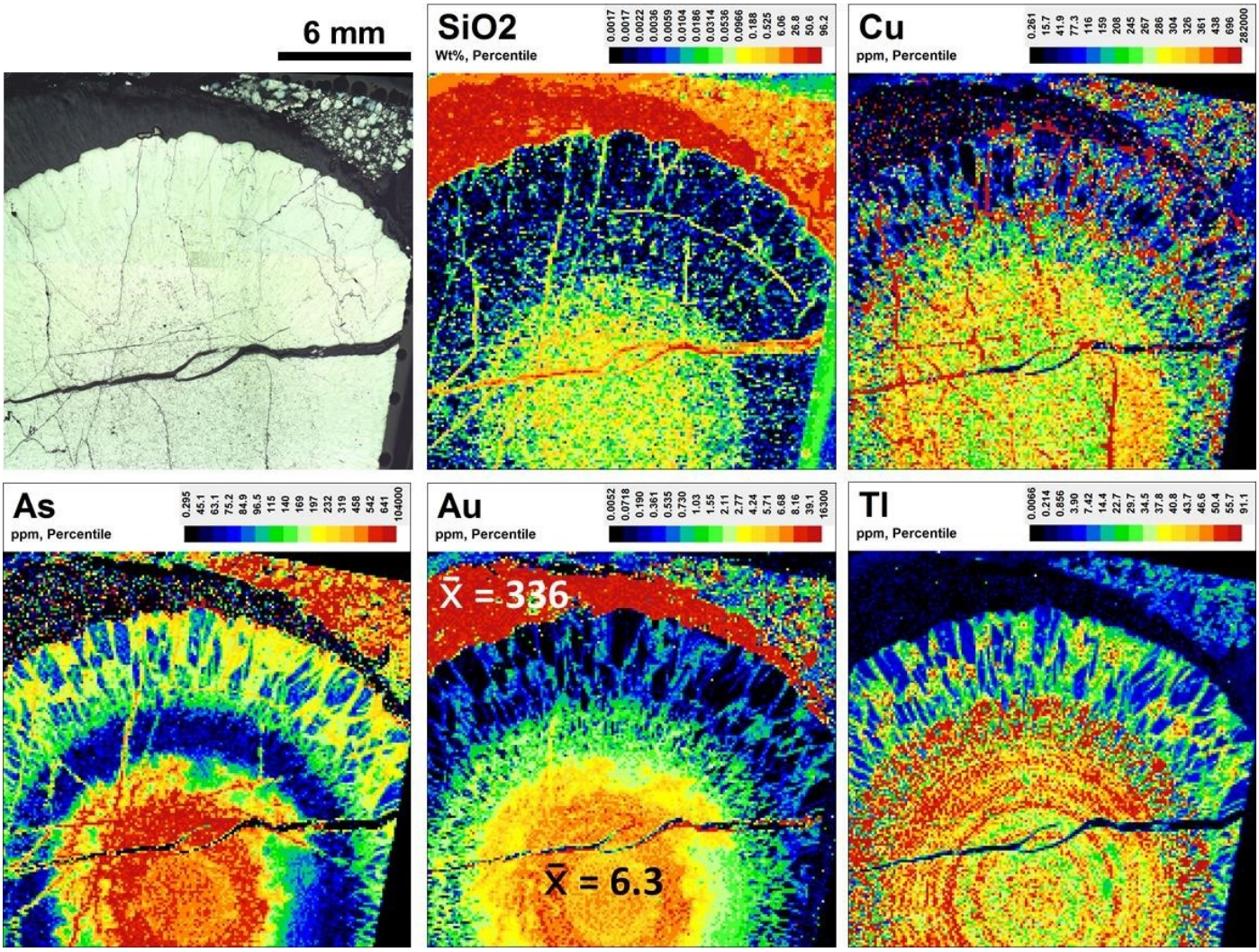


Figure 2 – LA-ICP-MS element maps of a pyrite nodule from the Holloway gold mine. Maps use a percentile scaling function with scales in ppm, except SiO_2 in wt%. Note: 1) the inclusion-rich, concentrically zoned pyrite core (cf. Tl map) with high Cu, As and Au contents (mean Au content = 6.3 ppm); 2) the inclusion-poor, radially bladed rim with low Cu, As and Au contents (Au content < 0.5 ppm) except along grain boundaries; and 3) quartz-calcite-chlorite pressure shadow (cf. SiO_2 map) with very high Au content (mean Au content = 336 ppm).

Four samples of nodular and hydrothermal pyrite from the Bell Creek and Holloway mines have been mapped by LA-ICP -MS. A pyrite nodule from the Holloway mine reveals a mean gold content for its concentrically zoned core of 6.3 ppm (Fig. 2). By contrast, the radially bladed rim has low contents of gold (<0.5 ppm) and associated elements (e.g., Cu, As), except along grain boundaries. A quartz-calcite-chlorite pressure shadow contains very high levels of gold (mean value = 336 ppm). The high gold content of the nodule's core is similar to that previously recorded in pyrite nodules from the Hollinger and Owl Creek mines (Timmins), and extends the east-west trend of local occurrences of gold-rich pyrite nodules in carbonaceous argillites to over 100 km.

The pyrite nodule from Bell Creek (Fig. 3) is a compound nodule, with an early Cu-As-Au enriched core (0.86 ppm mean Au content) and an overgrowing, less metal enriched nodule. No radially bladed rim is evident, but the nodule is locally recrystallized to gold-depleted (< 0.1 ppm) euhedral pyrite. The compound nodule has a gold-rich quartz-calcite-chlorite pressure shadow and enveloping rind (137 ppm mean Au content).

Methodology development

This activity has featured laboratory method development, especially to improve speed and efficiency of LA-ICP-MS element mapping. An ARIS (Aerosol Rapid Introduction System) has been acquired and tested. The ARIS is a recent innovation that connects a laser ablation sample cell to an ICP-MS instrument with minimal transfer volume, thus providing large improvements in sample washout time. Our testing has indicated that sample washout (defined as signal duration at FW0.1%M; i.e., 99.9% washout) can be improved from the current ca. 1.5 s to ca. 40 ms.

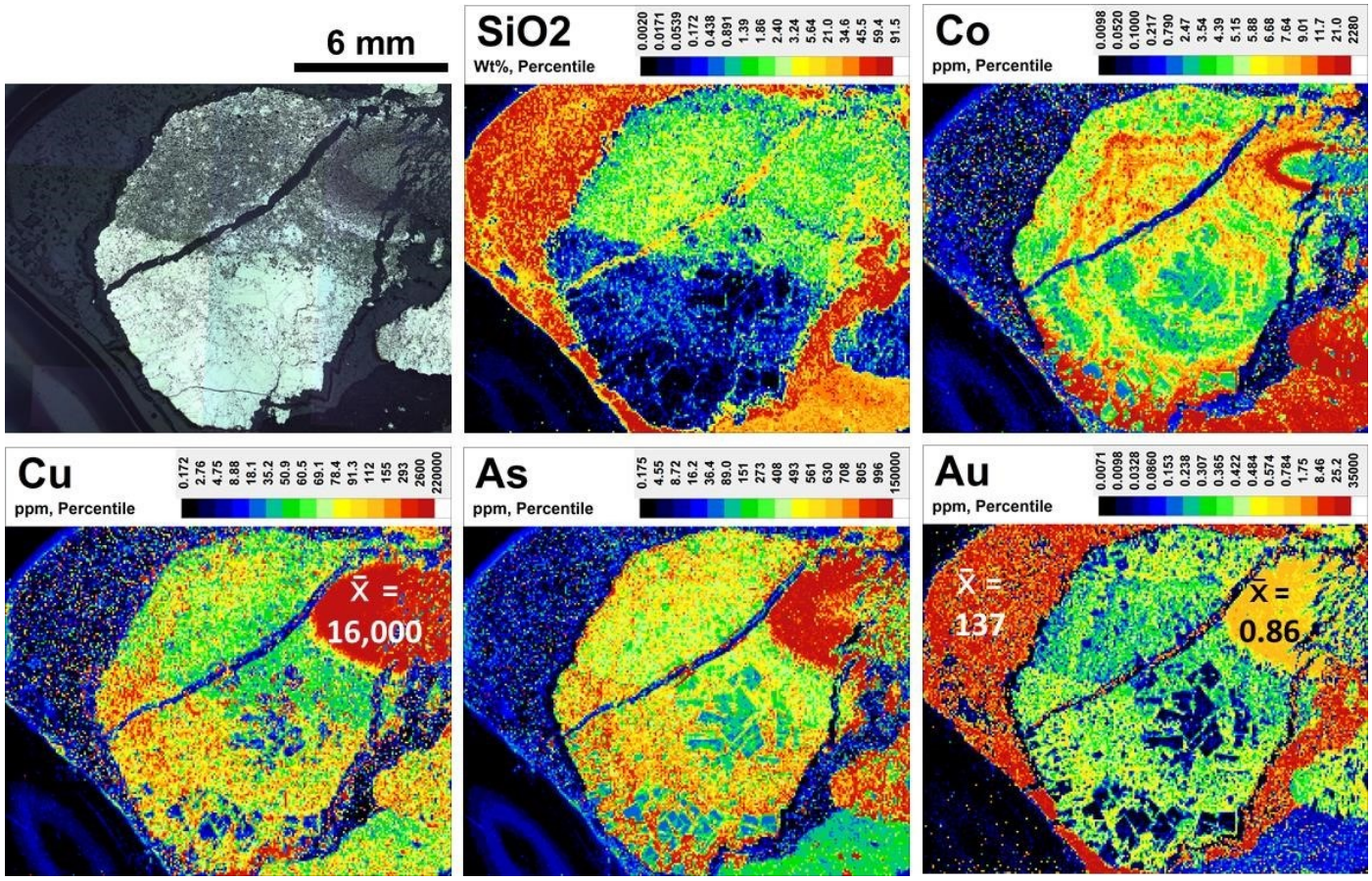


Figure 3 – LA-ICP-MS element maps of a compound pyrite nodule from the Bell Creek gold mine. Maps use a percentile scaling function with scales in ppm, except SiO_2 in wt%. Note: 1) inclusion-rich early core (top right) with high Cu, As and Au contents (mean Cu content = 16,000 ppm; mean Au content = 0.86 ppm); 2) overgrowing, concentrically zoned nodule (c.f., Co map); 3) lack of a radially bladed rim, but patchy recrystallization to euhedral pyrite with low Cu, As and Au (< 0.1 ppm) contents; and 4) quartz-calcite-chlorite pressure shadow and rind (cf. SiO_2 map) with a very high Au content (mean Au content = 137 ppm) .

Current state of knowledge

Concentrically zoned, spheroidal pyrite nodules that occur locally in thin Tisdale interflow carbonaceous argillites, Porcupine Assemblage carbonaceous mudstone near mafic Tisdale volcanic contacts, and overlying Timiskaming conglomerate (Fig. 1), have previously been interpreted as sedimentary/ diagenetic in origin (e.g., Jonasson et al., 1999; Gray and Hutchinson, 2001). The radially bladed nodule rims have been ascribed to metamorphic recrystallization and local remobilization (Jonasson et al., 1999).

From either graphite furnace atomic absorption analysis of pyrite separates (Jonasson et al., 1999) or in situ ion microprobe analyzes (Gray and Hutchinson, 2001), these authors recognized significant gold contents in Porcupine district pyrite nodules. Using these data, they inferred a pre-orogenic (i.e., pre -main phase of compressive deformation) mineralization period of gold enrichment in the Porcupine district, perhaps related to low temperature hydrothermal exhalations in sediment-starved anoxic and euxinic basinal environments (Jonasson et al., 1999). They also suggested that the gold in the subsequent lode deposits may have been sourced via metamorphogenic recrystallization of sedimentary pyrite and associated remobilization of S, Au, and associated metals. It is noteworthy that similarly gold-rich (3-4 ppm) pyrite nodules, interpreted to be of early diagenetic origin, have recently been identified in carbonaceous argillites in the world class Kalgoorlie gold field (Steadman et al., 2015).

To date, this study has confirmed the gold-rich nature of pyrite nodules in carbonaceous argillites (mean Au contents 0.9 -12 ppm) in the Porcupine mining district. This represents an exceptional level of gold enrichment were the nodules to have had a sedimentary/diagenetic origin. A recent study of metal contents in pyrite from 1,407 Archean to recent sedimentary (diagenetic and syngenetic) pyrites from unconsolidated sulphidic sediment and carbonaceous shales, that have not been affected by hydrothermal overprinting, recrystallization, or metamorphism, revealed a median gold content of just 16 ppb (Gregory et al., 2015). Moreover, for the first time, our LA-ICP -MS mapping has identified features suggestive of gold remobilization during deformation and metamorphism (e.g., gold-depleted zones of incipient recrystallization) in the Porcupine

district pyrite nodules. Thus gold-enriched sediment-hosted pyrite, if of sedimentary origin, could indicate early gold introduction in the Porcupine mining district and it could also have been a source of some gold in the Porcupine orogenic gold deposits.

Despite previous interpretations of pyrite nodule genesis, an alternative hypothesis being evaluated is that they are of hydrothermal origin rather than diagenetic. This is based on observations that pyrite nodules at the Bell Creek, Owl Creek and Holloway mines are found uniquely localised in envelopes to, and along projections of, quartz vein-bearing mineralized shear zones into graphitic units and in mineralized areas of high strain that are discordant to stratigraphy. Furthermore, they dissipate rapidly within a few meters from veins, where, laterally along carbonaceous horizons, pyrite cubes become the dominant pyrite form in the carbonaceous units more distally. Similar patterns are present in the Timiskaming conglomerate at the Pamour mine, where nodules are localised to areas of carbonate-albite alteration in envelopes to gold-bearing quartz vein arrays and are absent distal to the veins where the conglomerate is unaltered.

Science impacts

This study will help answer the critical question of whether gold-rich pyrite nodules in carbonaceous argillites in the Abitibi have a sedimentary/diagenetic origin, with gold enrichment perhaps related to low temperature hydrothermal exhalations (e.g., Jonasson et al., 1999, Gray and Hutchinson, 2001), or a structurally controlled, hydrothermal origin, as suggested by field relationships. If the nodules are sedimentary in origin, the study will address whether sedimentary pyrite could have been a contributing source of orogenic gold mineralization in the Abitibi. If so, it will be a significant contribution to the longstanding debate over the source(s) of orogenic gold. The presence of early gold enrichment in sedimentary units may also reflect an inherently gold-rich terrane in which later hydrothermal events could have tapped the same gold reservoir, forming different types of enrichments and deposits (Gray and Hutchinson, 2001). In this case, the different stratigraphic positions of the carbonaceous argillites bearing gold-rich nodules would have required multiple exhalative events and, perhaps, different source rocks, suggestive of a deep, possibly mantle-driven connection.

If it is shown that gold-rich pyrite nodules have a structurally controlled, hydrothermal origin, they are still of considerable scientific significance, given the geochemical record the pyrite nodules hold of the evolution of the gold-rich hydrothermal systems and genesis of the Porcupine district orogenic gold deposits.

Methodology development

Implementation of the ARIS fast washout device will potentially allow large gains in LA-ICP-MS element mapping speed. Currently, large maps can take over 36 hours of instrument time, placing a significant limitation on sample throughput. Speeding up LA-ICP-MS element mapping will have very significant positive impacts on this, and many other projects.

Next steps

Relevant samples from various collections are being prepared for petrographic, SEM and LA-ICP-MS analysis and mapping, with S, Fe, Cu and Pb isotopic analysis also planned to help elucidate pyrite nodule genesis. Of key importance will be to determine whether pyrite nodules occur remote from known mineralization. Underground mapping of pyrite nodule occurrences is also essential in determining the setting and origin of the nodules. If this work concludes that sediment-hosted pyrite nodules and their contained gold are primarily of sedimentary/diagenetic origin, mass balance calculations will be used to set limits on the amount of gold that sedimentary pyrite could have contributed to the huge gold endowment of the Porcupine mining district. A Ph.D. studentship is currently being developed to advance this research.

Instrument method development will be undertaken to modify LA-ICP-MS element mapping procedures to take advantage of the ARIS rapid washout device.

Acknowledgements

The authors would like to thank Dr. Mark Hannington for access to argillite samples from the Abitibi greenstone belt and Mr. David Diekrup for selecting, preparing for petrogaphic section and describing key samples. The authors also thank Ms. Rochelle Collins (chief mine geologist at Bell Creek) for enabling sample collection at the Bell Creek mine and Dr. Matthew Gray for providing samples of pyrite nodules from several localities in the Porcupine mining district. Dr. Zhaoping Yang is thanked for LA-ICP-MS support.

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Paleoproterozoic gold and its tectonic triggers and traps

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Introduction

Identifying the tectonic triggers for gold mineralization would be highly advantageous for regional-scale exploration efforts within complex, multiply-deformed geologic environments such as Paleoproterozoic metamorphic belts. This study addresses that knowledge gap by developing a temporal framework for gold, deformation and metamorphism within the Paleoproterozoic Lynn Lake greenstone belt (Fig. 1). The Proterozoic represents an important transitional period of Earth's history that separates modern, arc-tectonics from tectonic styles and rock associations that are unique to the Archean. Greenstone belts from both time periods host world-class gold districts, however, many of the largest Proterozoic deposits occur along Archean cratonic boundaries. The relationship between Paleoproterozoic gold and these Archean cratons is thus particularly striking although its significance is still not fully understood. Moreover, a comparative analysis of Proterozoic versus Archean gold districts and their lithotectonic controls has not been undertaken despite the economic importance of these younger deposits. For instance, the Paleoproterozoic Homestake gold deposit, situated at the reworked Wyoming cratonic margin, contained over 40 Moz of gold.

Activity highlights

Fieldwork completed in 2016 was focused on logging drill core and documenting the temporal relationship between veins, deformation fabrics, metamorphism and gold at the banded iron formation-hosted Farley Lake Deposit (Figs. 1 and 2). Previous studies interpreted this deposit as belonging to the youngest generation of gold mineralization within the Lynn Lake greenstone belt (Beaumont-Smith et al., 2000; Beaumont-Smith and Böhm, 2002). The relative chronologic framework and mineral paragenesis developed at this deposit will help direct further geochronology sampling. Several days were also spent visiting

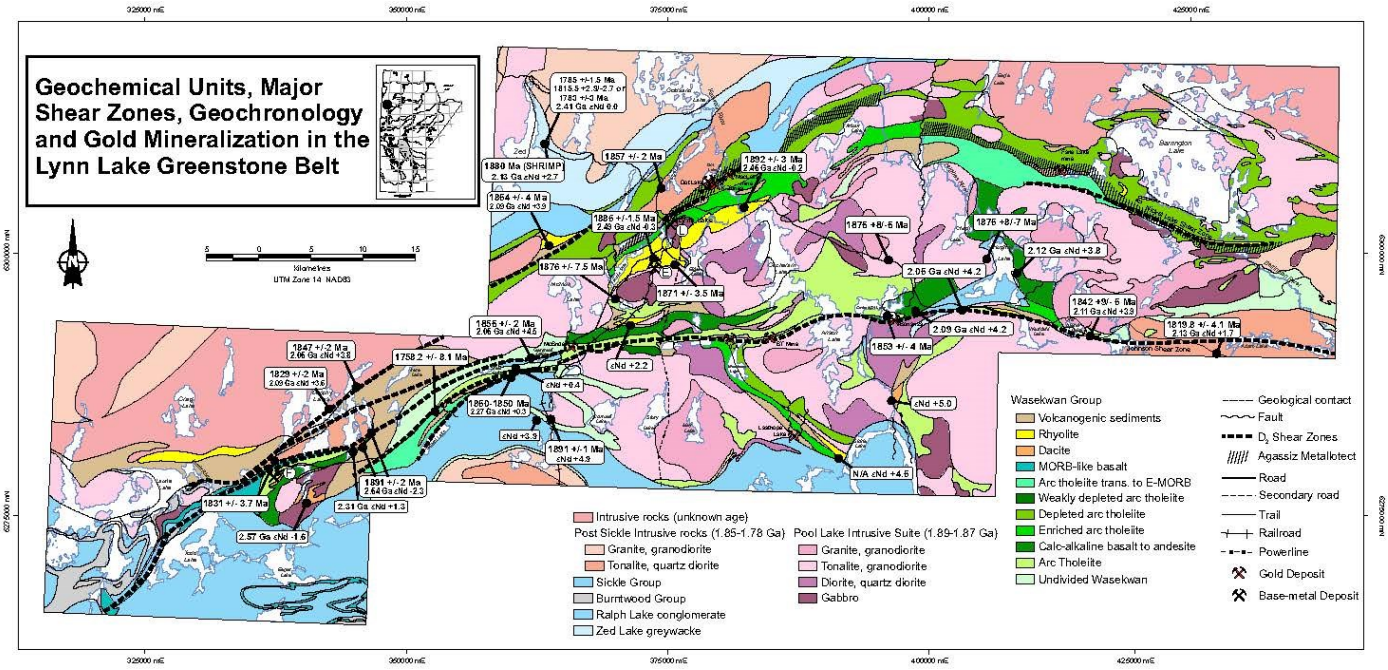


Figure 1 – Regional geology map of the Lynn Lake greenstone belt with U-Pb zircon ages and Nd isotopic compositions (modified from Zwanzig et al., 1999; Beaumont-Smith et al., 2006; Yang et al., 2015). Farley Lake and other gold deposits are shown for reference.

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Activity G-2.2

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Lawley, C.J.M., McNicoll, V.J., Davis, W.J., Jackson, S.E., Yang, Z., and Mercier-Langevin, P., 2017. Paleoproterozoic gold and its tectonic triggers and traps; *in* Targeted Geoscience Initiative – 2016 Report of Activities, (ed.) N. Rogers; Geological Survey of Canada, Open File 8199, p. 33-34. doi:10.4095/299573

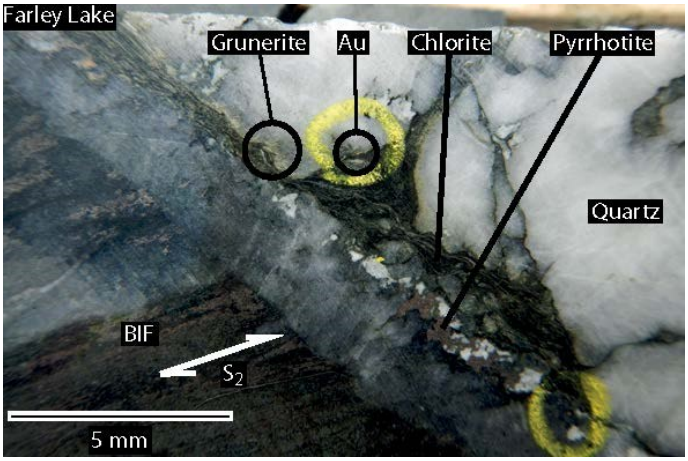


Figure 2 – Core photo from the Farley Lake deposit with visible gold. Auriferous quartz vein is at high-angle to the main deposit fabric (S2), but is reworked (syn- to post-S2) and metamorphosed. Gold is intergrown with chlorite.

the ore and waste piles of the MacLellan and Burnt Timber gold deposits, which may represent an older period of gold mineralization (Beaumont-Smith and Böhm, 2002). Together these three, past-producing gold mines represent the largest known deposits within the Lynn Lake greenstone belt and potentially record a diachronous gold history with unique triggers and/or traps (Fig. 1).

Next steps

Sample preparation for petrography and isotopic analysis is currently underway. The results from these analyzes will assist in the development of further field investigations planned for summer 2017. A masters-level studentship in support of this project's objectives is also being developed.

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Orogenic gold along Cordilleran faults: Key characteristics and analogies between Phanerozoic and Archean settings

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Introduction

This activity aims at documenting and comparing Phanerozoic orogenic gold deposits associated with major faults, and draw comparisons and analogies with Archean and Paleoproterozoic systems that are studied in companion activities of the Gold Project. The chosen field laboratory is the Tagish Lake area in northwest British Columbia (Fig. 1). This area is the locus of a series of orogenic gold prospects that are thought to have formed at various crustal depths along the long-lived, crustal scale Llewellyn fault. Also present along this corridor is epithermal polymetallic mineralization that has locally support some past-producing mines (e.g., Engineer mine). The temporal and spatial relationships between the orogenic- and epithermal-style systems along the Llewellyn fault remain to be clearly established. Previous research on these deposits has highlighted contrasting characteristics suggesting changing "depth-dependant" ore-forming conditions along the fault system. The area encompasses a wide variety of lithotectonic settings, it records several intrusive events, and it is cut by major, long-lived faults (Fig. 2). Thus, it provides tectonic and lithologic environments favourable for a wide variety of gold occurrences, similar in some ways to those of well-endowed Archean belts. This collaborative research activity complements and is integrated with a British Columbia Geological Survey (BCGS) research project.

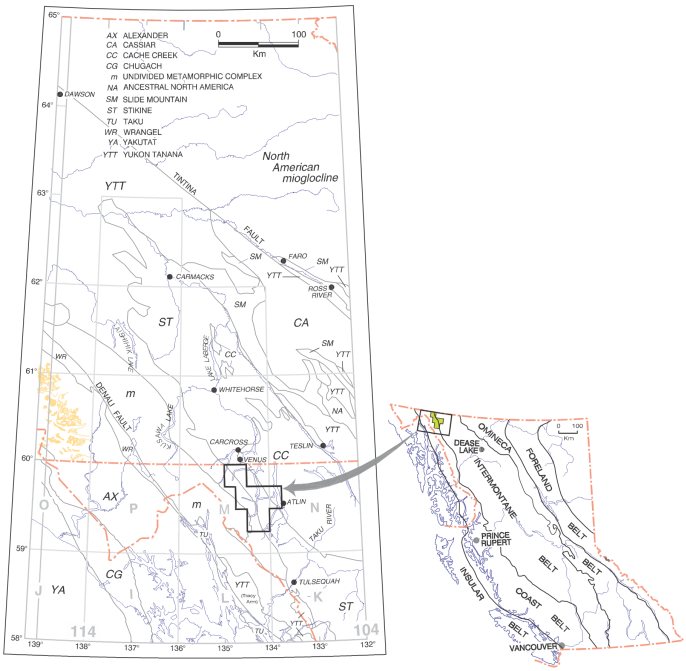


Figure 1 – Location map and regional geography and terranes (modified from Mihalynuk, 1999).

Activity highlights

A joint reconnaissance fieldtrip with BCGS in the Tagish Lake area, west of Atlin, British Columbia, was conducted in late July 2016 to gather first-hand information on the geology of the study area and establish a strong base on which a well-defined project can be designed and conducted (2017-2020). Key aspects of this fieldtrip included:

- Visiting a past-producing Engineer gold mine (epithermal-style mineralization; Figs. 2 and 3A, B) and prospects that are presumably associated with the Llewellyn fault.
- Visiting key exposures and drilled prospects along a 50 km+ segment of the Llewellyn fault to assess the style of deformation and mineralization of the various rock units (Figs. 3C, D).
- Sampling for U-Pb and Re-Os geochronology to better constrain the age of the systems.

A fieldtrip to key exposures along the Cadillac-Larder Lake and Destor-Porcupine breaks in Ontario and Quebec was also conducted.

Despite the fact that these major faults occur in very different geological settings (Cordilleran vs. Superior provinces) and were active at vastly different times (Phanerozoic vs. Archean), they share notable analogous characteristics:

- They are long-lived, and have a polyphase, synsedimentary to late-tectonic history.
- They juxtapose rocks packages of contrasting tectonometamorphic facies, originating from different crustal levels.
- Their consanguineous second/third-order structures appear to have had a major role/impact (from deposition to preser-

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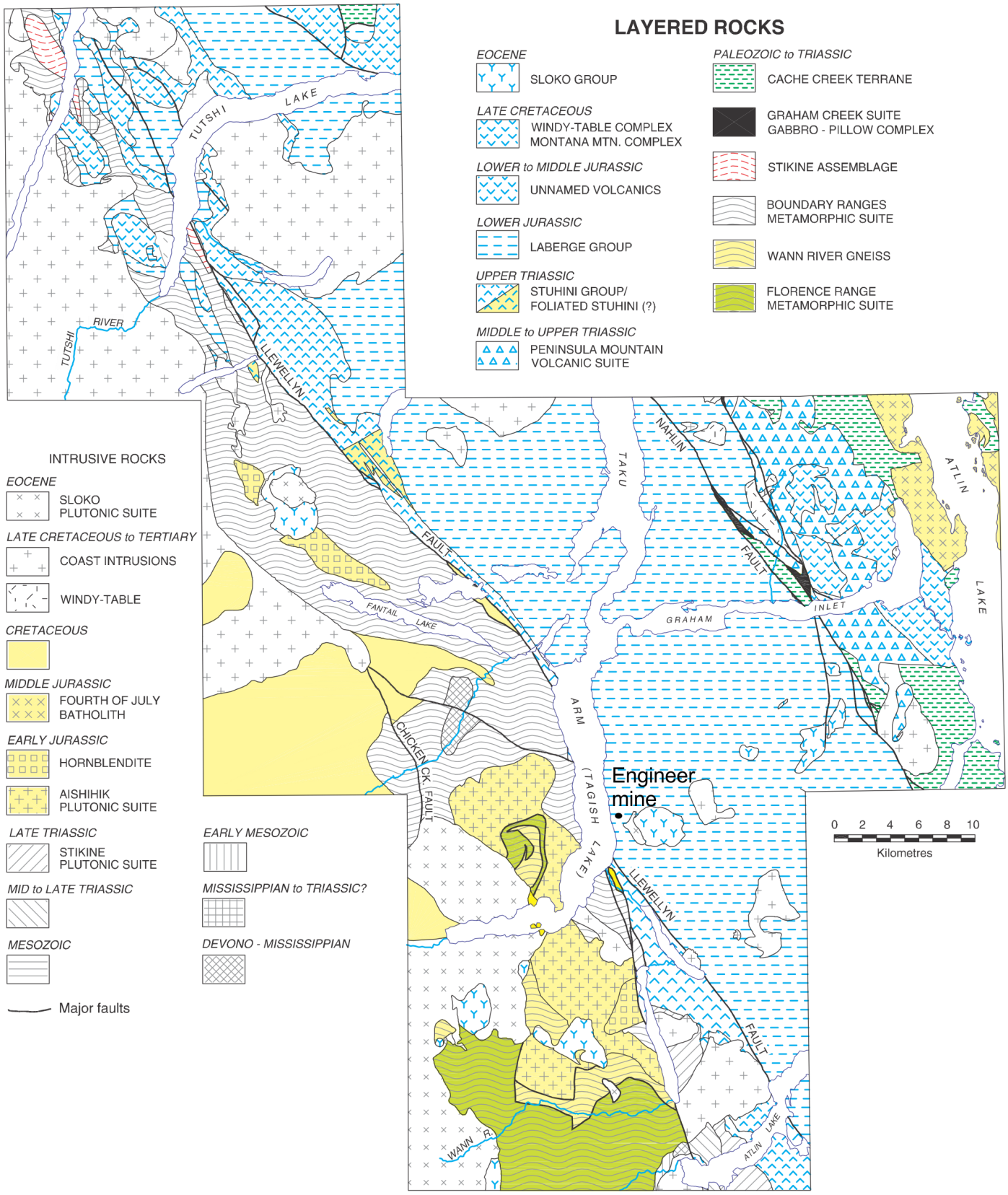


Figure 2 – Generalized geology of the Tagish Lake area (modified from Mihalynuk, 1999).

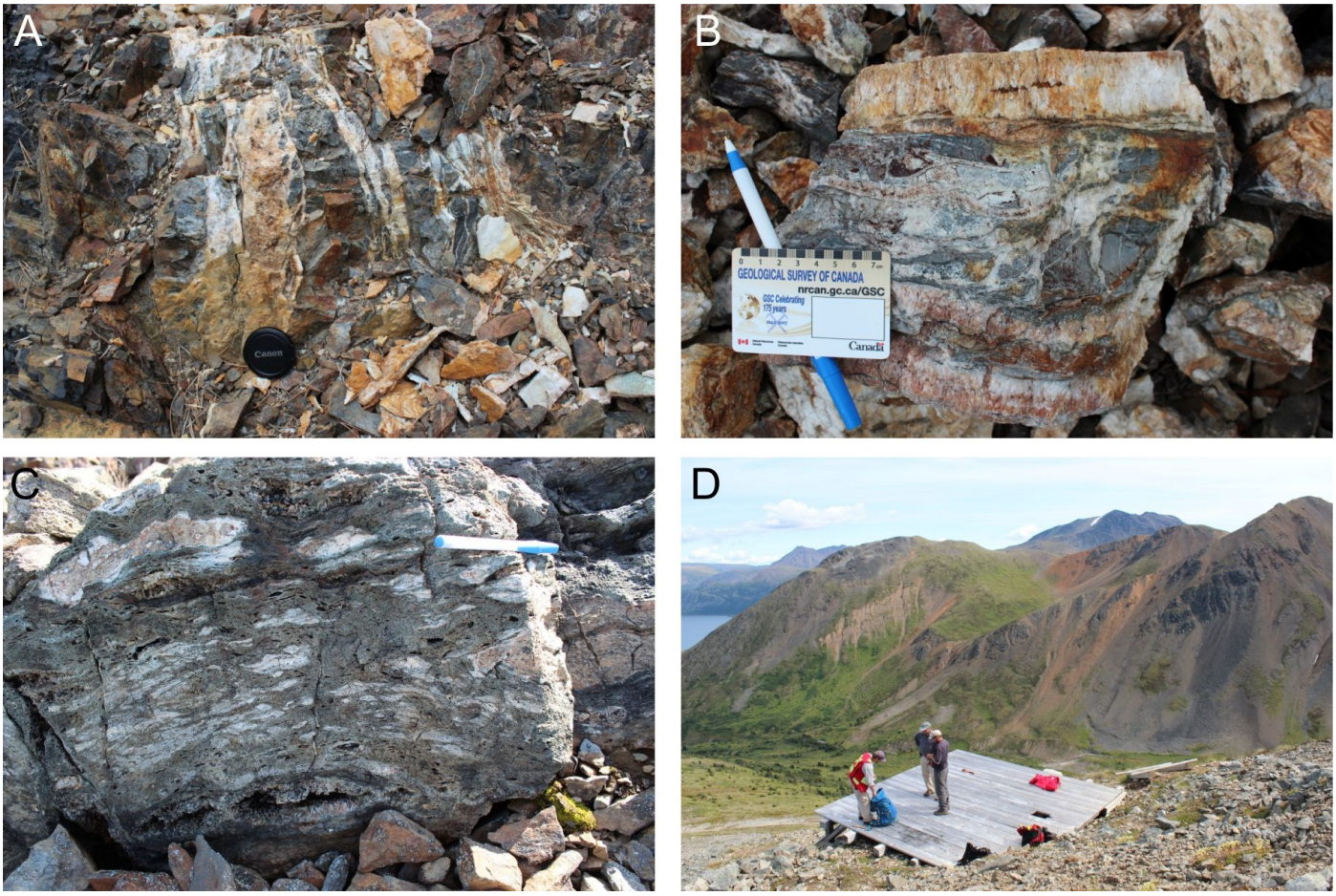


Figure 3 – A) Quartz vein associated with the Double-decker vein system at Engineer mine; B) Close-up of vein; C) Strongly sheared chlorite-amphibole-biotite schist of the Boundary Ranges Metamorphic Suite neighbouring the Llewellyn fault, west of Tutshi Lake; D) view of the Llewellyn fault section exposed, west of Moon Lake (far left); the fault juxtaposes the rusty weathered volcanic rocks and breccia of the Stuhini Group against a sliver of Late Triassic (?) granodiorite (right side of cliff face).

vation) on the occurrence and distribution of gold mineralization.

- They have some spatial association with syntectonic magmatism.

Scientific impacts

The Llewellyn fault is a long-lived/inherited major fault zone (Jurassic to Eocene), the earlier history of which is obscured by late strike-slip faulting. However, the various styles of mineralization along the fault attest to different age and crustal levels of formation.

This activity will compare the attributes of gold deposits formed along a single fault, but presumably at different crustal depths or position relative to the hydrothermal centre(s), in order to differentiate common processes from those that are specific to the depth of formation. It will also serve to further constrain the geological setting of orogenic gold deposits through time and space. This knowledge will be transposed to Paleoproterozoic and Archean deposits and will provide a testing ground for geologic models for gold deposits (e.g., the controversial crustal-scale continuum model) and establish more robust generic metallotects.

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Lithologic and tectonic controls on Paleoproterozoic BIF-hosted/associated gold

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Introduction

Recent research and exploration for banded iron-formation (BIF)-hosted gold deposits indicate complex, varied styles of gold mineralization. Such diversity and complexity is documented in the Kivalliq region of Nunavut, within its emerging gold districts (e.g., Meliadine, Meadowbank, and Amaruq), making this area a prime laboratory to study lithotectonic controls on BIF -hosted/associated gold. In these areas, gold is associated with a crustal-scale fault and its splays at Meliadine (Lawley et al., 2015a, b, c, 2016), with intensely poly-deformed BIFs at the Portage and Goose deposits of the Meadowbank mine (Sherlock et al., 2004; Janvier et al., 2015) and Three Bluffs exploration project (Davies et al., 2010), or with shallow-dipping sericite-carbonate shears at the Vault deposit (Meadowbank mine). Although gold zones are controlled by Paleoproterozoic structures (e.g., Hrabi et al., 2003; Pehrsson et al., 2013), it is hosted in Neoarchean rocks, therefore, there is a possibility for an Archean heritage on the gold budget. In this context, magnetite-rich BIFs are considered as very favourable hosts to gold due to a combination of key tectonic features such as major faults, specific rheology of some units, and high reactivity to gold-bearing fluids. But other types of iron-rich volcanosedimentary rocks (e.g., silicate-facies BIFs, cherts, etc.) and distinct deformation zones with contrasting orientations and histories also appear to be favourable hosts to gold in the area, as indicated by recent major gold discoveries made in the region. Key issues that are being addressed are the timing of gold introduction and the age and nature of the major ore-forming events in the region (i.e., Archean versus Paleoproterozoic), and test the hypothesis of an Archean heritage on the gold budget (favourable source), which remains a key scientific question in Paleoproterozoic orogens.

Activity highlights

Objectives of the lithologic and tectonic controls on Paleoproterozoic BIF-hosted/associated gold activity are to: 1) document the nature, structural setting, and age of Archean and/or Paleoproterozoic orogenic BIF-hosted gold; and 2) assess the potential controls of contrasting chemical, textural, and rheological characteristics of sedimentary and volcanic units on gold precipitation/concentration (conduits and traps) through the study of the recently discovered gold zones of the Amaruq gold project, 50 km northwest of the Meadowbank mine in the Neoarchean Woodburn Lake Group (Fig. 1, Côté-Mantha et al., 2015), acquiring new data and knowledge.

Ongoing work includes structural mapping at deposit scale, drill core logging, geochemical characterization of the host rocks and mineralized zones, U-Pb ID-TIMS/SHRIMP geochronology on zircon and monazite, Re-Os geochronology on sulphides and radiogenic and stable isotope analyzes.

Preliminary results indicate that the Amaruq gold system exhibits contrasting ore styles with dominantly stratabound, replacement-style ore zones in the Whale Tail zone (Grondin-LeBlanc et al., 2016; Lauzon et al., 2016), and dominantly discordant, shallowly-dipping shear-hosted veins in the I, V, and R zones (Valette et al., 2016).

The deposit area is mainly underlain by complexly deformed (folding and faulting) greywacke, chert, silicate-facies BIF and mafic to ultramafic rocks. The nature of stratigraphic versus faulted contacts and any genetic relationship with the gold zones remains to be established (Grondin-LeBlanc et al., 2016). The stratabound auriferous zones consist of semi-massive to disseminated pyrrhotite with coarse arsenopyrite porphyroblasts (Lauzon et al., 2016) associated with zones of "silica-flooding" (field term for diffuse, greyish, silica rich zones or dismembered quartz veining) preferentially developed in the silicate-facies BIF layers, cherts and greywackes (Fig. 2). The discordant auriferous zones seem to form shallowly-dipping planar corridors with pinch-and-swell, cm- to m-thick sugary quartz veins that commonly contain visible gold (Valette et al., 2016).

Preliminary results on Re-Os geochronology and Pb isotope analyzes suggest a long, protracted hydrothermal history and/or mixed source for the metals. Further work and analyzes are ex-

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Activity G-2.4

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Mercier-Langevin, P., Valette, M., De Souza, S., McNicoll, V.J., Grondin-LeBlanc, P., Creaser, R.A., Côté-Mantha, O., Simard, M., and Malo, M., 2017. Lithologic and tectonic controls on Paleoproterozoic BIF-hosted/associated gold; *in* Targeted Geoscience Initiative – 2016 Report of Activities, (ed.) N. Rogers; Geological Survey of Canada, Open File 8199, p. 39-42. doi:10.4095/299573

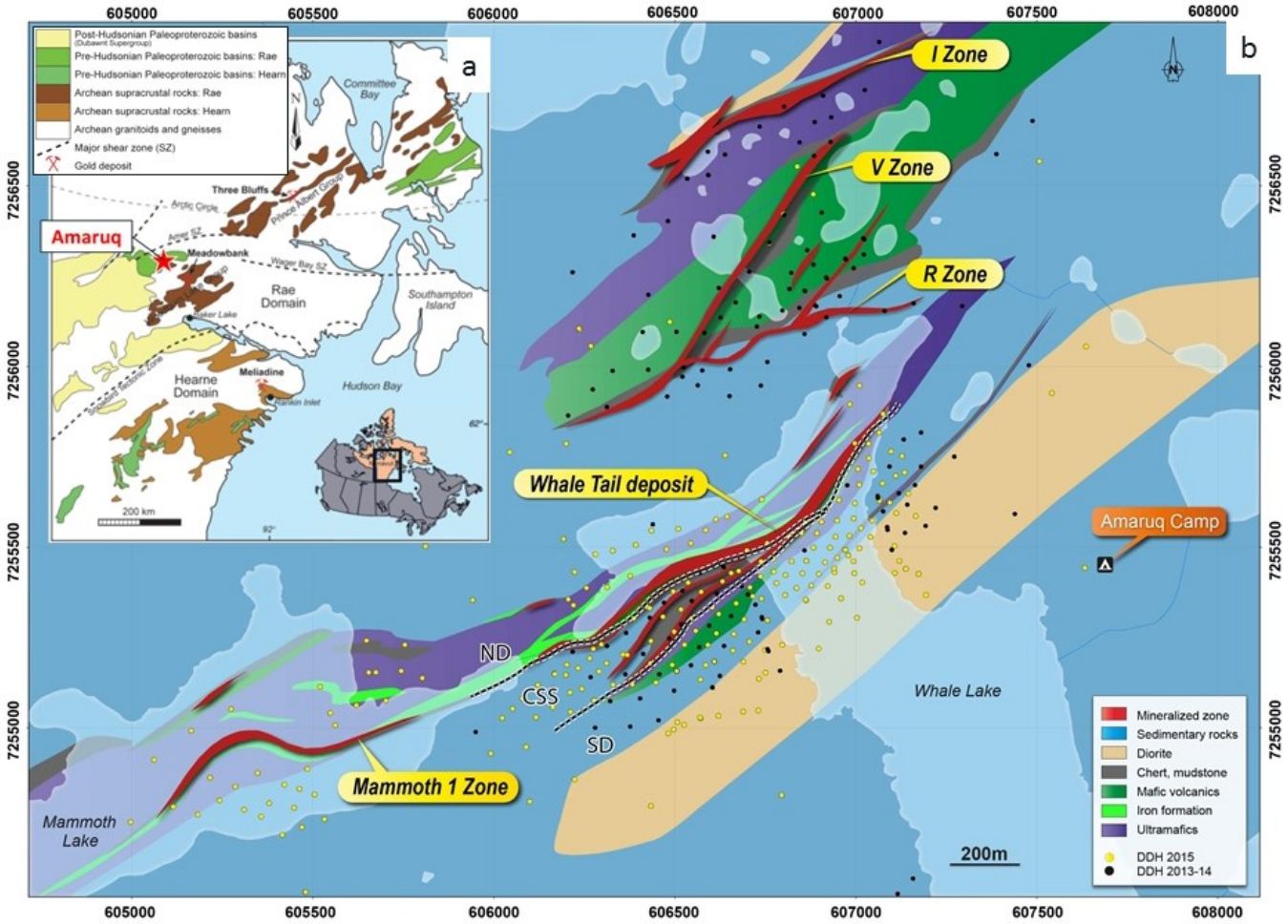


Figure 1 – a) Simplified geology of the Rae and Hearne domains of the western Churchill Province showing the location of the Amaruq gold project (modified from Davies et al., 2010). b) Simplified geological map of the Amaruq property showing the location of the mineralized zones. ND = north domain, CSS = central sedimentary succession, and SD = south domain. Figure courtesy of Agnico Eagle Mines Ltd.

pected to shed more light on the timing of events and potential metal sources in the area.

Summary

Preliminary research on the Amaruq gold system indicates that the structural setting, nature of host rocks, and ore and alteration styles are different from the Meadowbank deposit and Meliadine camp. This also indicates that the mineralizing processes can differ significantly in otherwise apparently similar contexts, bringing further information and constraints on the metallogenesis of BIF-hosted/associated gold deposits and of the Churchill Province in general.

Next steps

In-depth characterization of the protolith (lithogeochemistry and petrography) will help refine the stratigraphy in the area and provide further constraints on the geometry of the system. The characterization of the alteration and ore chemistry and mineralogy will contribute to define vectors to ore and ore-forming conditions. Geochronology (U-Pb on zircon and Re-Os on sulphides) will help constrain the geological history of the area and the timing of events. The detailed structural study will provide the relative timing and highlight the importance of the deformation in the area and facilitate district scale correlations. This information will largely come from the ongoing Ph.D. (M. Valette, UQAM), M.Sc. (P. Grondin-LeBlanc, INRS -ETE) and B.Sc. (M.-C. Lauzon, Université Laval) projects at Amaruq, and directly contribute to the objectives of the Gold project (Mercier-Langevin et al., 2017).

Acknowledgements

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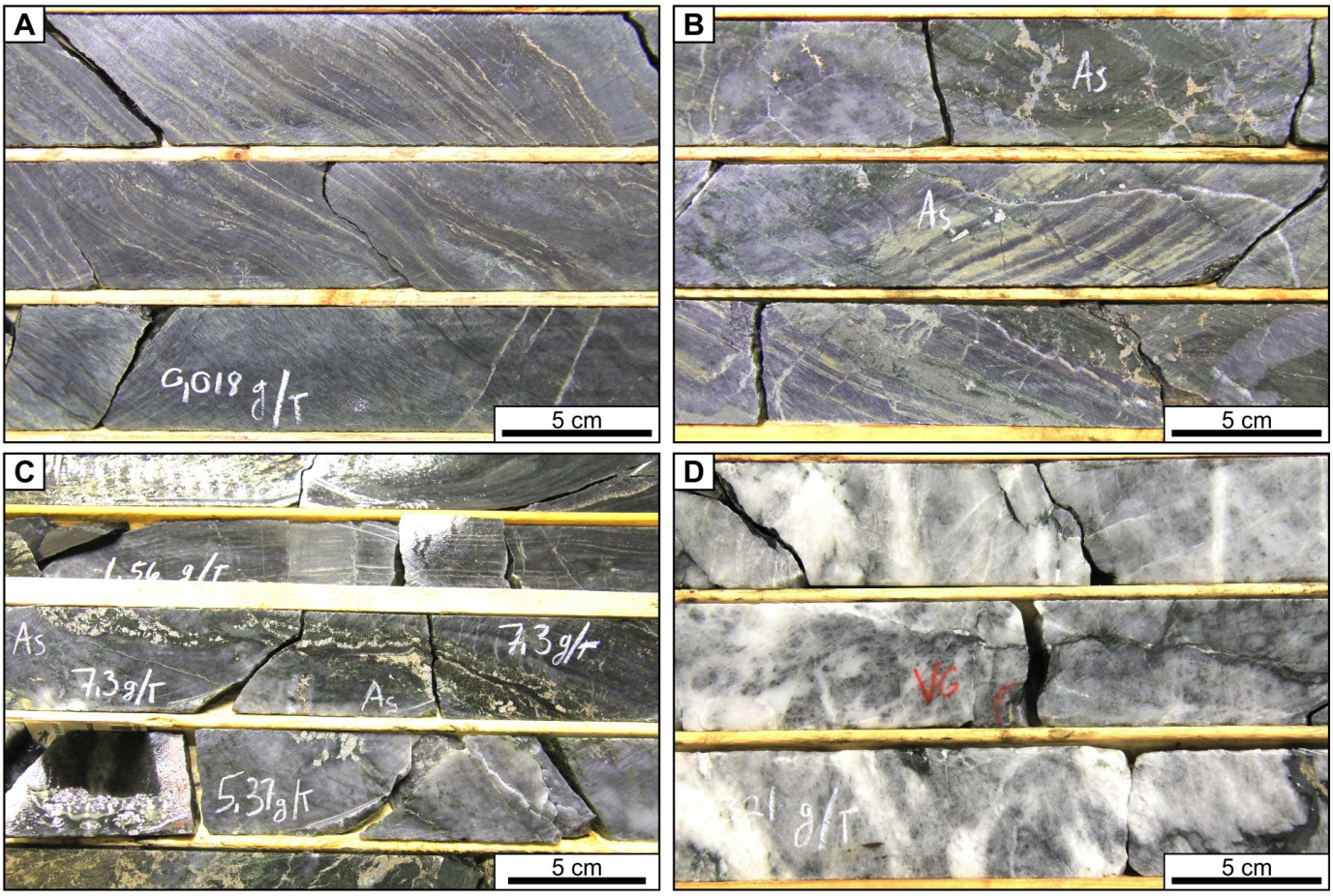


Figure 2 – Photographs of drill core intersections, ddh AMQ15-250, Whale Tail zone, Amaruq project. A) Finely laminated cherts and barren pyrrhotite-bearing argillaceous layers (top two rows) and unaltered mafic volcanic rocks (bottom row). B) Mineralized chert bands with diffuse silicification, local chloritization and or greyish quartz veins associated with fine- to coarse-grained arsenopyrite, Whale Tail ore zone. C) Gold-rich grey quartz veins with apparent stratiform arsenopyrite-pyrrhotite replacement. D) Late quartz veins with visible gold.

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Lithotectonic controls on the genesis and distribution of carbonate replacement-type ("Carlin-type") gold zones, east-central, Yukon

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Introduction

A series of carbonate replacement-type gold prospects were recently discovered in east-central Yukon. These prospects are located in an over 80 km-long corridor known as the Rackla Belt, which strikes parallel to regional major faults and to the Selwyn Basin – MacKenzie Platform boundary (Fig. 1; Colpron et al., 2013). Despite its remote setting, the understanding of the Rackla Belt has been recently improved through a multiyear mapping project conducted by the Yukon Geological Survey (e.g., Colpron et al., 2013) that provides a robust geological framework in which more detailed works may be integrated.

Previous studies of these gold prospects (e.g., Poulsen et al., 1996; Tucker et al., 2012; Arehart et al., 2013; Tucker, 2015; Thiessen et al, 2016; Palmer and Kuiper, 2016) suggest that the Rackla Belt hosts mineralized zones with distinct characteristics, including one of the rare examples of true "Carlin-type" mineralization identified outside of Nevada.

Carlin-type deposits in Nevada are a major source of gold and one of the main world exploration targets because of their potential size. Among the important scientific questions related to Carlin-type deposits are: why one region has so many of the disseminated gold in sediment-hosted deposits; and, does some Nevada-specific combination of geological events and/or fertile source rocks (cf. Sillitoe, 2008) explain this exceptional endowment?

Study of the Rackla Belt provides an opportunity to review, outside of Nevada, but in a geological setting that shares many similarities with the type area (passive margin of Rodinia during the Neoproterozoic/Paleozoic; part of the Cordilleran accretionary wedge during the Mesozoic/early Tertiary, Siluro-Devonian impure carbonate rocks), the geological characteristics that are necessary to form Carlin-type deposits with the long-term objective of improving genetic and exploration models for such gold deposits in the northern Canadian Cordillera.

Current state of knowledge

Although significant structural control on mineralization is documented locally, correlations between sites and linkages to larger scale structural features/events are not fully established. Indeed, the structural styles vary significantly between prospects, whereas uncertainties about the geometry and kinematics of major structures hamper the development of more rigorous tectonic and metallogenic interpretations.

At the district scale, mineralization is not restricted to a single rock unit, and lithological controls, if there are any, are not established. However, subtle variations in the chemistry, porosity/permeability and/or mechanical properties of the original host rocks may have locally influenced mineralized fluid circulation, the development of favourable traps and metal precipitation.

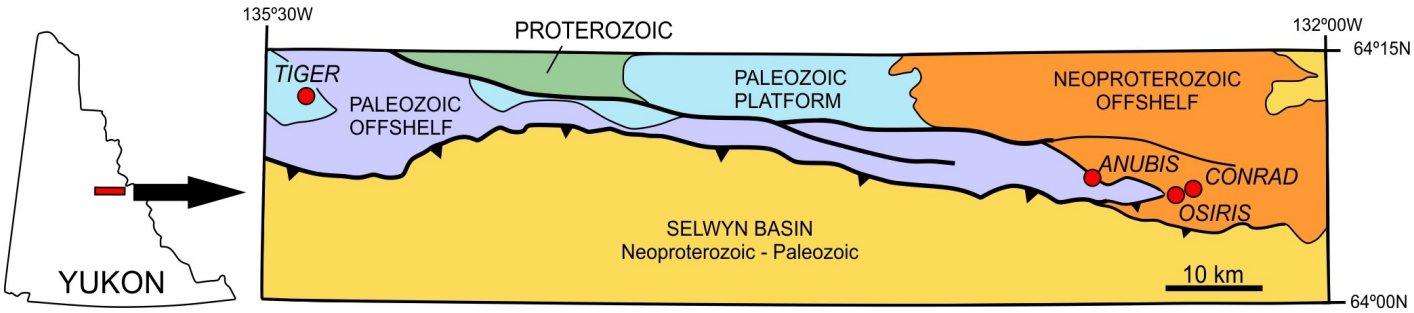


Figure 1 – Geological setting of the Rackla Belt in east-central Yukon (simplified from Colpron et al., 2013). Red circles correspond to the four main prospects studied or visited in 2016. Other prospects are known between the Tiger and Conrad prospects but are omitted for clarity.

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TGI 5 (2015-2020) Gold project
Subproject 2: Tectonic influences on gold deposits (tectonic drivers and conduits)
Activity G-2.5

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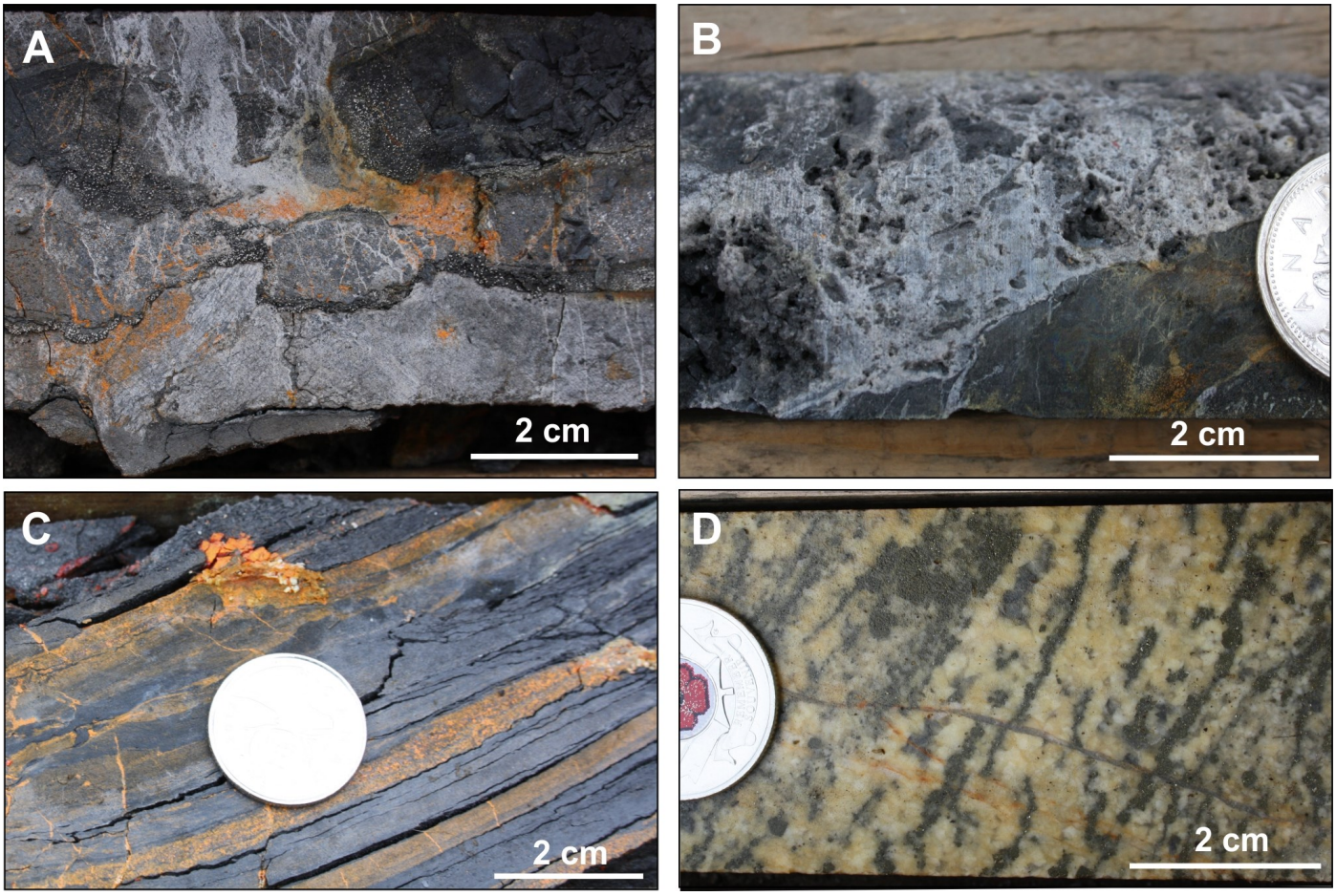


Figure 2 – Mineralization styles within the Rackla Belt. A) Conrad prospect- Mineralized breccia with realgar filling fractures and breccias. B) Anubis prospect- High-grade silica-rich breccia with a vuggy silica texture; C) Osiris prospect- Mineralized interval with realgar-rich millimetric bands sub-parallel and perpendicular to bedding; D) Sample from the intrusion-associated replacement-style Tiger prospect showing pyrite-rich veinlets and ankerite/dolomite irregular replacement layers forming a pseudo-bedding.

The Carlin-type deposits of Nevada are commonly spatially, and, according to some, possibly genetically associated with intrusive rocks. Such an association is not clearly displayed in the Rackla Belt, as intrusive rocks are scarce, limited to a poorly outcropping granitic pluton and a few gabbroic dikes in the Tiger and Conrad prospect areas, respectively.

Activity highlights

Field reconnaissance of the four main prospects of the Rackla Belt was conducted in July 2016. These prospects are hosted in four distinct lithologic units composed of limestone, dolostone and calcareous mudstone that range in age from Neoproterozoic to Devonian. The 2016 reconnaissance studies were aimed at documenting, on a very preliminary basis, the mineralization styles and potential lithological/structural/magmatic controls, as well as clarifying and prioritizing the knowledge gaps to be addressed going forward.

Initial field studies indicate that the structural styles vary significantly between prospects. They also confirmed that the Conrad, Osiris and Anubis gold prospects, which are located in the eastern part of the Rackla Belt, have some characteristics commonly associated with Carlin-type deposits (Fig. 2). At the macroscopic scale these traits include: 1) clear structural control (faults and folds); 2) sedimentary-hosted mineralized zones with a fine dark grey to black colour matrix; 3) decarbonatization hosting, or close to, mineralized intervals; 4) the common occurrence of realgar and orpiment; 5) multiple generations of calcite/dolomite veins commonly surrounding the mineralized zones; 6) the presence of silica-rich hydrothermal breccias and vuggy silica zones; 7) mm- to cm-thick mineralized zones sub-parallel or at high-angle to bedding; and 8) the local occurrence of bitumen.

A visit of the Tiger prospect in the western part of the Rackla Belt suggests that the mineralization style is markedly different from typical Carlin-type deposits and may share more similarities with intrusion-related replacement mineralization.

Next steps

Although striking similarities between the gold prospects in the eastern part of the Rackla Belt and the Carlin-type deposits

of Nevada have been established, the structural, lithologic and possibly magmatic controls, as well as the age of mineralization, await resolution. The diversity of styles of gold mineralization and how this impacts exploration guidelines also need to be resolved. These key knowledge gaps will be addressed through a multidisciplinary study based on available information and on new geochronological, geochemical and paleontological data, as well as field observations and core logging.

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System scale and deposit scale controls on Ni-Cu-PGE mineralization in cratonic areas and their margins

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Introduction

Magmatic ore deposits of Ni-Cu-PGEs, Cr, and Fe-Ti-V represent an important class of mineral deposits across Canada, forming the backbone to a number of established and emerging mining camps (e.g., Thompson, Raglan, Sudbury, Voisey's Bay, Mid-Continent Rift (MCR), Ring of Fire and other Archean, Proterozoic, and also younger settings: e.g., Ames and Houlé, 2015). They are the product of magmatic ore systems, ultimately fuelled by large volumes of deep-seated magma derived from the Earth's mantle. Thus, they are an integral component of larger magmatic systems (generally referred to as "igneous provinces", or at the largest scale "large igneous provinces" or LIPs), with typical footprints on the ~200-2000 km scale (e.g., Ernst and Bleeker, 2010). Within these larger magmatic systems, the majority of mineral deposits form near the magmatic centre of the system, often in clusters, where magma fluxes are highest and more focused, and the geological conditions are more dynamic (e.g., rifting, upwelling mantle, trans-lithospheric faults, active magma conduits). Final character of the mineral deposits, enrichment of specific metals, and size and grade depend on magma composition, magma flux, nature of the wall rocks, efficiency of the trapping mechanism, and numerous other local variables and conditions. Sudbury (Pye et al., 1984; Ames et al., 2008a, b) is both unique and an exception, in the sense that the large magma pool and the conditions for efficient metal segregation were created not by endogenic processes but by a large meteorite impact (e.g., Stöffler et al., 2002) and a superheated, density stratified, melt sheet (e.g., Zieg and Marsh, 2005).

An in-depth understanding of this class of deposits, and improved, accurate and more predictive models for their formation and localization requires, fundamentally, a system-wide understanding of the magmatic systems at the true system scale: i.e. the magma sources and their composition (source and fertility); melting processes and partition coefficients; what was the magmatic plumbing system (conduits); where were the highest fluxes; where and how were metals concentrated (traps); sulphur sources and timing of sulphide saturation; local and regional stratigraphic controls; and which specific magmatic pulses were most productive, and what were their specific tectonic drivers or triggers?

This subproject will significantly advance the understanding of this class of deposits, and their fundamental ore systems, by integrating data across all scales, from the deposit scale to the full magmatic system scale. Numerous incremental advances have been made in recent years, but rarely have they been integrated across the full system scale. Only a national project of the scope of TGI, and executed by collaborative teams, is able to make this critical advance in established and emerging camps, and across Canada.

Research Activities

This subproject is divided into three activities (summarised below) each focussed on somewhat different research themes.

Activity NC-1.1: Extent, origin, and deposit-scale controls of the 1883 Ma Circum-Superior large igneous province, northern Manitoba, Ontario, Quebec, Nunavut and Labrador

World-class Ni-Cu-PGE mineralization of the "Circum-Superior belt" (e.g., Thompson, Raglan) formed during voluminous ultramafic magmatism at the onset of a major magmatic event, at 1883 Ma. The overall tectonic setting of this event, and its triggers, remain poorly understood. New ages (e.g., precisely dated gabbro sills at Raglan, 1883.0±1.7 Ma; ages of similar precision at Thompson; and coeval dykes across the Superior craton) underscore a common process and force a new look at this unique event. Comparison with Phanerozoic global tectonic events would suggest involvement of a starting mantle plume in association with necking of the continental lithosphere and/or continental breakup. This activity intends to develop a new integrated model for this large igneous province and its magmatic mineral systems from Manitoba to northern Quebec and Labrador, and across a range of scales (from the deposit scale to the full system scale). It will evaluate and add critical new knowledge to all segments of the Circum-Superior belt (Winnipegosis, Thompson, Fox River, Sutton Inlier, Hudson Bay, Cape Smith, northern Labrador Trough), in collaboration with provincial and territorial partners, and industry. By integrating new and existing information, this activity will define the overall architecture of the magmatic system(s) and characterize system- to deposit-scale controls on mineralization, which will assist in the identification of areas of additional mineral potential. Petrologic studies will characterize mantle sources and address questions of source fertility. The overall system architecture, aided by high-precision U-Pb geochronology, will address tectonic triggers and system-scale conduits. This will also involve a new sequence-stratigraphic synthesis of the entire margin, again aided by high-precision geochronology on key stratigraphic packages and critical magmatic units. Deposit-scale studies at Thompson and Raglan will help define or refine local controls and traps, and styles of structural remobilization, and will contribute to finding extensions of known

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TGI 5 (2015-2020) Ni-Cr-PGE systems project
Subproject 1: System scale and deposit scale controls on Ni-Cu-PGE mineralization in cratonic areas and their margins

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ore deposits and/or structural repeats of known ore horizons. One research focus will be the Cape Smith segment, which now hosts several mature Ni-Cu-PGE mines and advanced projects. In this belt, deposits occur predominantly within two main "trends", the Main trend (i.e., Raglan-Katinniq) and the South trend (i.e., Expo-Ungava). Although the mafic-ultramafic intrusions/flows of these two trends are interpreted to be coeval and comagmatic, there appear to be significant differences in emplacement (extrusive vs. intrusive), mineralization styles and metal endowment. Through detailed studies of the volcanic and subvolcanic architecture of these two trends, and a comparison of the petrological and geochemical characteristics of the different ultramafic and gabbroic units, we will develop predictive models that explain these differences.

Activity NC-1.2: Localization of high-value footwall mineralization within the Sudbury Impact Structure.

Sudbury is one of Canada's most prolific mining camps with >70 Ni-Cu-PGE deposits. As mines are getting deeper, and more expensive, more and more effort is being spent on finding vein-type "footwall deposits" where fractionated sulphide liquids enriched in Cu, Ni, and precious metals have infiltrated the fractured footwall of the 1849.7 Ma impact crater. These footwall veins are highly valuable but represent difficult targets to locate at depth. Even more difficult to identify and locate are low-sulphide precious metal-rich (Pt-Pd-Au) footwall deposits—the newest and different type of footwall mineralization in the district. Although Sudbury is to some degree unique, the ultimate cause of melting and magma generation being a large meteorite impact, it has been and remains one of the main natural laboratories for understanding the migration and progressive fractionation of magmatic sulphide liquids, and sub-solidus secondary remobilization of sulphide mineralization in response to on-going regional deformation and younger hydrothermal/metamorphic events. There is no better place in Canada to improve our understanding of these fundamental ore system processes. The more than 70 mines and deposits and numerous deep drill holes provide unparalleled access to the mineralized settings, and a century of geological research provides a more detailed context than available at other Canadian deposits. This activity will focus on documenting these sulphide mobilization, re-mobilization, and metal fractionation processes to determine key physical and chemical processes involved. A new mechanical model that makes specific predictions on the distance of remobilization of sulphide veins into the deformed footwall will be developed and tested. Furthermore, processes responsible for hydrothermal Pt deposits (i.e., McCreedy West PM zone, Denison) will be unravelled using cutting-edge research techniques involving noble gas isotopes, fluid inclusion chemistry, stable isotopes (i.e., compound-specific δ13C and δD on bulk inclusion samples), stable isotope LA-ICP-MS mapping (garnets), and melt inclusion chemistry. The activity will also address various gaps in the complex history of the Sudbury area, thus improving the overall knowledge base for the Sudbury Impact Structure and its world-class mineralization, and providing the necessary background knowledge to correctly interpret and attribute metal remobilization events. New observations will be synthesised by means of the first detailed, integrated, cross-section across the entire area that will have the same "look and feel" as the well-known GIS-based map of the Sudbury area. These products will foster a better understanding of the Sudbury structure and its complex ore systems and thus both enhance exploration efficiency and education of a next generation of industry professionals. Finally, this research will provide fundamental knowledge on source to ore processes that can be applied to other Ni-Cu-PGE settings across Canada.

Activity NC-1.3: Controls on the localization and timing of mineralized intrusions in intra-continental rift systems , with a specific focus on the c. 1.1 Ga Mid-Continent Rift (MCR) system.

North America's Mid-Continent Rift (MCR) is one of the largest and best-preserved intra-continental rift systems of late Mesoproterozoic age. It hosts the second largest layered intrusion (Duluth Complex) in the world, with extensive low-grade Ni-Cu-Co-PGE resources, and possibly reef-type PGE mineralization. The failed rift also hosts a number of smaller, localized, conduit-type intrusions ("chonoliths") that are mineralized with higher grade Ni-Cu sulphides (e.g., Eagle). These intrusions remain attractive but challenging targets for mineral exploration, on both side of the Canada-US border. Key scientific questions are: 1) what localizes the mineralized intrusions; and 2) how do they relate in time and space to the overall evolution of the rift system and its various magmatic pulses. These key questions relate directly to the overall objective of the magmatic Ni-Cu-PGE subproject, at both the system and deposit scale, and they address various aspects of a source-to-ore understanding of magmatic ore systems in rift settings. Although the MCR rift system has a rich legacy of past and ongoing research, including a number of comprehensive dating studies, most of these studies were carried out prior to the introduction of routine "chemical abrasion" methods in U-Pb zircon dating studies. Also, we now have a better understanding of the subtle differences in isotopic systematics between zircon and baddeleyite, both of which are common accessory minerals in gabbroic and alkalic intrusions, and may also occur in thick ponded basalt flows. Therefore, we now have unprecedented ability to resolve million year, or even sub-million year-scale events in the complex magmatic evolution of well-preserved rift systems such as the MCR. By resolving and untangling some of the key processes we will gain insights into how the rift evolved, its various magmatic pulses, and why mineralized intrusions occur where they do. There are other good reasons to do this fundamental ore system research in the MCR, beyond its remarkable preservation: it is very accessible, it is being actively explored by a number of companies, and it provides a fertile environment for multidisciplinary collaboration with a number of academic centres of expertise.

Activity highlights

To illustrate some of the ongoing research activities we briefly describe new results from the Raglan belt, Northern Quebec, with reference to Figure 1. At Raglan, a generally north-dipping sequence of volcanic and sedimentary rocks, overlying basement of the northern Superior craton, has long been viewed as a multiply imbricated thrust pile (e.g., St-Onge and Lucas, 1993; see Fig. 1a). In very broad outline, from

south to north, the (tectono)stratigraphy consists of autochthonous to para-autochthonous lower Povungnituk sedimentary rocks, a thick pile of Povungnituk basaltic lavas, more sedimentary rocks, numerous mafic-ultramafic sills, Mg-rich and more primitive Chukotat volcanic rocks, additional sedimentary panels, and a complex of overlying and possibly allochthonous tectono-stratigraphic units, including the c. 2000 Ma Watts Group (e.g., St-Onge et al., 1992; Lucas and St-Onge, 1992; St-Onge and Lucas, 1993). Many thrust have been interpreted based primarily on the reappearance of clastic sediments in the otherwise volcanic dominated pile. If these tectono-stratigraphically higher panels of clastic sedimentary rocks indeed represent structural repeats of lower Povungnituk sedimentary rocks, from the base of the stratigraphic section, then such thrusts are required. However, as shown in Figure 1b, our alternative interpretation is that many of the higher sedimentary intercalations are in fact unique stratigraphic units, each with their own character, i.e. they are not structural repeats. In sim-

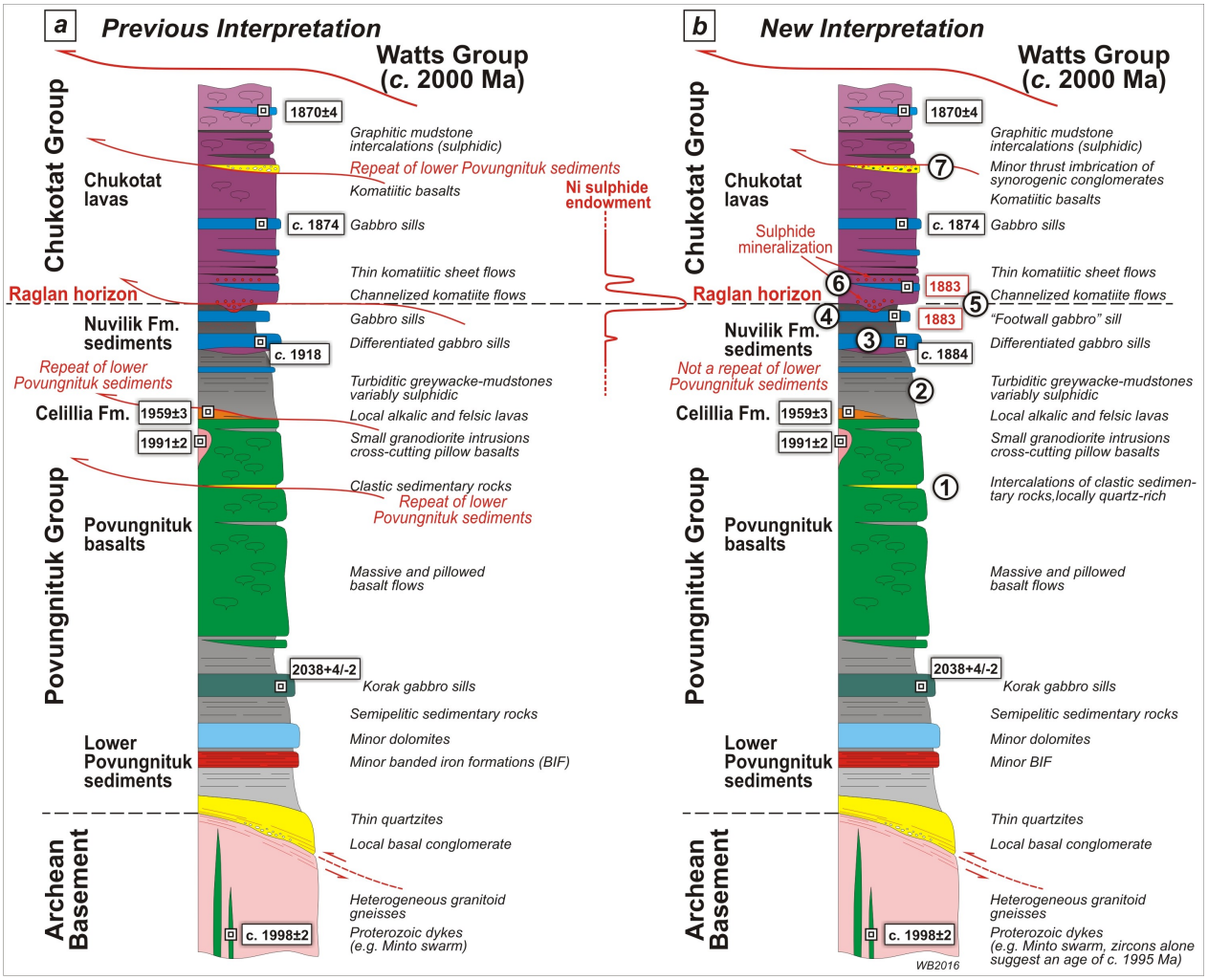


Figure 1 – Tectono-stratigraphic columns for the Raglan area, Cape Smith Belt. a) Previous interpretation of a strongly thrust-imbricated tectono-stratigraphic pile, with north-dipping thrust bringing back lower Povungnituk sedimentary rocks at various levels throughout the pile (after St-Onge and Lucas, 1993). The main Povungnituk–Chukotat Group contact was also considered a regional thrust. b) Revised interpretation based on the current study, with considerably fewer thrusts. Stratigraphically higher sedimentary units represent distinct sedimentary formations (e.g., Nuvilik Fm.) rather than thrust repeats of lower Povungnituk sedimentary rocks. Points 1 to 7 are briefly discussed in the text. Numbers in rectangles represent U-Pb ages (in Ma). Bold red curve schematically highlights the strong concentration of the Ni sulphide endowment at or near the basal contact of the Chukotat Group, along which komatiitic lavas (Chukotat Group) overlie greywackes and sulphidic mudstones of the Nuvilik Formation (top of the Povungnituk Group). Interaction (thermo-mechanical erosion, assimilation) of the hot and low-viscosity komatiites (metal source) with the mudstones (sulphur source) led to sulphide saturation and ore deposition. Ore formation is now precisely bracketed at 1883 Ma. Note that in situ thermal erosion contacts at the base of the komatiites cannot be reconciled with a major thrust contact between the Chukotat and Povungnituk Groups. Age references: Machado et al. (1993); Parrish (1989); Wodicka et al. (2002) and pers. comm., 2013; Bleeker (2013) and (2014); Buchan et al. (1998); see also St-Onge et al. (2000).

ple terms, there are fewer thrusts and there is more stratigraphy.

Nevertheless, the Raglan belt is obviously deformed and the entire Raglan horizon is structurally repeated by a major south verging syncline-anticline pair, the overturned limb of which evolved into a thrust plane (for details, see Bleeker, 2013), the only clearly resolvable major thrust in the area based on structural and field observations. This structure repeats the mineralized Raglan horizon to the north of main mineralized belt that currently has half a dozen producing deposits. Smaller scale parasitic fold structures, on the scale of individual deposits, also occur and locally resulted in overturned or south facing stratigraphy of both ore and host rocks, such as at the Kikialik deposit (again, see Bleeker, 2013 for details).

With reference to the new stratigraphic interpretation as shown in Figure 1b, we specifically discuss seven important points:

1. Thin intercalations of clastic sedimentary rocks, some rich in quartz, occur within the continental Povungnituk basalts and, as alluded to above, are stratigraphic intercalations rather than thrust repeats of lower Povungnituk sedimentary rocks. No major thrust is required at the base of these sedimentary units, nor did we see obvious evidence for a thrust in the field.

2. Similarly, the mostly deep water, turbiditic, greywackes and mudstones of the Nuvilik Formation represent a distinct formation at the stratigraphic top of the Povungnituk Group (as currently defined), not a repeat of its basal sedimentary section. These sediments must significantly post-date the main pulse of Povungnituk basaltic volcanism, perhaps representing the thermal subsidence phase following the waning of Povungnituk magmatism. Sulphide-bearing mudstones of this formation acted as the sulphide source for the Raglan ore bodies at the base of the Chukotat Group (this notion has long been recognized in the exploration community; see Lesher, 2007, for a relevant summary).

3. Differentiated gabbro sills intruding into the Nuvilik Formation were thought to be perhaps as old as c. 1918 Ma (Parrish, 1989). However, careful evaluation and reinterpretation of the variably discordant baddeleyite and zircon data suggest that these gabbro sills may be ca. 1884 Ma in age, and within error of 1883 Ma (Bleeker, 2014; see also Wodicka et al., 2002). A variety of available data, both published and unpublished, currently suggests that the dates on these gabbro sills start to converge on a single short-lived event at ca. 1883 (see also Randall, 2005; and Mungall, 2007).

4. A new (preliminary) U-Pb zircon age on the main "footwall gabbro" sill at Katinniq shows this sill to be also c. 1883 Ma, based on chemically abraded concordant zircons (work in progress under TGI; Bleeker and Kamo, unpubl. data).

5. Some of the main sulphide lenses at the base of the Chukotat Group komatiites sit directly on this footwall gabbro sill, with a contact that is characterized by 1) only weak shearing, directly overlying 2) medium-grained gabbro that lacks a chilled margin (Fig. 2). These observations stratigraphically tie the Chukotat lavas to the Nuvilik Formation and rule out that the main Povungnituk Group – Chukotat Group contact is yet another major thrust (cf. Lucas and St-Onge, 1992; St-Onge and Lucas, 1993). The absence of a chilled margin in the gabbro supports

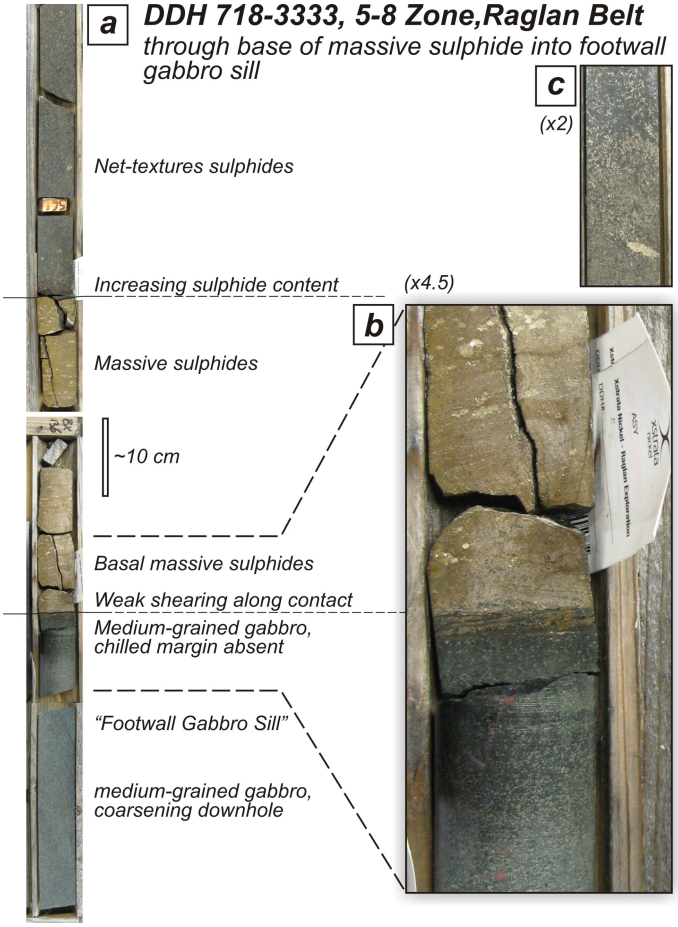


Figure 2 – Image collage of diamond drill hole (DDH) 718-3333, "5-8 Zone", Raglan belt. Intersection shows the basal contact of the massive sulphide lens on the underlying "footwall gabbro" sill. Diameter of core ca. 4.8 cm in all images (NQ). a) Overview image of ca. 1 m of core through basal sulphide contact. Note massive sulphide straight on medium-grained gabbro. b) Close-up of this contact. Only weak shearing seen in sulphides, and no chilled margin in the gabbro. c) Image of net-textures sulphides with larger sulphide blebs ca. 1 m above the massive sulphide zone.

the interpretation that the komatiites thermally eroded down into the gabbro sill, with exsolved sulphides collecting in flow channels and pools. Local absence of the uppermost Nuvilik Formation turbiditic mudstones may support their removal by thermo-mechanical erosion at the base of the komatiites (e.g., Lesher, 2007). It is important to realize that the alternate interpretations of 1) a thermally eroded basal contact of the first Chukotat komatiite flows into Nuvilik Formation and/or gabbro sills (Fig. 1b), and 2) a major early thrust contact (Fig. 1a), are irreconcilable. Current observations do not support the presence of a major regional thrust at this upper contact of the Nuvilik Formation, neither here nor at the lower contact of the Nuvilik Formation where it overlies and blankets Povungnituk lavas.

6. We have also precisely dated a gabbro sill which intruded within the lower Chukotat lavas, above some of the main sul-

phide ore lenses. This gabbro sill clearly post-dated the onset of komatiitic volcanism and the main phase of sulphide ore accumulation and shows chilled margins at both contacts. At the age resolution of currently available data (ca. 2 Myr), there is no resolvable age difference between this hanging wall gabbro sill and the main footwall gabbros, thus precisely bracketing the onset of komatiite volcanism and ore formation at 1883 Ma.

7. Higher in the tectono-stratigraphy, distinct lenses of clastic sedimentary rocks (Fig. 3) may also be unique stratigraphic units rather than yet again repeats of lower Povungnituk sedimentary rocks. Polymict conglomerate lenses at this level may represent infolded units of syn-orogenic conglomerates, i.e. the youngest stratigraphic units in the belt rather than the oldest. This interpretation is easily tested by means of detrital zircons. It is predicted that these conglomerates and sandstones contain young zircons with ca. 1850-1800 Ma ages. If so, only a moderate amount of late, syn-orogenic, thrust imbrication or infolding would be required to capture these synorogenic rocks within the main belt of Chukotat Group lavas.



Figure 3 – Polymict conglomerate of probable syn-orogenic origin, with a variety of granitoid and mafic volcanic clasts. Conglomerates such as these are intercalated in the Chukotat Group lavas north of the Raglan belt. If indeed of syn-orogenic origin, only minor, late, thrust imbrication or infolding is required. If on the other hand this conglomerate represents lower Povungnituk sedimentary rocks (cf. St-Onge and Lucas, 1993), major early thrust imbrication is required. Detrital zircons may provide an easy test for these radically different hypotheses.

Finally, and beyond the scope of Figure 1, a broad, first-order, basement-cored antiform to the north of the Raglan Belt, the Kovik Antiform (Fig. 4; see Hoffman, 1985; Lucas and St-Onge, 1992), has many characteristics of an extensional core complex, rather being related to on-going shortening and high-amplitude folding. Deformed sheets of leucogranite on the contact of this antiform may date the formation of this core complex. On-going work will test these new ideas.



Figure 4 – A view of the broad, domal, basement-cored antiform to the north of the Raglan belt, the Kovik Antiform, in which retrogressed granitoids and gneisses of the Superior craton are brought back to the surface. Deformed leucogranite sheets occur along the sheared contacts of this dome, recording "off-the-dome" kinematics. These observations are consistent with an extensional core complex origin for this large antiform in the metamorphic internal zone of the orogen.

Next steps

Work currently in progress is testing the new ideas for the Raglan belt in more detail, and additional fieldwork will be undertaken in 2017 and 2018. Each activity will also support one or two graduate student thesis projects.

Research similar in scope to that at Raglan is also planned or is in progress under the Sudbury (NC-1.2) and MCR (NC-1.3) activities. An important new result at Sudbury is the 1748±5 Ma age (upper intercept, U-Pb zircon) for the regional "Trap dyke" swarm across the South Range of the Sudbury impact structure (see Bleeker et al., 2015). This curved dyke swarm, convex to the north, mimics the curved shape of the South Range. This dyke swarm thus provides an important strain gauge and time marker, showing that the curvature of the South Range is a late feature, imposed after 1748 Ma due to open refolding on a regional scale.

As part of our studies of the MCR, we characterized the platinum group minerals (PGMs) in four Cu-PGE sulphide deposits hosted by cogenetic gabbros in the Coldwell Alkaline Complex, and defined the relationship between PGM assemblages and ranges for Cu/Pd geochemistry (Ames et al., 2016; Good et al., submitted). The "W Horizon", Marathon Cu-Pd deposit, is one of the highest grade platinum group element (PGE) repositories in magmatic ore deposits globally. In a comprehensive study of the 52 precious metal minerals identified in the extremely enriched W Horizon orebody, several new PGMs were discovered (i.e., marathonite ($Pd_{25}Ge_9$), coldwellite (Pd_3Ag_2S)), in addition to three unknown sulphides that are clearly enriched in Rh (averaging 4.2, 8.5 and 28.21 wt% Rh, respectively), and unknown Au-Ag-Pd-Cu 'palladian gold' phases (MacDonald et al., 2015, 2016; Ames et al., 2016; and

Ames et al., submitted). The PGE-enriched W Horizon ores exhibit a complex post-magmatic history dominated by the effects of oxidation during cooling of a Cu-PGE-enriched magma source from a deep reservoir. We also developed PGM index minerals as an exploration vector for extreme PGE enrichment in the Coldwell Alkaline Complex (see Good et al., submitted).

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Architecture of magmatic conduits in Cr-(PGE)/ Ni-Cu-(PGE) ore systems

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Introduction

Ni-Cu-(PGE) and Cr-(PGE) mineralization is associated with a wide range of ages, parental magma compositions, volcanic-subvolcanic-plutonic settings and host unit geometries, but all important deposits occur within lava/magma conduits that: 1) focussed magma flow, facilitating incorporation of sulphur (and sometimes metals) from the wall rocks; and 2) enabled sulphide xenomelts to interact with and extract metals from the magma. Although we have a good understanding of how tectonic/structural environments influence the geometries of the plumbing systems (dikes versus sills versus chonoliths), of the most important deficiencies in our understanding is how to predict where sulphides or oxides will accumulate in the plumbing systems.

Research goals

The goal of this study is to establish the architecture of the magmatic conduits of the Black Thor (BTIC) and Double Eagle (DEIC) intrusive complexes in the McFaulds Lake greenstone belt (Figs. 1 and 2). By resolving the geometries of the magma plumbing systems, the locations of mineralization within the systems, and the dynamic conditions that led to the deposition and localization of magmatic sulphides and oxides within or proximal to the conduits, we will investigate the complete architecture (intrusive-subvolcanic-extrusive) of one mineralized mafic-ultramafic system from the magma conduits to the deposition sites (traps).

Three main components are encompassed in this activity: 1) establishing the petrogenesis and metallogenesis of the Eagle's Nest Ni-Cu-(PGE) deposit that is hosted within the interpreted magmatic feeder of the DEIC; 2) defining the 3D architecture of the magmatic plumbing system of the BTIC-DEIC; and 3) developing of an integrated metallogenic model for the orthomagmatic Cr-(PGE) and Ni-Cu-(PGE) mineralization hosted within the BTIC-DEIC komatiitic complexes. The first two parts will provide the framework for graduate student projects.

Activity highlights

Research is being undertaken in close collaboration with Noront Resources Ltd., Laurentian University and the Ontario Geological Survey. Two graduate level studies have been instigated. The first of these is based at Laurentian University and will investigate the geology and petrogenesis of the Ni-Cu-(PGE) mineralization at the Eagle's Nest deposit in the Double Eagle Intrusive Complex, McFaulds Lake greenstone belt. The second one, based at Carleton University, will develop 3D geological modelling of the Double Eagle - Black Thor intrusive complexes in the McFaulds Lake greenstone belt.

Contributors to this activity have presented a new geological model for the genesis of conduit-style chromium deposits in the McFaulds Lake greenstone belt (a.k.a. Ring of Fire) at the 13th International Ni-Cu-(PGE) Symposium held in Fremantle, Australia (Carson et al., 2016; Houlé et al., 2016; Spath et al., 2016) and the 35th International Geological Congress held in Cape Town, South Africa (Lesher et al., 2016). Additionally, this activity has assisted in the production of three 1:100,000 scale bedrock geological maps of the Ring of Fire region (Metsaranta and Houlé, 2017a, b, c), one of which covers the central part of the McFaulds greenstone belt, where most the deposits occur.

Science impact

The completion of the three 1:100,000 scale geological maps are important milestones that will be instrumental in the development and success of future research activities in the region. They provide a critical geological framework constraining the overall magmatic architecture of the Black Thor and the Double Eagle intrusive complexes (Fig. 2), but also support development of a global metallogenic model for orthomagmatic mineralization hosted within mafic and ultramafic intrusions such as those in the McFaulds Lake greenstone belt.

There are many anticipated outcomes of the current project, including: 1) establishing the geological and geochemical footprints of the Eagle's Nest deposit to aid the identification of the critical parameters responsible of the genesis of the deposit and potentially the development of new exploration tools to vector toward prospective settings; 2) defining the 3D magmatic architecture of the BTIC-DEIC, which will potentially identify the magma pathways leading to the most prospective part of this ultramafic to mafic magmatic system; and 3) developing

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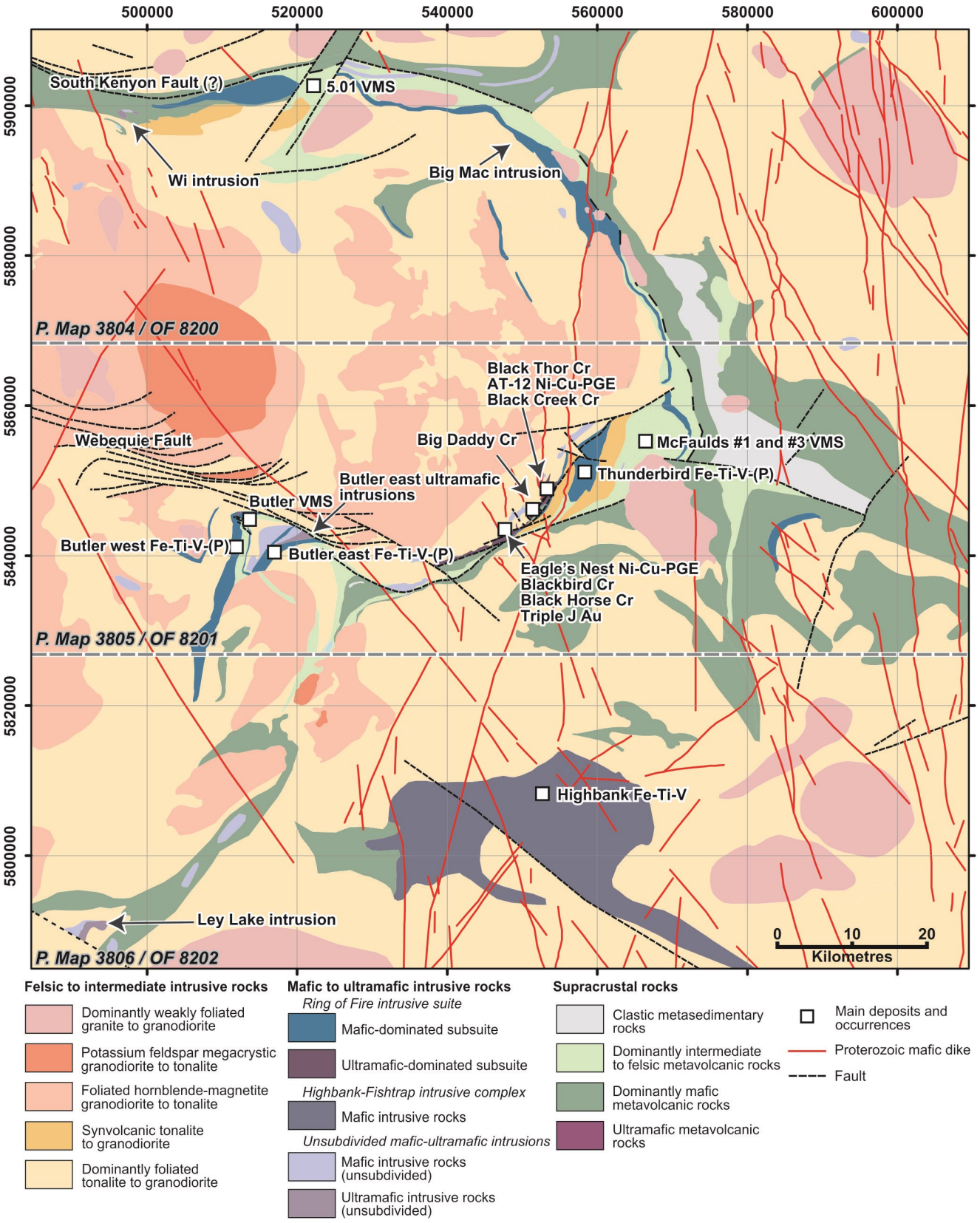


Figure 1 – Simplified geological map of the McFaulds Lake greenstone belt showing the location of mineral deposits in the "Ring of Fire" region (from Metsaranta et al., 2015). Dashed grey lines represent the approximate map boundaries between newly released 1:100,000 scale maps (Metsaranta and Houlé, 2017a, b, c).

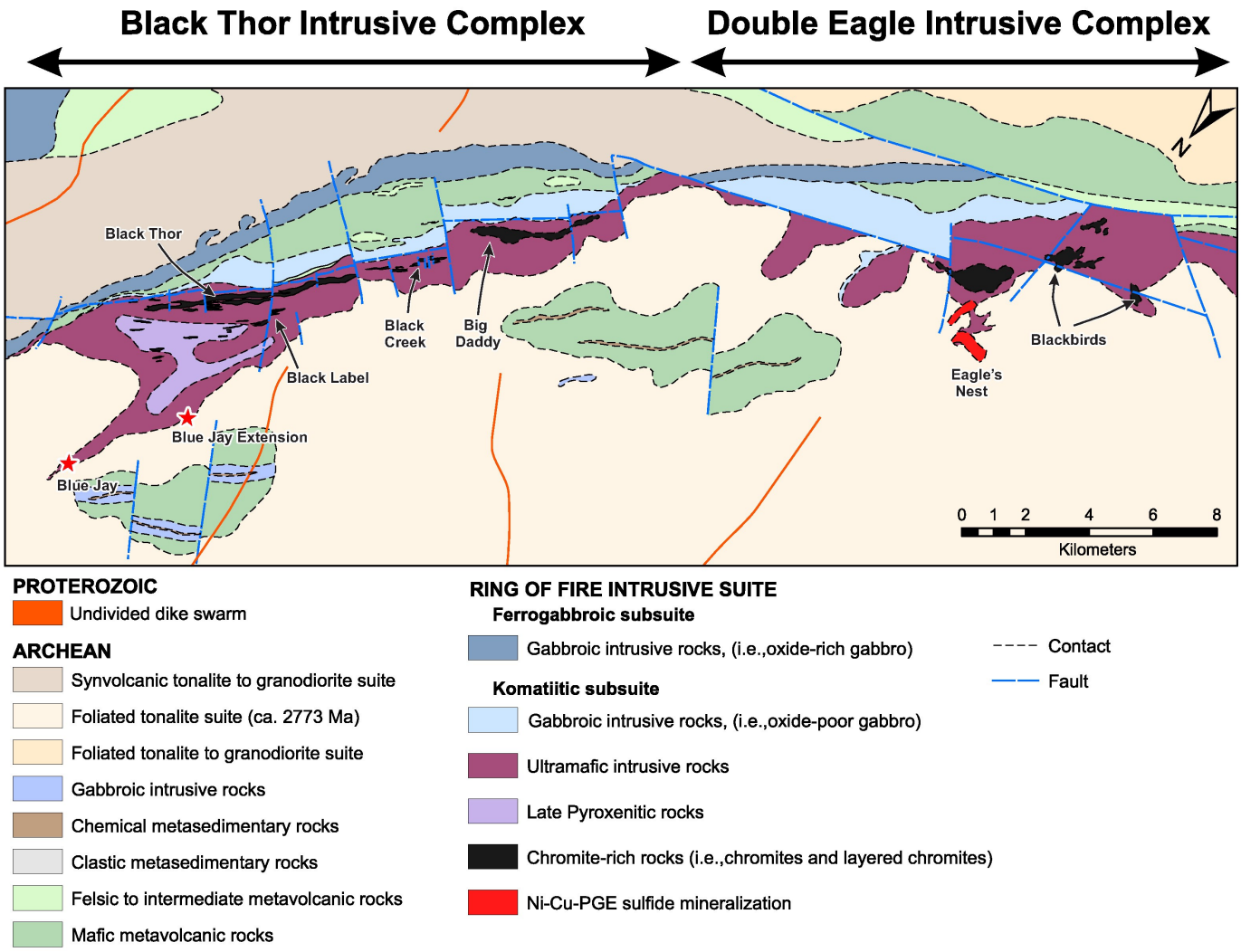


Figure 2 – Geological map of the Black Thor (BTIC) and Double Eagle (DEIC) intrusive complexes in the McFaulds Lake greenstone belt showing the location of the main mineral deposits in the "Ring of Fire" region (adapted from Metsaranta and Houlé, 2017b) .

an integrated metallogenic model that will help to target mineralization within ultramafic to mafic systems.

Next Steps

These research activities are progressing as planned with two graduate students that have been hired under the Research Affiliated Program of the Geological Survey of Canada. These graduate projects had started last September and a thorough assessment of the available data provided by companies is currently underway. This will be followed by an entire harmonization of these datasets to layout the ground for the 3D modelling Black Thor and Double Eagle intrusive complexes. Furthermore, new field data acquisition is planned this winter to better characterize the Ni-Cu-(PGE) mineralization based on past and recent drilling programs conducted in the area. In the meantime, all the geoscientific data produced over the years will be integrated to help refined our global understanding of this world-class Cr, Ni-Cu-(PGE), and Fe-Ti-V ore system associated with mafic and ultramafic magmatism in the Superior Province.

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Ni-Cr Metallotect: Synthesis, updates, and revised models for the Superior Province

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Introduction

The discovery of world-class Cr-(PGE) deposits, a major Ni-Cu-(PGE) deposit and significant Fe-Ti-V occurrences in the McFaulds Lake greenstone belt (a.k.a. "Ring of Fire") of northern Ontario have greatly contributed to the renewed interest for orthomagmatic mineralization associated with mafic-ultramafic intrusions in the Superior Province. Mafic-ultramafic intrusions and ultramafic volcanic rocks are widespread throughout the Superior Province, but the co-occurrence of significant Cr-(PGE), Ni-Cu-(PGE), and Fe-Ti-V mineralization is not evenly distributed across the craton. A majority of deposits/occurrences, mainly Cr-(PGE) deposits/occurrences, are located in the northern part of the Superior Province, predominantly within the Meso to Neoarchean supracrustal successions of the Bird River–Uchi–Oxford-Stull–La Grande Rivière–Eastmain domains (referred to here as BUOGE domains) (Fig. 1). These domains define a new metallogenic province characterized by the presence of major Cr-(PGE) with Ni-Cu-(PGE) and Fe-Ti-(V) metal associations that appears to be fundamentally different from other parts of the craton (Houlé et al., 2015).

Research goals

As part of this research activity, the Geological Survey of Canada (GSC), in collaboration with provincial and academia partners, is conducting a broad investigation on the Cr-Ni-Cu-PGE bearing ore systems across the BUOGE metallogenic province, as well as the Abitibi-Wawa terrane, to determine the primary controls responsible for mafic and ultramafic intrusion metal endowment in these specific areas of the Superior Province.

Although the determinant factors behind this distinctive metal endowment remain to be resolved, previous studies have highlighted some critical features that may represent efficient metallotects for Cr-(PGE) mineralization (Houlé et al., 2015; Carson et al., 2015). These include: 1) the presence of a large magmatic event of fertile mantle-derived magmas emplaced over a short duration of time; 2) the presence of nearby crustal-scale discontinuities that could have focussed the passage of magma through the crust; and 3) the presence of a favourable crustal architecture with potential sulphur (e.g., sulphide-facies iron formation) and oxide (e.g., oxide-facies iron formation) reservoirs for generating the sulphides and chromitites within these ultramafic to mafic magmatic systems.

This research activity aims to develop an integrated model for a key metallogenic province across the northern Superior Province. The main goals include establishing crucial parameter controlling metal endowment in specific terranes, as well as resolving the potential ore environments that triggered the metal endowment.

Activity Highlights

During the 2016 field season, field work focussed only on two study sites located in the northern part of the Abitibi terrane. Reconnaissance field work was conducted in the Grasset nickel deposit area, the most recent nickel discovery in the Abitibi terrane. Preliminary observations suggest that the thick ultramafic sequence has a komatiitic affinity and is mainly composed of three different units, each of which hosts Ni-Cu-(PGE) mineralization. Several samples for geochronology studies have been collected in the area to constrain the ages of the host units and the country rocks. Reconnaissance field work was also conducted on the Dumont sill in the Launay area, where a geochronology sample has been collected to constrain the age of the komatiitic host unit.

As part of a larger-scale effort to update and expand the inventory of mafic and ultramafic intrusions in the Superior Province, archival samples, thin sections, and notes from previous GSC projects conducted in the Bird River area are being re-examined.

Science impact

The development of a comprehensive, Superior craton-wide inventory of significant Cr-(PGE)/Ni-Cu-(PGE) mineralized mafic and ultramafic intrusions, their main characteristics and country rocks will constrain nickel and chrome metallotects at various scales and promote key criteria for improved exploration models. This comprehensive dataset could also help provide better constraints on the genesis of these orthomagmatic deposits and indicate the likelihood of discovering additional mineral resources within the BUOGE metallogenic province, the Superior Province as a whole or even throughout the Canadian Shield.

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TGI 5 (2015-2020) Ni-Cr-PGE systems project
Subproject 2: Magmatic architecture of Cr-bearing ore systems
Activity NC-2.2

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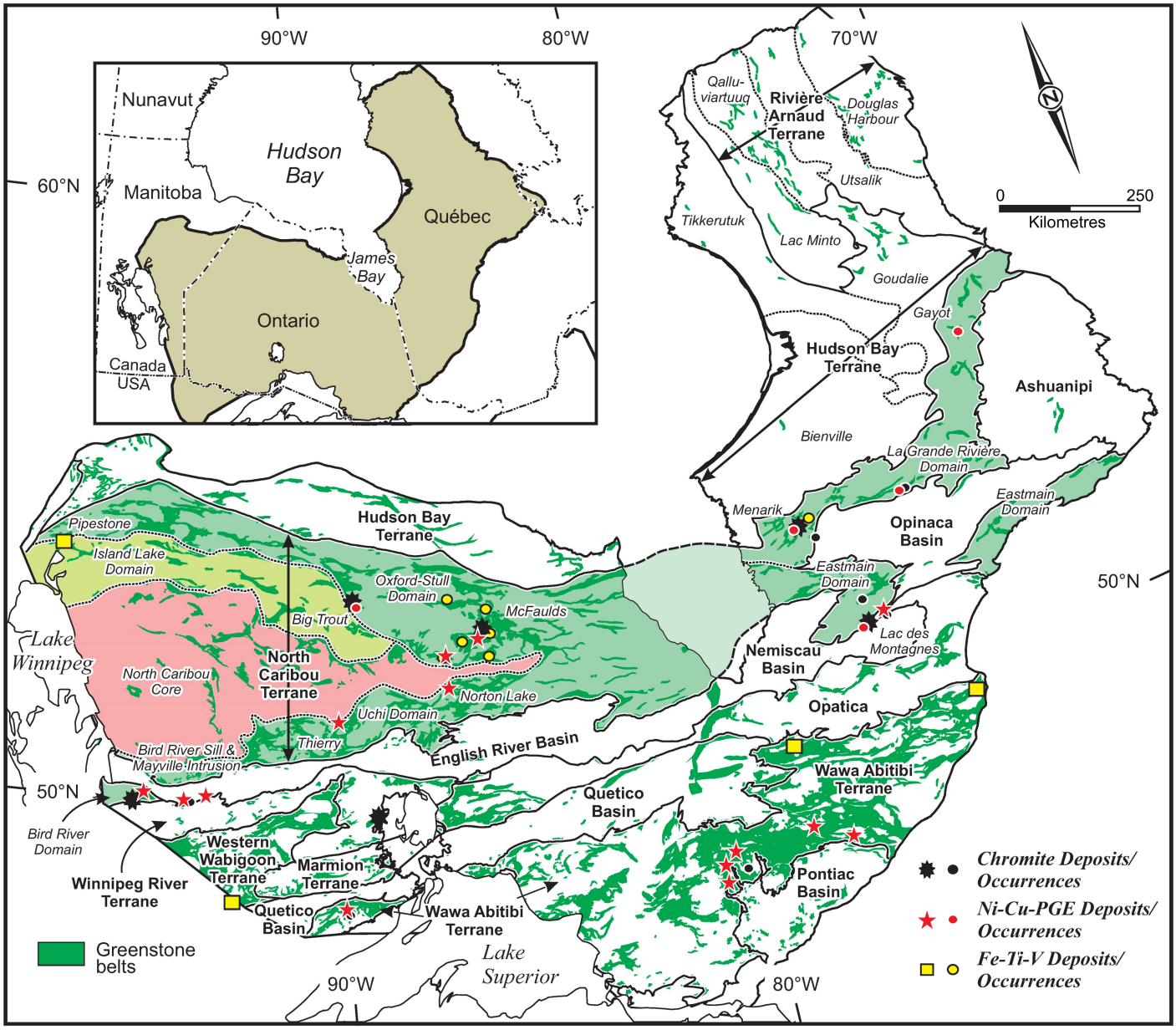


Figure 1 – Schematic geological map showing the main Cr-(PGE), Ni-Cu-(PGE), and Fe-Ti-V deposits/occurrences of the Oxford –Stull, La Grande Rivière, and Eastmain domains, and the Bird River and Abitibi greenstone belts within the Superior Province (From Houlé et al., 2015).

Next Steps

The next steps for this activity include undertaking the geochronological analysis of samples collected during the summer from the northern Abitibi terrane in Québec. These geochronological data will constrain the timing of komatiitic magmatism in this part of the Abitibi, which could change the overall perspective and fertility of the entire area with regards to komatiite -associated Ni-Cu-(PGE) sulphide deposits.

The inventory and compiling of archival samples for key areas of the BUOGE metallogenic province will continue, in order to build the framework data for establishing the main factors responsible for the distinctive metal endowments of different regions in the Superior Province.

Targeted field work and further analytical work (e.g., lithogeochemistry, geochronology, isotopic analyzes, geological transects across prospective units) will be also conducted to fill data gaps and generate a more complete assessment of the key geologic attributes of the main prospective mafic and ultramafic units and mineral occurrences and/or deposits. Key areas will be selected and prioritized in collaboration with our provincial partners, including the Manitoba Geological Survey (Eric Yang, Scott Anderson and others), the Ontario Geological Survey (Riku Metsaranta, Sonia Préfontaine, Bronwyn Azar,

and others), and the Ministère de l'Énergie et des ressources naturelles du Québec (Jean Goutier, Daniel Bandyayera, and others) and in conjunction with industry. Discussions are in progress with the Mineral Exploration Research Centre at Laurentian University regarding their Metal Earth Project, recently funded by the Canada First Research Excellence Fund (CFREF), FedNor, and the Northern Ontario Heritage Fund Corporation, to investigate future collaborative opportunities and synergies.

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Subduction controls on the nature and spatial distribution of Cordilleran porphyry-related deposits

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Introduction

It is commonly recognized that steady-state subduction does not result in the formation of porphyry copper, gold and molybdenum deposits of significant size in either island arc or continental arc settings. However, such subduction is the principal driver for metasomatism and associated metal enrichment of the overlying mantle wedge, a process that may be key to pre-concentration of porphyry metals and, ultimately, mineral deposit formation. Petkke et al. (2010) suggested that the Bingham Canyon deposit owes its enormous scale to pre-fertilization of its underlying subcontinental lithospheric mantle and lower crust during Proterozoic subduction associated with the accretion of Laurentia. Much later, Cenozoic magmatism entrained metals from this enriched source and resulted in the formation of the Bingham deposit. This pattern has been reconfirmed for many other giant deposits of western USA, including the Henderson porphyry molybdenum deposit, and recent work in southwest China has indicated that a similar pattern of Triassic mantle metasomatism and Cretaceous magmatism may have played a role in the formation of the Hongshan deposit.

Within the Canadian Cordillera, porphyry mineral deposit formation only occurred during limited periods of time (<10 my) within Devonian to Jurassic evolution of the Quesnel and Stikine arc terranes. Within these brief time windows, porphyry development was heterogeneously distributed both laterally and longitudinally through each terrane. It is unclear what role the island arc lithospheric mantle played in the localization of deposits in both space and time; whether mantle metasomatism and metal endowment was distributed evenly along the arc or whether the subduction system itself imparted significant provinciality to the metal distribution. More fundamentally, little is known of the nature of the lithospheric mantle beneath the Canadian Cordillera, such that the extent, provenance and age of subcontinental lithospheric mantle that remains is unclear, as is the relationship between this and its overlying crust. Hence, before any interpretation of the lithospheric mantle controls on major mineralization in the Mesozoic and later Palaeocene and Neogene mineral systems, this fundamental knowledge gap must be addressed.

This activity will examine fundamental controls on arc-related porphyry within the Canadian Cordillera, to test the relative influence of factors such as depth of emplacement, primary magma composition, fluid segregation and basement controls. The activity is split broadly into three parts: P-1.1a, petrological investigation of the crust and mantle structure beneath the Quesnel and Stikine arc terranes through xenolith analysis; P-1.1b, investigation of four-dimensional evolution within the subduction regime beneath Quesnellia through analysis of its eruptive and plutoninc magmatic components; and P-1.1c, development of a comprehensive database of key bedrock characteristics related to both barren and prospective mineral districts within the Cordillera of BC and Yukon.

Sub-activity P-1.1a

This sub-activity will develop a detailed model for the architecture and evolution of the mantle lithosphere and crust underlying porphyry prospective regions of the Cordilleran realm, with work centred principally on the Quesnel and Stikine terranes. This model will help refine existing geophysical models for deep Cordilleran structure obtained during the LITHOPROBE program, and similar. A principal output of the model will be determination of the provenance of mantle lithosphere underlying the prospective terranes within British Columbia, and whether the material preserved is allochthonous or autochthonous.

Various hypotheses relating to the development of Cordilleran mineral endowment will then be tested against this model, to explore the influence and significance of mantle and lower crust processes (metasomatization, metal fertilization, partial melting, MASH) to ore-forming systems. By refining our knowledge of these fundamental, first order controls on the distribution of metal prospectivity we will be able to develop new and improved models for porphyry formation within the Cordillera, and hopefully answer some outstanding questions relating to the distribution and size of porphyry systems within this portion of North America. Questions to be addressed include: i) Does lithospheric mantle and lower crust play a significant role in sourcing or storage of ore metals?; ii) Were mantle metasomatism, melting and metal migration developed equally along and across the island arc axis?; iii) Did subduction zone macrotectonic influences control metal distributions within the Cordillera?; iv) Do the locations of known ore deposits reflect deep controls imparted by mantle processes?; and v) Are there zones of high prospectivity for the discovery of a Canadian

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Subproject 1: Arc-related porphyry mineralisation in time and space
Activity P-1.1

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'Tier 1' deposit that have been underexplored, or perhaps even missed, in previous exploration work?

Sub-activity P-1.1b

This sub-activity will examine the original whole-rock chemistry of igneous rocks of the Triassic Nicola Group, which form the bulk of the surface expression of the Quesnel Terrane in central and southern British Columbia. This district is host to multiple world-class porphyry Cu-Mo and Cu-Au deposits. Although many of these rocks have been altered by post-magmatic metasomatic and regional metamorphism, they provide the best opportunity to probe the four dimensional evolution of subduction that occurred beneath the Quesnellia arc. This sub-activity seeks to determine the along and across arc geochemical variability of this richly-endowed crustal block, and understand the fundamental subduction controls that led to the type, size and location of porphyry-style ore deposits formed therein.

Sub-activity P-1.1c

The backbone of this activity will be provided by updating and expanding existing porphyry deposit databases (e.g., Kirkham and Dunne, 2015) to create a true research database structure that can be manipulated and queried to test deposit models and genetic hypotheses. Key geodynamic genetic controls will be investigated at orogen scale through symbiotic activities that will probe the underlying lithospheric mantle, effusive magmatic systems, and depositional controls active before and during the key porphyry forming events.

Activity highlights

Work conducted to date has largely centred on developing research partnerships, and instigating a doctoral level studentship at the University of British Columbia to assist in modelling Cordilleran mantle lithospheric and crustal architecture and evolution in relation to porphyry prospectivity.



Figure 1 - Exposure of Nicola Group basalt flows and basaltic ash tuff, Lower Horsefly Falls.



Figure 2 - Nicola Group conglomerate sub-angular limestone clasts in altered and weathered basaltic tuff 'sandstone' matrix. Horsefly River valley.

Preliminary, exploratory fieldwork was conducted during summer 2016 in Yukon and British Columbia, visiting a number of mineralization occurrences and extensive surface exposures of the Nicola Group igneous rocks (Figs. 1 and 2). In the company of Paul Schiarizza, of the British Columbia Geological Survey, key similarities and differences between eruptive units within the Nicola Group were studied and compared, and a preliminary sample suite for geochemical examination collected. This trip also provided key practical and logistical experience in preparation for more extensive, detailed fieldwork in the 2017 and 2018 summer seasons.

Next steps

Sub-activity P-1.1a

Samples of volcanic-hosted mantle and crustal xenoliths will be drawn from archival collections held by Prof. Kelly Russell at UBC, augmented by significant additional field sampling from known and new xenolith-bearing locations within central and southern British Columbia, centred on the Quesnel Terrane. If so indicated by results in Years 1 and 2, additional sampling may be conducted in northwestern BC during Year 3 to procure a comparator suite of samples centred on the Stikine Terrane.

Once in hand, detailed petrological, geochemical, geochronological and volcanological characterization will be conducted using a broad palette of physical, mineralogical and geochemical methods likely including, but not limited to: optical microscopy; scanning electron microscopy; electron backscatter diffraction analysis; electron probe microanalysis; laser-ablation ICP-MS analysis; bulk geochemical analysis; stable, radiogenic and geochronological isotope analysis; high-resolution synchrotron micro-XRF and -XRD analysis; and various physical rock properties techniques.

Data obtained by these methods will form the basis for mathematically- and empririically-derived petrologic models of the vertical structure of the crust and mantle underlying central and southern British Columbia and previous evolution of same through the processes of terrane formation, accretion and subsequent tectonic movement. These new models will be quantitatively compared to existing geophysical models.

Sub-activity P-1.1b

Samples returned from fieldwork in the summer of 2016 will be examined by multiple physical and chemical methods (including SEM, XRD, EPMA, whole-rock chemistry and isotopic analysis) to determine their suitability for further study. The extent and style of any post-magmatic alteration will be determined, and suitable methods established to enable future research to 'see through' this alteration to the original compositions. In addition, experience gained in bedrock outcrop abundance and distribution, and working practices necessary to conduct fieldwork in central and southern BC will be reviewed in order to define the detailed and comprehensive sample collection required during future work.

Sub-activity P-1.1c

Following a review of the current state of existing bedrock databases, the size and scope of this sub-activity has been identified. Initial conversion of existing database structure to a modern format suitable for research input will be instigated shortly, with future population of the database with additional public domain and new data to be conducted on an ad hoc basis.

Acknowledgements

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Deep mineralization processes within porphyry deposits of the Canadian Cordillera

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Introduction

Recent deep exploration beneath Cordilleran porphyry-style mineral deposits has identified cryptic deep mineralization (e.g., Red Chris; New Afton; Valley) that suggests within fertile systems there are processes operating at deeper levels than would normally be anticipated by existing porphyry mineralization models. Such mineralization has resulted in 'game changing' approaches to exploration within British Columbia and Yukon, increasing the tonnage and grade of many known deposits, and has resulted in at least one instance of a worked out deposit being reopened and mined anew. In addition, recent exploration work conducted on transitional porphyry-epithermal gold mineralization in central Yukon (Fig. 1) has suggested that ore formation may have occurred due to processes akin to those of so-called 'carbonate-base metal' (CBM) low sulphidation models, described from deposits in the southwest Pacific Rim and Colombia, but previously unrecorded within North America.

Since the mid-1970s, various workers have built upon the classic Lowell and Guilbert (1970) porphyry Cu-Mo deposit model. Cheney and Trammell (1975) identified their 'batholithic' model as significantly different in style and genesis, and Sutherland Brown (1976) expanded this to include a 'volcanic' type alongside his formulation of a 'plutonic' (cf. batholithic) type. More recent work has shown that within batholithic/plutonic deposits, modes of fluid flow, vein formation and ore deposition are directly related to the depth of emplacement of a source pluton, and that at palaeodepths below 3-4 km the occurrence of A-vein type (AVT) mineralization diminishes and early halo type (EHT) mineralization is dominant (Proffett, 2009).



Figure 1 - Quartz-sericite-pyrite alteration in the exposed, upper portion of the Cyprus porphyry intrusion, Mount Nansen Camp, Yukon .

In British Columbia, many porphyry deposits are inferred to have formed at significant depth. EHT mineralization has been documented from the Valley deposit, and further potential EHT mineralization is reported from the IKE, Brenda, Mitchell and Gibraltar deposits (John Proffett, pers. comm.). However, the true prevalence and economic significance of EHT mineralization within Canada is not well understood. Temporal and vertical evolution of porphyry mineralization between EHT and AVT controls, possibly indicating fundamental shifts in the depth of magma chamber crystallization, are only briefly described globally, and are not described within BC other than for a subordinate EDM vein set within the Red Chris deposit (Rees et al., 2015). Fundamental fluid chemistry, alteration and sulphide precipitation mechanisms have been inferred by Proffett, but have not been systematically quantified, nor have mineral chemical signatures of EHT mineralization and alteration ('bowtie' sericite formation, paragonite to phengite transition, etc.).

Deep epithermal mineralization of the CBM type shares many characteristics with Cu-Au porphyry-style deposits. Mineralized veins appear to have been formed at relatively high temperatures, and are intimately associated with igneous dykes of assumed co-genetic provenance, at comparatively short distances from the parental plutonic intrusion.

Activity highlights

Work to date has centred on the Klaza Au-Ag-Zn-Pb deposit, central Yukon. In collaboration with staff of Rockhaven Resources and Archer Cathro, putative CBM mineralization was examined in drill core taken from the Klaza deposit by Chapman in July 2016. Sulphide abundances and gangue mineral associations were documented from strategic locations within the deposit, as a first order exploration of the relationships between mineralization and magmatic intrusive centres. In consequence, a limited suite of samples was recovered to

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Activity P-1.2

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provide illustrative examples of pyrite- and chalcopyrite-rich sulphide assemblages, likely representing higher temperature fluid conduits, for exploratory Re-Os geochronology and mineral chemistry analysis.

Next steps

The first phase of a study to elucidate the occurrence, significance and mechanisms of EHT mineralization within the Canadian Cordillera will involve systematic investigation of deposits already identified as having EHT characteristics, to explore the spatial, temporal, chemical and mineralogical variation associated with EHT mineralization. From this we will develop descriptive models and fingerprints that will be used for comparison with lesser-known and cryptic systems during later phases of the study. Initial EHT mineralization will be examined from archival diamond drill core. Detailed paragenetic vein relationships and mineralogical variation will be documented, and samples taken for further mineral and fluid inclusion chemistry analysis to characterize the spatial and temporal evolution of an EHT system. In addition to detailed examination of recognized EHT mineralization, literature research, data mining and site visits will be conducted to establish the likely true prevalence of the EHT mineralization style across British Columbia. This first work will be used to determine the likely benefit of subsequent, targeted, graduate-level research work. Work will be overseen by Chapman, with consultation and advice from Brock Riedell and John Proffett. Access to samples and supporting data from a suitable deposit will require collaboration from the requisite property owner.

Work at the Klaza deposit in summer 2016 confirmed the scope of unknown and uncertain characteristics of this deposit in relation to the CBM model. Fundamental aspects of this deposit, including the true timing and magmatic association between sulphide mineralization and multiple proximal felsic intrusive units, remain unresolved, and the dimensions of the bulk hydrothermal system and relative fluid flow magnitudes and pathways are poorly understood. The setting of this deposit within the wider 'Casino age' early Late Cretaceous porphyry-related magmatic episode in Yukon remains poorly constrained, and aspects of the putative CBM mineralization style cannot be squared with the prevailing understanding of the tectonomagmatic setting of similar age mineralization. Hence, Chapman and a suitable academic collaborator are in the process of developing a detailed post-graduate research program to advance this study.

Acknowledgements

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Integrated 3D model of magmatic-hydrothermal evolution of the Iron Mask Batholith Complex near the New Afton Mine

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Introduction

Magmatism within convergent margins is inherently episodic, with the resultant regional ore distribution heterogeneous in both space and time. This activity will focus on processes that concentrate metals in the mid- to-upper crust by modelling the magmatic and hydrothermal conduit network of the mineralized Iron Mask Batholith Complex near the New Afton Mine using geological, physical rock property and geophysical data. Geophysical data will include new 3D magneto-telluric (MT), new vertical seismic profile (VSP), and existing airborne magnetic surveys. Excellent 3D exposure of mineralized porphyry and associated fluid conduit systems, an extensive database of co-located lithogeochemical and petrophysical measurements from outcrops and drill holes to calibrate and validate models will facilitate 3D interpretations from mine to crustal scales. A complimentary activity will integrate geophysical, geochemical and petrographic data to determine the chemical and mineralogical evolution of alteration minerals associated with magnetite, as a proxy for hydrothermal processes. Once established, the multi-parameter 3D model of the hydrothermal conduits will be interpreted in the context of the deep crustal architecture of this fertile porphyry system, including its magmatic source. The 3D model will enhance our understanding on how mid- to deep crustal processes contribute to the formation of economic porphyry ore systems.

Magmatic and hydrothermal conduits are essential elements of an ore system, because they accommodate fluid flow that is required for transporting metals in sufficient quantities to form a mineral deposit of economic tonnage and grade. Although mineralogical and geochemical studies are highly deterministic in reconstructing the pressure, temperature and chemical conditions during hydrothermal fluid flow, direct observation of the conduits is only accessible for a minor fraction of their entire pathway connecting the metal source to its final deposition (trap). Consequently, to enhance our understanding of the hydrothermal conduit system on the scale of the ore system itself, complementary data from these inaccessible parts are needed, which requires one or more geophysical methods. This is not only important to resolve the outflow zones close to the traps, but is particularly pertinent where hydrothermal conduits tap into fertile metal sources at greater depths. In this activity, we will integrate analyzes of lithogeochemical, mineralogical, physical rock property and geophysical data to generate a constrained model of hydrothermal fluid conduits on the scale of the ore system with particular emphasis on:

- Geological structures outlining the conduit network, their associated alteration, metal grade and physical rock property contrasts across proximal, distal segments and exit conduits (close or within the magmatic source).
- Preferential localization of the hydrothermal conduits in particular lithofacies with high primary or secondary permeability.
- Identification of the transition zone from non-mineralized to mineralized segments of the conduit network and assessment of the associated gradients in physical rock properties.
- The role of hydrothermal alteration in pre-conditioning host rocks for localizing strain during post-ore deformation processes controlling the structural disposition of the ore deposit.

All geophysical exploration methods are based on detecting contrast in physical rock properties. These contrasts are controlled by a number of geological factors, including host rock environment, metamorphism, metasomatism, weathering and hydrothermal alteration and their mutual interactions. Although much work is done on understanding physical rock property contrasts associated with mineralization, very little is known on how hydrothermal alteration zones affect physical rock property contrasts. Increased knowledge on physical rock properties of altered zones will facilitate improved geophysical characterization of deep alteration zones and provide a better perspective on hydrothermal alteration systems. This will be accomplished by integrating all available exploration data in a 3D multi-parameter model that will be used to determine linkages between geochemistry, geology, petrophysics, and geophysics. The 3D model will also be used for forward seismic modelling and as soft and hard constraints for 3D magnetic and electromagnetic data inversion. 3D inversion results will contribute to image the alteration conduits and associated structures at depths below borehole control. In the final step, this 3D model will highlight the spatial associations between the hydrothermal fluid conduit system and other ore system elements, including the magmatic source and the sulphide mineralized zone

This report is a contribution to:
TGI 5 (2015-2020) Porphyry-style mineral systems project
Subproject 1: Arc-related porphyry mineralisation in time and space
Activity P-1.3

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and will be interpreted in the context of the deep crustal architecture.

Iron Mask Batholith Complex and the New Afton Mine

The integrated geophysical and 3D modelling work will focus on alteration conduits near and at the New Afton porphyry deposit. This deposit is underlain primarily by rocks of the Upper to Lower Palaeozoic Quesnel Terrane, an island-arc assemblage that was accreted onto the North American continent during the Early to Mid-Jurassic (Ross et al., 1985). In the New Afton Mine area, the Quesnel Terrane consists of Late Triassic to Early Jurassic Nicola Group island-arc volcanic and sedimentary rocks, and coeval alkalic to subalkalic intrusions of the Iron Mask batholith (Bergen et al., 2009). The New Afton deposit is mainly hosted in crystalline and polymictic fragmental volcanic rocks of the Nicola Formation (BXF on Figure 1) and lesser monolithic intrusive breccias associated with the Cherry Creek member of the Iron Mask batholith (Lipske and Wade, 2014). Cherry Creek rocks comprises fine to medium grained pyroxene-hornblende monzodiorite and fine grained biotite-monzonite, varying to more dioritic composition, and minor syenite (Bergen et al., 2009). Monzonite intrusive rocks of the Iron Mask Batholith Complex are interpreted as the heat source that caused the alteration and mineralization of the fragmental volcanic rocks and intrusive breccias (Lipske and Wade, 2014). An ultramafic picritic flow (Fig. 1) located south of the western part of the deposit is composed of chlorite and serpentine altered mafic phenocrysts occasionally mixed with magnetite-altered olivine crystals within a moderately to strongly serpentine-chlorite-magnetite altered groundmass (Lipske and Wade, 2014). The picrite has a high magnetic susceptibility and is significantly less competent than other rock types at New Afton. Younger sediments of the Ashcroft Formation and Kamloops Group are juxtaposed to volcanic and intrusive rocks along NNW-trending faults that bound the deposit (Fig. 1). The deposit is also cut by numerous faults with various orientations. The main mineralized zone is a generally sub-vertical tabular body plunging at approximately 50o to the SW from the bottom of the open pit to approximately 1,250 m. Figure 1 provides an approximate location of the surface projection of the main ore zone. The deposit also comprises two smaller bodies located on the hanging wall side of the main zone (Lipske and Wade, 2014).

Alteration at New Afton comprises five principal facies (Fig. 1b) which consist of a biotite-dominant potassic (KB), potassium feldspar-dominant potassic (KK), inner propylitic (PI), phyllic (PH), and outer propylitic (PO) zones. The biotite-dominant potassic alteration is commonly hosted in fragmental volcanic rocks and is closely associated with the primary copper sulphide mineralization (Lipske and Wade, 2014). The potassium feldspar-dominant potassic alteration has been identified in all rocks except in the picrite and late intrusive dykes, but is strongest within the monzonite. Bornite and increased copper grade are found in feldspar-altered volcanic rocks in the mineralized zones. The inner propylitic, phyllic, and outer propylitic alteration facies have patchy to pervasive distribution throughout the rock mass. More details about the New Afton Mine geology including on the alteration and mineralization can be found in Bergen et al. (2015).

Activity highlights

The following surveys and studies are being instigated at or near the New Afton deposit.

Wireline logging

A multi-parameter drill hole wireline log survey will be carried out in 4-6 drill holes with a minimum depth of 750 m to support physical rock property modelling. The physical rock properties, in turn, are used to support the interpretation of forward modelling and inversion of geophysical data (e.g., VSP, MT, potential fields). The parameters to be measured include: density, magnetic susceptibility, conductivity, resistivity, gamma-ray spectrometry, P- and S-wave velocity.

VSP survey

A vertical seismic profile (VSP) survey will be carried out in a deep open borehole with a depth of 780 m and HQ diameter. The objective of the VSP is to image the structures that control or are associated with alteration and mineralization in the up flow zone(s) of the porphyry ore system. Shot points for the VSP will be located at the surface within a distance of approximately 1,000 meters from the drill hole. The seismic sources will be provided by approximately 80 small, near surface charges. The exact distribution of charges will depend on the orientation and location of the target. The VSP data will be recorded using a fiber-optic cable preferably during 'quiet times' at the New Afton mine.

MT survey

A magnetotelluric survey will be conducted to image and model deeper parts of the magmatic and hydrothermal conduits (1 – 5 km) associated with porphyry mineralization, targeting alteration zones in spatial association to the fluid conduits. Before the MT survey will commence, a re-interpretation of existing TITAN MT survey data will be conducted to optimise the survey design.

Magnetic survey

High-resolution magnetic data will be interpreted using 3D forward modelling and inversion constrained by the modelled 3D distribution of magnetic susceptibility within the main geological units.

Drill core sampling and logging

Drill core intersecting the main alteration and mineralization zones will be logged and sampled for whole-rock and trace element lithogeochemical and petrophysical laboratory analysis to support 3D modelling of the hydrothermal and magmatic conduits. Logging will include magnetic susceptibility, seismic velocities, density, induced polarization, resistivity, spectral and XRF measurements. The joint analysis of lithogeochemistry and physical rock properties together with mineralogical analysis will allow establishing the relationship between the intensity of the hydrothermal alteration (via alteration indices) and physical rock properties. The lithogeochemical survey will also include metal assays to quantify gradients in metal depletion and how these gradients effect physical rock properties.

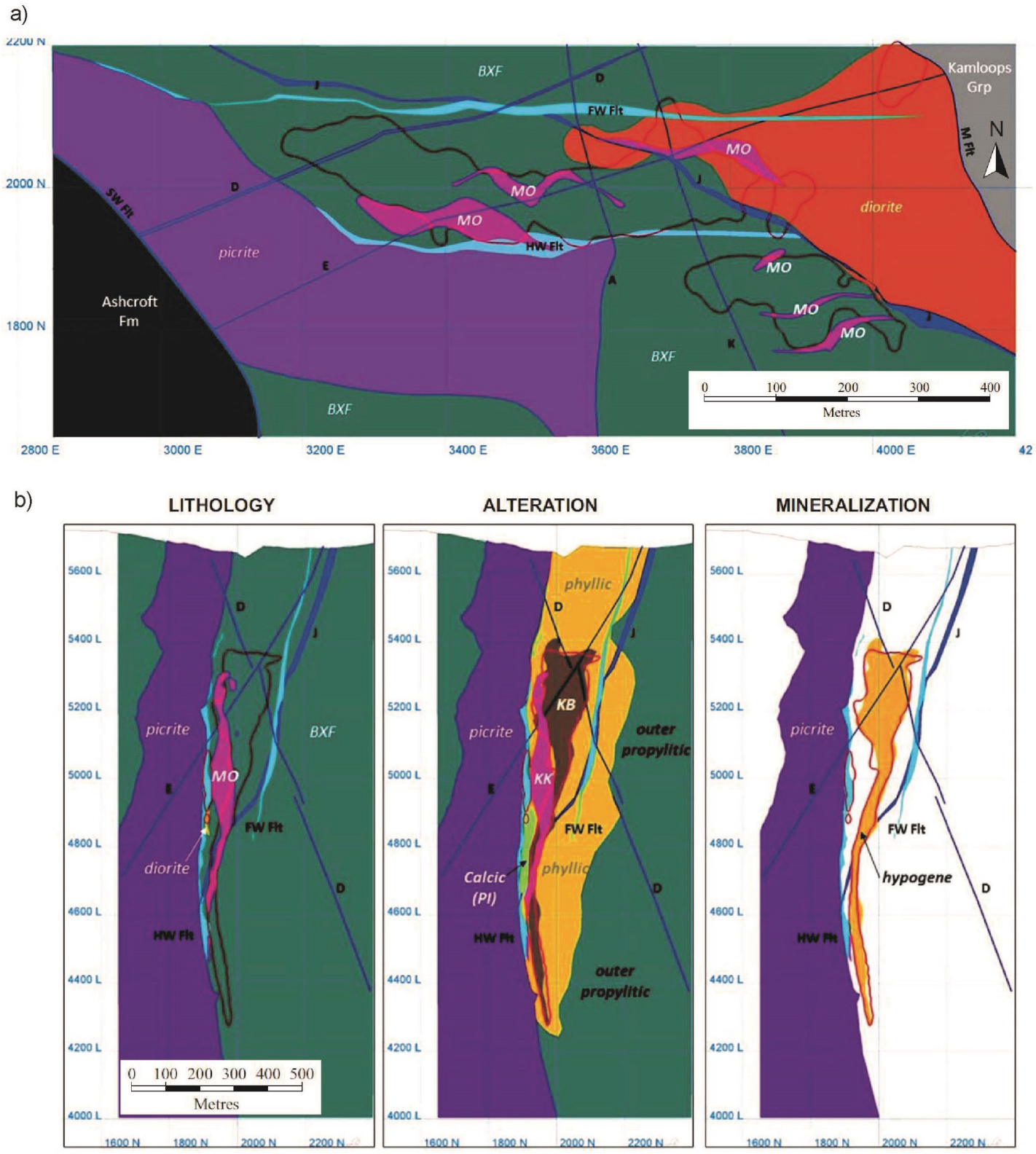


Figure 1 - a) Level plan of the main geological units at the 5150 m elevation in the New Afton mine. b) North-south section through the New Afton mine. Lithology, alteration, and mineralization are show in each of the panels in b). Mo: monzonite; BXF: Fragmental volcanic rocks; HW Fkt: Hanging wall fault; FW flt: footwall fault. A, D, E, K, J are faults. Modified from Bergen et al. (2015) and Lipske and Wade (2014).

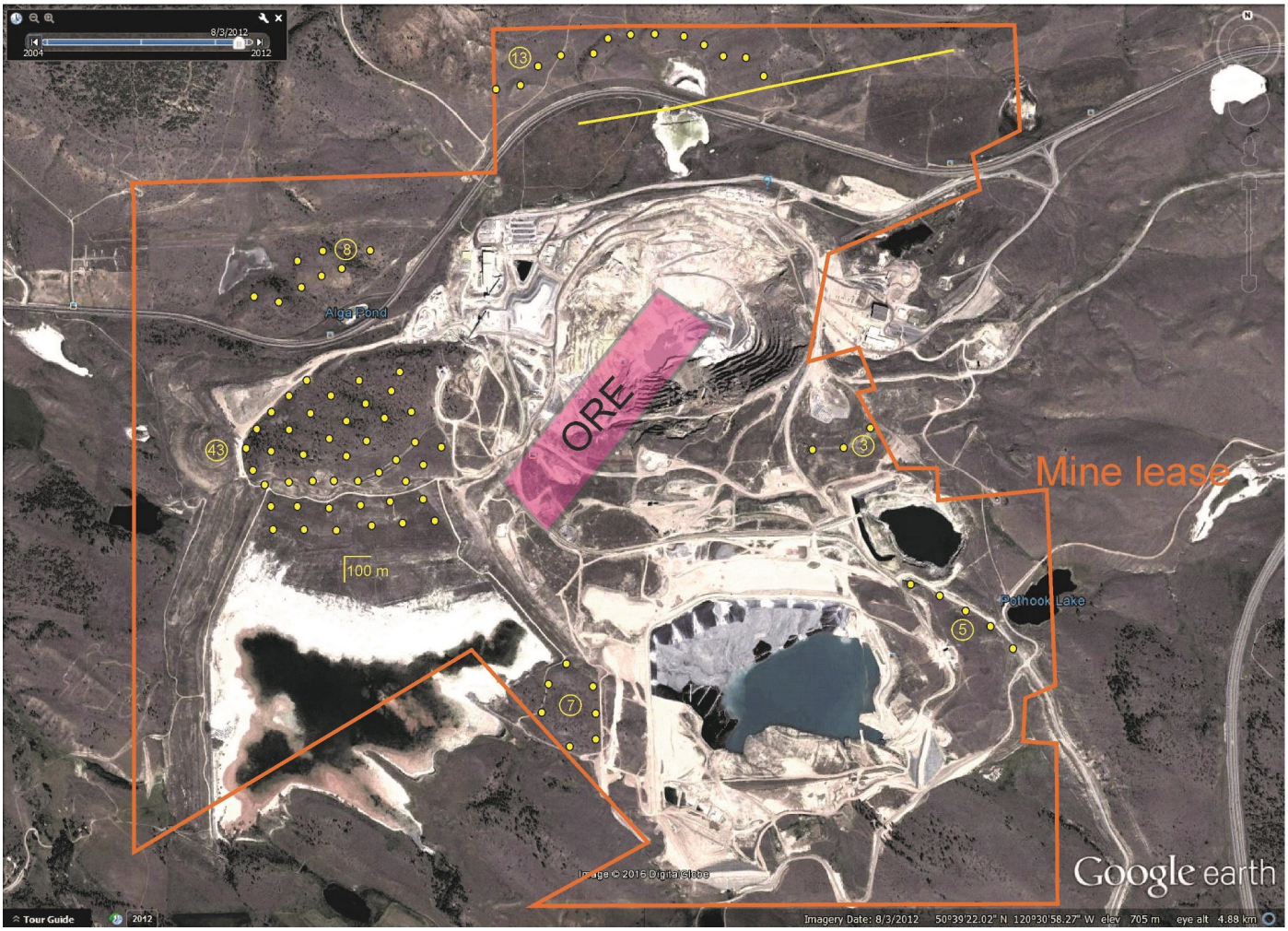


Figure 2 - Google Earth image showing the location of the Afton open pit and approximate location of the mineralized zone of the New Afton mine (from Bergen et al., 2015). Shot points are placed to provide the best illumination to the ore zone, alteration conduits, faults, and picrite which bounds mineralization to the south.

Data integration and 3D modelling

In order to achieve optimal interpretation of the hydrothermal fluid conduit system on the scale of the ore system itself, stochastic 3D modelling provides the vital link to reconcile the locally-sampled segments of the hydrothermal conduits and geophysical signatures available on the scale of the ore system. Once such 3D continuous physical rock property models (of density, magnetic susceptibility, Vp, Vs and conductivity) are available, they will be used to run forward modelling and/or validate inversion results. Physical rock property modelling will permit to produce simulations with and without the effects of alteration. This allows differentiating the effects of alteration from the other geological factors that control physical rock property contrasts, including host rock environment and mineralization. In the final step of the proposed activity a multi-parameter 3D model will be constructed that highlights the spatial associations between the hydrothermal fluid conduit system and other ore system elements, including the magmatic source and the sulphide mineralized zone.

New Afton site visit

The New Afton mine site was visited from September 12-16, 2016 to gain additional insight on the study site. This reconnaissance included: 1) an underground visit to inspect open drill holes where wireline logging and vertical seismic profile will be conducted; 2) drill core examination under guidance of New Afton exploration team that allowed us to become familiar with main rock units, alteration and mineralization zones; 3) a field survey for determination of shot points for the VSP survey taking into account existing infrastructure, favourable seismic illumination and outcrop distribution; and 4) an assessment of the various data sets available at New Afton that will be used to support interpretation of geophysical data and construction of the 3D model.

Next steps

The wireline logging program and the Vertical Seismic Profiling are scheduled for the second half of fiscal year 2016-

17. Planning is well-advanced for both surveys. Figure 2 shows the tentative locations of shot points to be used in the VSP (subject to permitting and approval). Samples for physical rock property measurements, including magnetic susceptibility will also be collected this year. Those new datasets combined to the data provided by New Gold will allow us to start data processing and analysis as early as March-April 2017. At that time, we will be planning field work for new magnetotelluric measurements which should contribute to the imaging of the deeper geology, alteration and, structures in the study area.

Acknowledgements

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Linking characteristics of post-orogenic, polymetallic porphyry-style ores to tectonically-driven temporal and spatial controls across an accretionary orogeny

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Introduction

Post-orogenic granitoid development is commonplace within accretionary orogenic systems, and in protracted orogens with multiple accretionary episodes such as the Canadian Appalachians, they can be generated in several distinct pulses. However despite these granitoids sharing compositional and genetic models, only select temporal and spatial subsets are associated with polymetallic, porphyry-style mineralization. The objectives of this study are: i) to characterize key post-orogenic porphyry-style ore occurrences and their enveloping hydrothermal systems through novel analytical approaches; and ii) to resolve how those observed temporal and spatial metallogenic events fit within the overall tectonic framework and thus determine what characteristics are fundamental for a predictive model of ore distribution. This study is based in the Canadian

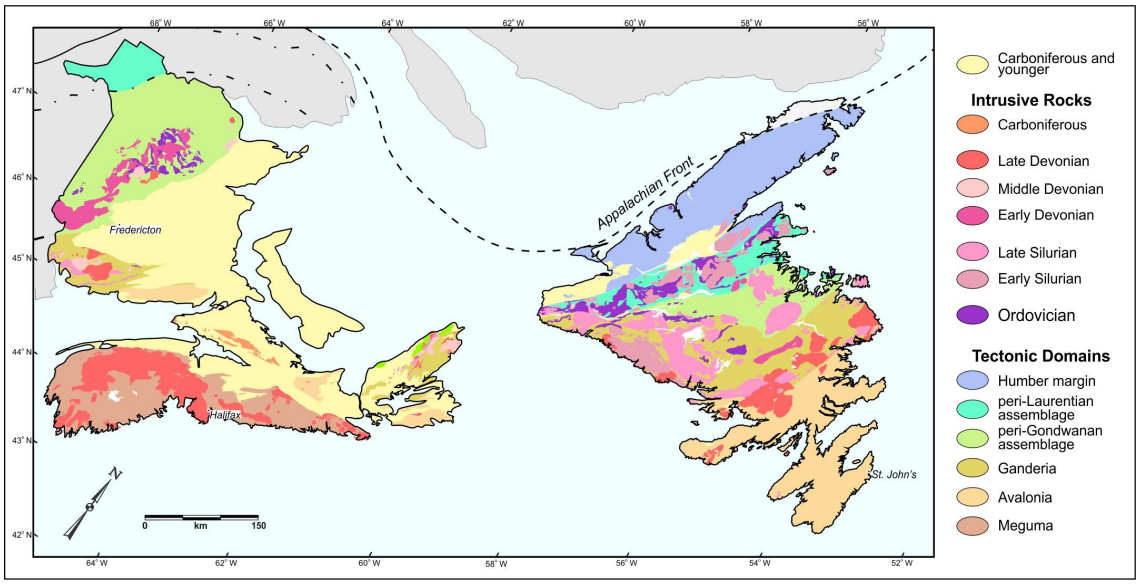


Figure 1 – Distribution of Palaeozoic granitoids and interpreted tectonic subdivisions of the Appalachian Orogen in Newfoundland, New Brunswick and Nova Scotia (modified after Hibbard et al. (2006), van Staal et al. (2009), Rogers et al. (2014) and references therein).

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Subproject 2: Post-orogenic porphyry systems in space and time
Activity P-2.1

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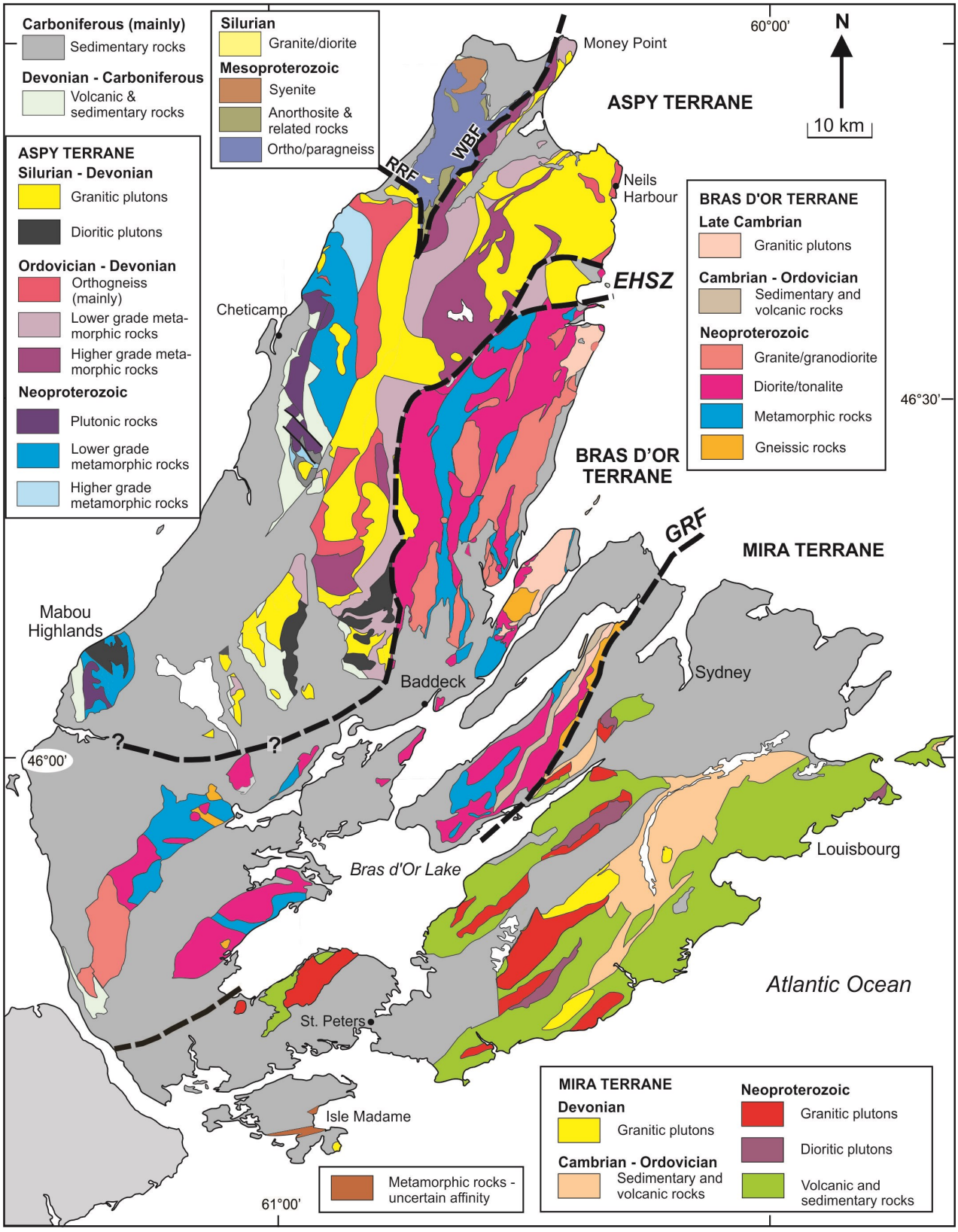


Figure 2 – Simplified geological map of Cape Breton Island showing main geological units and terrane-bounding faults and shear zones. Abbreviations: EHSZ, Eastern Highlands Shear Zone; GRF, Georges River Fault; RRF, Red River Fault; WBF, Wilkie Brook Fault. Map is modified from Barr et al. (1998).

Appalachians, a relatively well-constrained accretionary orogen (Fig. 1), although the resultant tectonic/predictive models should be applicable/transferable to other accretionary orogens.

Initial studies are primarily focused on the Cape Breton Appalachians (Fig. 2) with extensions into southern New Brunswick and Newfoundland, with the aim of cataloguing the timing of accretionary events in association with the reactivation of hinterland structures and relate these with the various types and position of magmatism/mineralization generated. Cape Breton is viewed as particularly important for resolving the precise timing and distribution of magmatism in relation to fault reactivation as it represents the pivot point for accretionary structures within the Canadian Appalachians due to the orientation of peri-Gondwanan microcontinent accretion and relative position of the St Lawrence Promontory on the Laurentian Margin.

Activity highlights

The fundamental key to the success of this activity is a comprehensive, orogen-wide dataset of granitoid age data. Thus, during this 2016-2017 project year we have focused on identifying and closing gaps in timing constraints for various igneous suites in the Canadian Appalachian orogen. Towards this end, we have initiated collaborative studies with the Nova Scotia Department of Natural Resources, New Brunswick Department of Energy and Resource Development, Acadia University, Cape Breton University, Laurentian University, Université Laval and the University of British Columbia – Okanagan. To date, eight key samples from undated units on Cape Breton Island (CBI), Nova Scotia, have been obtained for U-Pb age and Sm-Nd isotopic determination. These results will be critical for PhD and MSc student projects that will begin field work on CBI in summer 2017. Additionally, samples of the Eastern Highlands shear zone, CBI, have been collected for microstructural analysis to help direct future field investigations into the evolution and timing of this shear zone (Fig. 3).



Figure 3 - Eastern Highlands shear zone. Strong planar fabric and elongated clasts/lapilli consistent with plane strain. The picture frame is parallel to the dominant foliation. The lithology can be interpreted as a matrix supported pebble conglomerate or a lapilli tuff.



Figure 4 - Lookout along west coast of Cape Breton highlands. Jumping Brook metamorphic suite rocks on the coast faulted against Carboniferous sedimentary rocks (two small islands).



Figure 5 - Decades to century old adit at Galena mine, Cheticamp area, CBI. Purported Aspy terrane, with mineralization hosted in strata associated with foliated and crenulated garnet-bearing quartz mica schist – sampled for Ar/Ar .

Kellett visited the Nova Scotia Department of Natural Resources' Cheticamp area (CBI) field mapping site (Fig. 4) to assess regional knowledge gaps and collect samples for Ar/Ar analysis to determine the timing of overprinting regional metamorphism (Fig. 5). Both of these CBI-based activities will contribute to unravelling the tectonic framework of CBI within which post-orogenic porphyry-style mineralization has occurred. A complimentary study is also being instigated in southern Nova Scotia to better constrain the emplacement history of the South Mountain batholith, and in particular attempt to determine the date of formation of the East Kemptville intrusion-related Sn deposit. The East Kemptville deposit, along with other mineral occurrences in the South Mountain batholith, are believed to be broadly coeval with post-orogenic porphyry-style deposits in New Brunswick, CBI, and Newfoundland, but the current data quality is insufficient to determine potential correlations.

Finally, in collaboration with the New Brunswick Department of Energy and Resource Development, we will conduct U-Pb dating of 12 samples from across New Brunswick to help delineate granitoid emplacement history there. Thus our 2016-2017 collaborations will provide 25 new U-Pb age data for the region, as well as complementary isotopic and microstructural data.

Next steps

The new age data outlined above will provide new constraints on the regional tectonic development of the Canadian Appalachians, which will provide context for refined ore distribution models. In particular, these new data will provide a critical foundation for graduate and post-doctoral research studies anticipated to start in early 2017. A post-doctoral fellowship will investigate isotopic tracers of magma sources and metals through time and space, while graduate studies will include a doctorate on tectonic controls on granitoid emplacement in CBI, and a masters comparing host-rock controls on porphyry-style mineralization between two terranes in CBI.

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Deconvolution of complex spatial-temporal records of porphyry fertility recorded in till minerals

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Introduction

The objective of this study of porphyry copper indicator minerals (PCIM) in till and bedrock is to aide development of innovative mineral exploration methods in glaciated areas using minerals in till to quantify fertile porphyry mineralization. This activity builds on TGI-4 results that shows igneous, alteration and porphyry ore minerals in till in the vicinity of the Gibraltar, Mount Polley and Highland Valley Copper mines and the Woodjam prospect (Fig. 1; Hashmi et al., 2015; Plouffe et al., in press). Some of these minerals, solely based on their abundance and regional distribution in till, reflect the presence of mineralization. Specifically, they are more abundant in till near and down-ice (5-10 km and even farther in some cases) of mineralization compared to background regions (Plouffe and Ferbey, 2015; Plouffe et al., in press). This new activity is targeting minerals that survive glacial transport and post glacial weathering to assess what their composition and physical attributes tell us about ore forming processes.

Research on PCIM in till in the Canadian Cordillera conducted as part of the TGI-4 program has generated great interest by industry and academia given its direct applicability to mineral exploration. Consequently, a number of detailed studies on PCIM composition have already been conducted as derivative research of the TGI-4 program. For instance, Rukhlov et al. (2016) has completed a study on apatite composition in till and bedrock in the region of four porphyry mineralized zones. A study on magnetite composition from till and bedrock at the Mount Polley Cu-Au porphyry deposit has demonstrated that hydrothermal magnetite reflecting porphyry mineralization can be detected in till up to 6 km down-ice from mineralization (Grondahl, 2014; Piziak et al., 2015; Canil et al., 2016). At the Woodjam porphyry prospect, tourmaline is generally more abundant in till near the mineralized zones compared to background regions (Fig. 2; Chapman et al., 2015). By comparing the composition of tourmaline in till and bedrock, Chapman et al. (2015) showed that only the till close to mineralization (sample 11PMA012 in Fig. 2) contains tourmaline grains with an ore-forming fluid "fingerprint".

Activity highlights

Processing of mostly legacy bedrock and unconsolidated sediment samples for the recovery of indicator minerals is being undertaken in commercial laboratories with quality assurance and quality control procedures in place(QA/QC) (e.g., Plouffe et al., 2013). The QA/QC protocol includes the usage of spiked, blank, and duplicate samples. Given the current research on the development of indicator minerals for mineral exploration, new QA/QC protocols need to be developed and tested. A number of blank, spiked and naturally enriched samples were submitted for indicator mineral processing in two independent commercial laboratories. Results demonstrate that the current procedures utilized in commercial laboratories is efficient at discriminating samples from background (devoid of mineralization), slightly anomalous (low indicator mineral content), and highly anomalous (samples from near mineralized zones) regions. This testing also served to identify required improvements to the QA/QC protocol, including the homogenizing method for QA/QC samples and that the spiking grains need to be chemically and physically characterized prior to their artificial introduction into the base material.

Following the interest generated by the study of indicator minerals in glacial sediments in the Canadian Cordillera, A.S. Hickin, T. Ferbey and A. Plouffe co-organized a two-day workshop on indicator minerals in till and stream sediments at the 2016 Geological Association of Canada – Mineralogical Association of Canada (GAC-MAC) conference in Whitehorse. The workshop included one day with classroom presentations and a field trip on the second day. On the first day, attendees learned about basic glacial processes and recent research on indicator minerals in the Canadian Cordillera, with the second day dedicated to hands-on glacial sediment identification and ice-flow indicator measurements required in a till sampling survey. The workshop was followed by a one day special session on indicator minerals which included eleven presentations on various case studies from Canada and two from abroad plus six posters. Indicator mineral studies conducted on massive sulphides, copper porphyry, and orogenic gold deposits, and kimberlites were part of the session. A joint GAC-MAC special publication on indicator minerals in till and stream sediments is currently in progress.

A master's level study at the University of Ottawa investigating Gibraltar deposit mineralogy has been instigated. For the first phase of this study, petrographic analyzes of thin sections from selected bedrock samples of the Granite Mountain

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Subproject 3: Mineral markers of porphyry processes
Activity P-3.1

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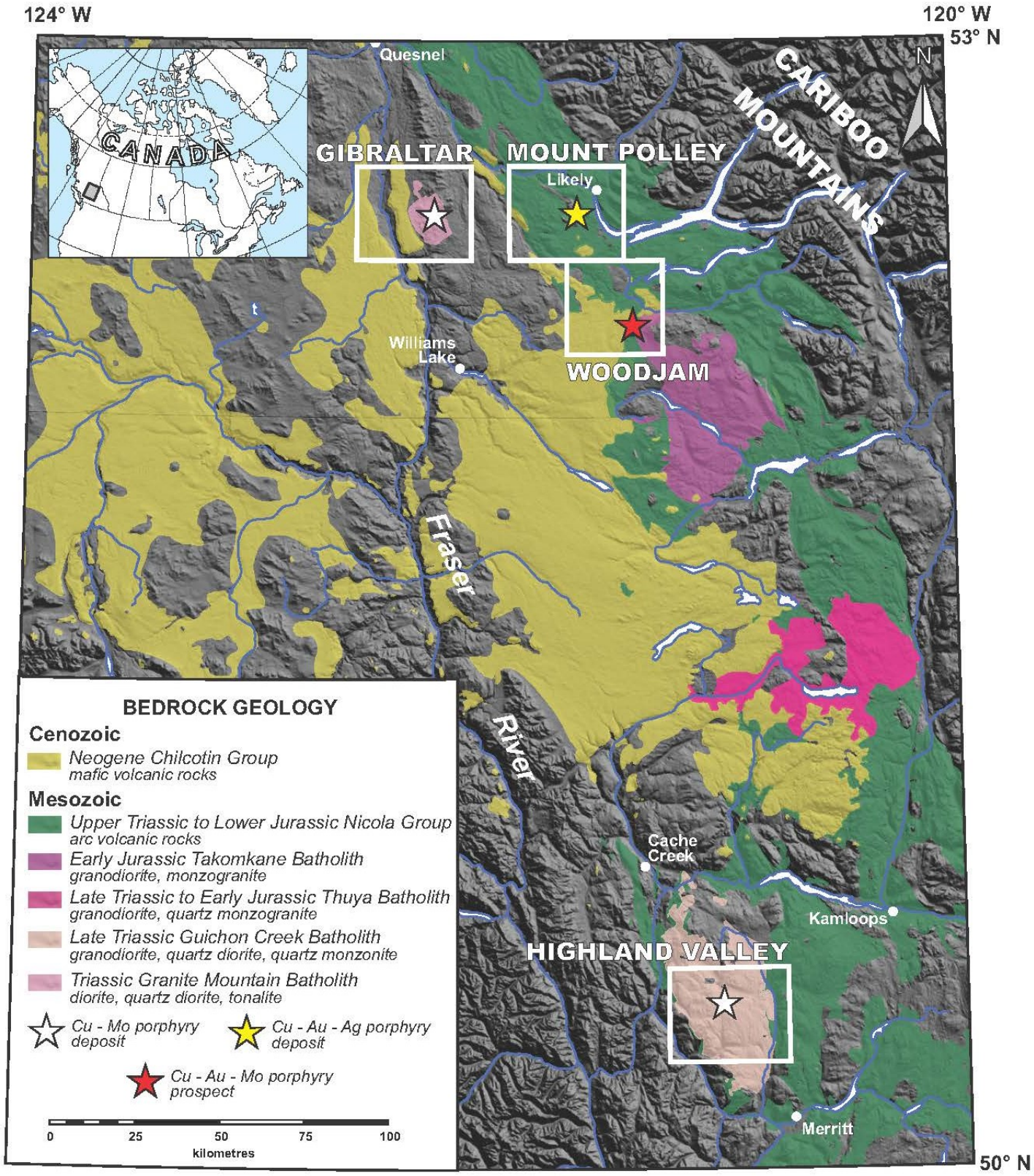


Figure 1 – Location map of the TGI-4 study sites: Gibraltar, Mount Polley and Highland Valley Copper mines and the Woodjam prospect .

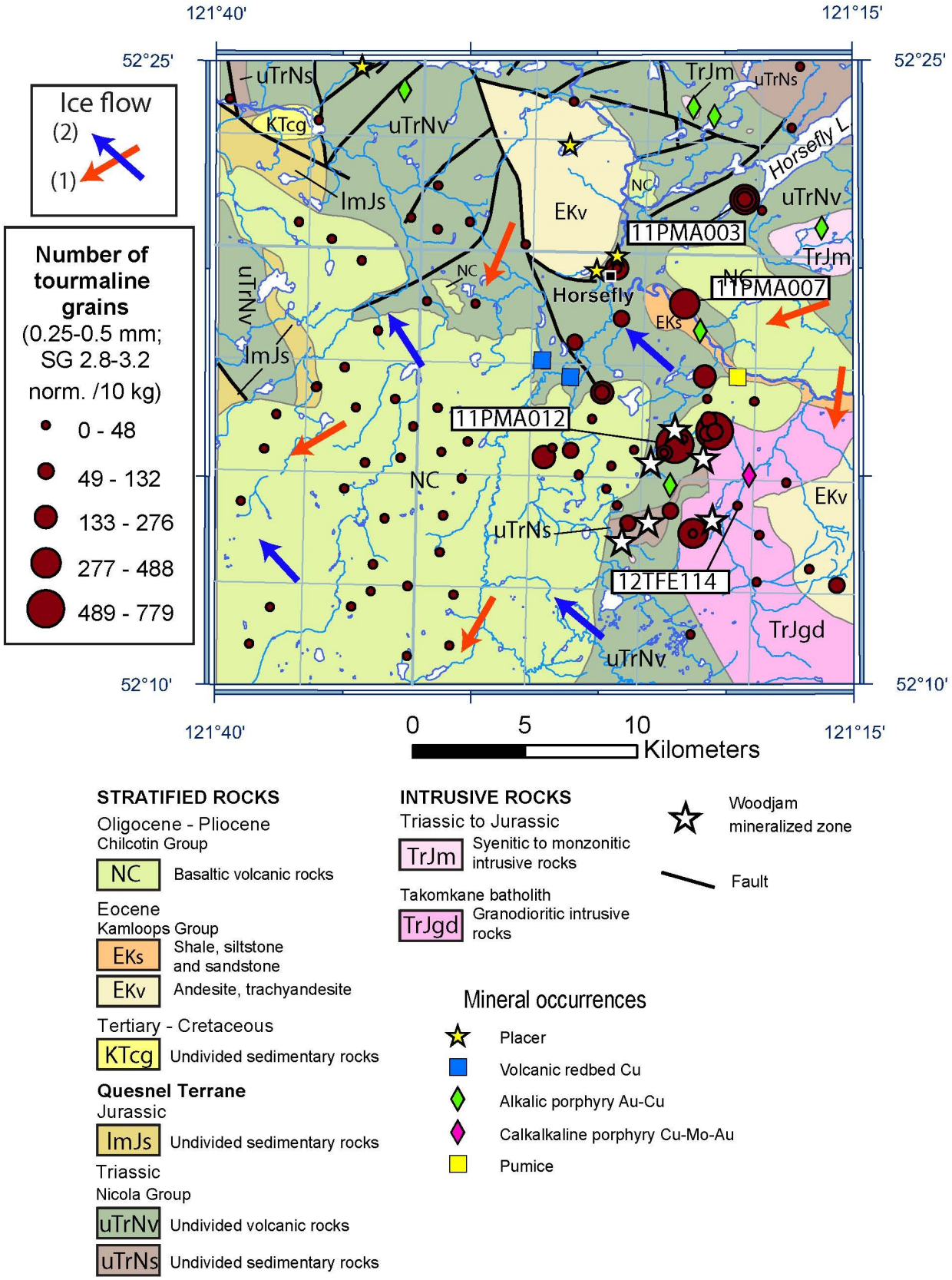


Figure 2 – Distibution of tourmaline in till at the Woodjam prospect (modified from Chapman et al., 2015). Geology from Massey et al. (2005), Logan et al. (2010) and unpublished data from P. Schiarizza (2012).

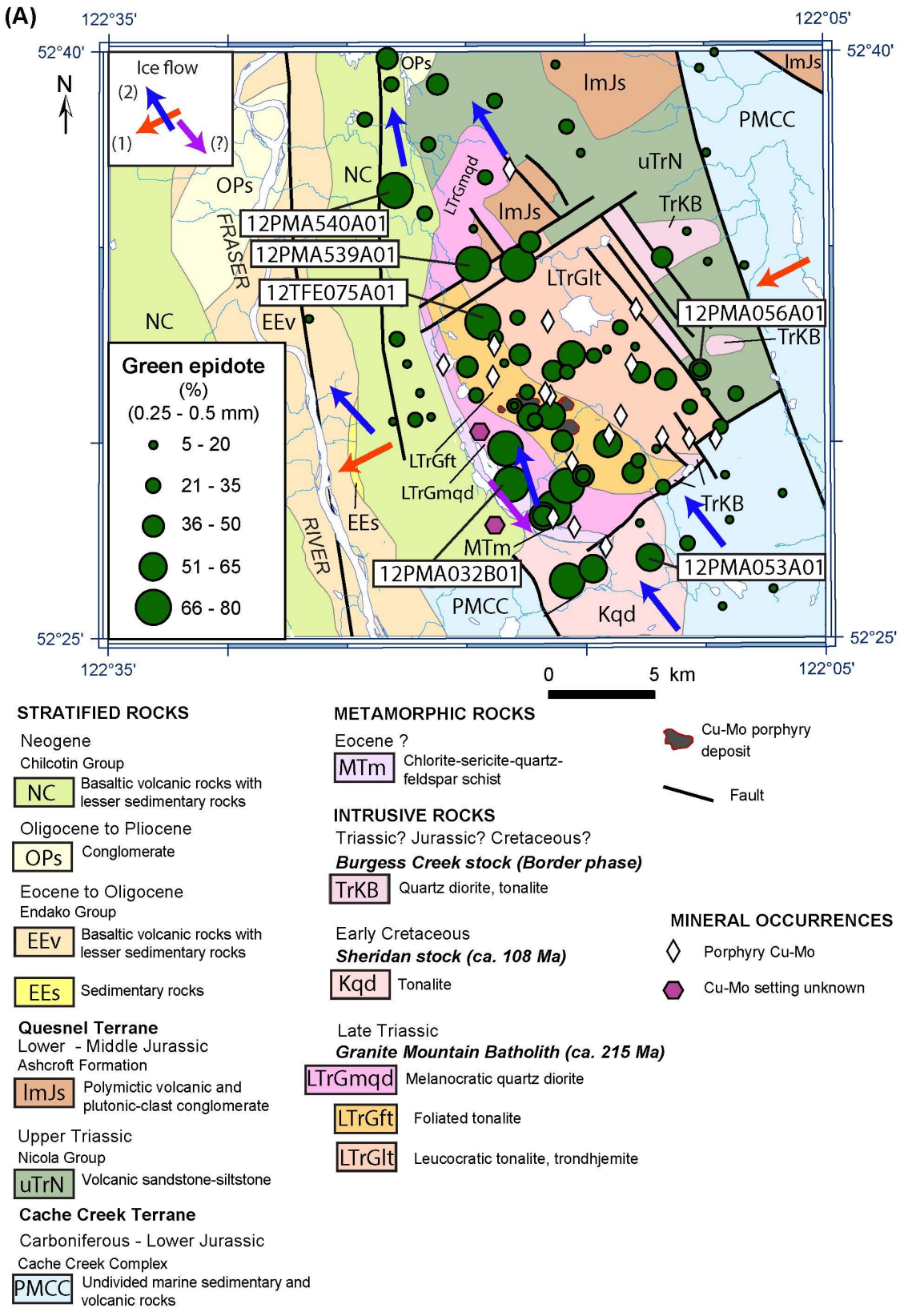


Figure 3 – (A) Epidote, (B) rutile and (C) zircon in till in the region of the Gibraltar deposit. The composition of mineral grains from the labelled samples will be analyzed as part of an honours thesis project. Geology from Ash et al. (1999), Massey et al. (2005), and Schiarizza (2014).

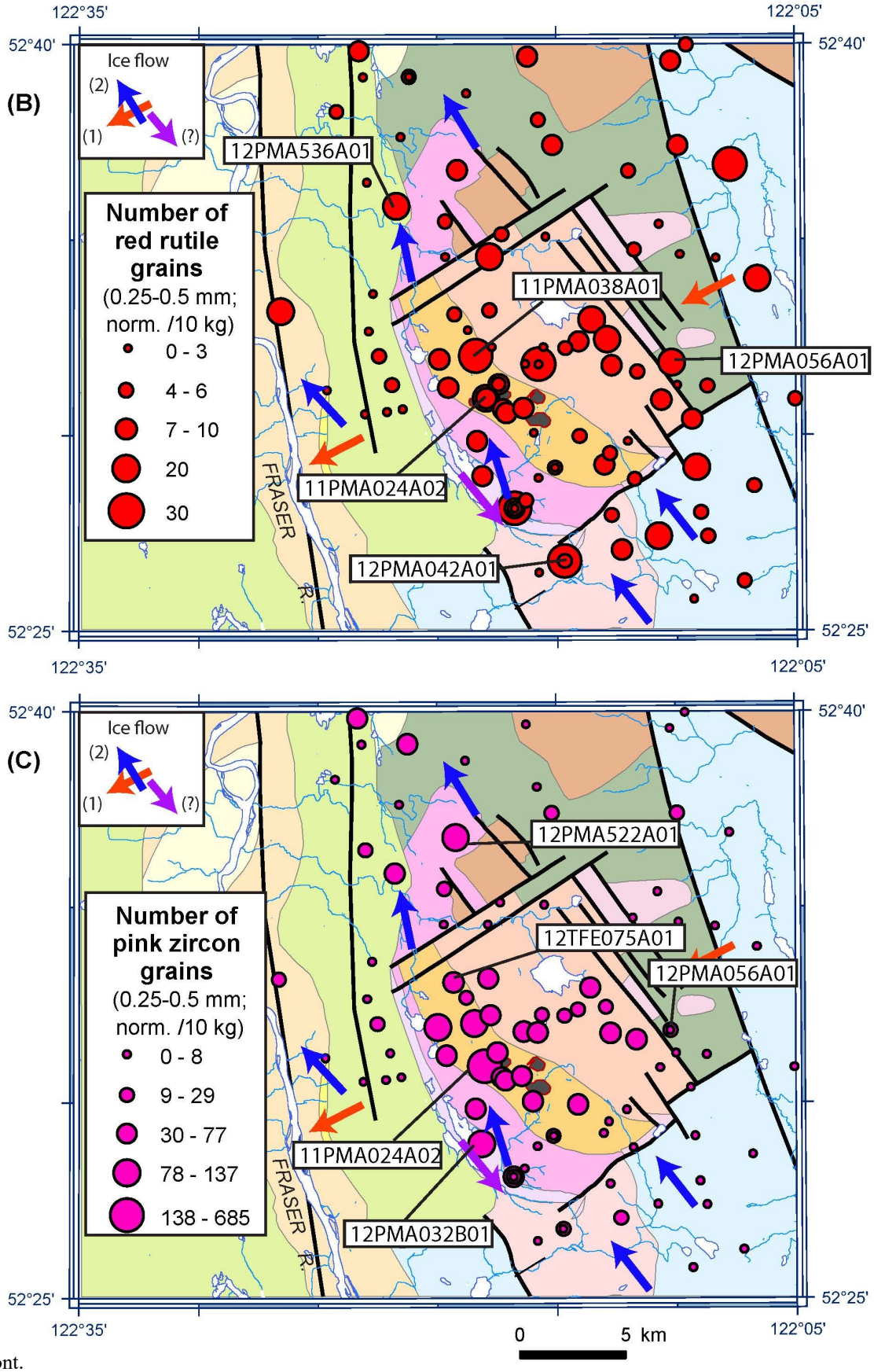


Figure 3 – Cont.

batholith, which hosts the porphyry mineralization, along with composition analyzes of titanite, epidote and rutile by scanning electron microscope equipped with an energy dispersive spectrometer (SEM-EDS) have been completed (Kobylinski et al., 2016). One key highlight of the preliminary results is the identification of hydrothermal epidote that is enriched in Ce and La reaching concentrations of 14.7 wt % Ce2O3 and 9.5 wt % La2O3. Elevated concentrations of light rare earth elements (LREE) was also reported by Cooke et al. (2014) outside pyrite halos in the Baguio porphyry district, Philippines, where it was interpreted as representing lateral outflow of fluids from the main mineralized zones and possibly the roof of an underlying pluton. During 2016 fieldwork, Kobylinski collected additional bedrock samples of the Granite Mountain batholith and regional, and has made a potentially key observation that epidote veins strike towards the mine pits. Petrographic evaluation and chemical composition analyzes of minerals is in progress.

An honours thesis project is in development for the study of the composition of epidote, rutile and zircon from till samples in the region of the Gibraltar deposit (Fig. 3). The objective is to test the detectability in till of PCIM identified in bedrock by Kobylinski, and thus evaluate if the PCIM identified in bedrock are abundant enough to be routinely detected in till and if so how far from mineralization.

Discussion

The study of PCIM, as their composition relates to ore formation processes and their use in mineral exploration in glaciated landscape, has generated interest from academia and industry. Fundamental questions that will be addressed during the evolution of this activity include:

- Are there other potential PCIMs present in till that warrant study?
- What is the diagnostic physical and chemical characteristics of these minerals and how are these related to the porphyry ore formation processes?
- Can these minerals be identified effectively and routinely as part of a mineral exploration program in glaciated landscape and serve for the detection of buried mineralization?
- How large is the PCIM footprint in till or how far can these PCIM be efficiently detected in till?

Results from this activity will serve to develop more efficient mineral exploration methods that will make a link between ore formation processes recorded in PCIMs and the detection and recovery of these minerals in the near surface environment.

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Controls on the fertility of porphyry mineralizing systems recorded in indicator minerals

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Introduction

This research activity is focussed on indicator minerals of porphyry and other mineral deposits, and built around two main research themes: 1) the investigation of tourmaline as an indicator of porphyry mineralization; and 2) the investigation of porphyry and VMS deposit indicator minerals that occur in the underutilized fine fraction of heavy mineral concentrates.

Activity highlights

1) Investigation of tourmaline as an indicator of porphyry mineralization

Tourmaline, as a relatively common and resistive mineral phase within porphyry ore systems, has the potential to be a very useful indicator of porphyry-style mineralization. Following on from some previous work by Chapman et al. (2015), this new study led by Andy McDonald and Matt Leybourne (Laurentian University) will examine in detail the variations in tourmaline composition across a mineralized system. To date there have been a limited number of studies directed at testing the applicability of tourmaline as an indicator mineral in the porphyry environment (e.g., Baksheev et al., 2012), but these have been overly broad in scope, have relied heavily on relatively simplistic substitutional mechanisms, major element chemistry, and have not attempted to analyze any one deposit at a sufficient level of detail to holistically understand the variations that exist at the deposit-scale.

For this activity we shall employ a variety of microanalytical techniques (e.g., SEM-EDS, cathodoluminescence, EPMA-WDS, LA-ICP-MS) to document the textural and chemical variations that exist within tourmaline. We will be critically evaluating variations that exist within a single deposit and between deposits by determining the extrinsic versus intrinsic effects on tourmaline. Understanding the intrinsic and extrinsic effects of the crystal chemistry of tourmaline and removing these masking features, should delineate the identifying qualities of tourmaline in terms of majors, minors, and traces, along with isotopic signatures that are exclusive to mineralized porphyry environments.

Initial bedrock sampling in August 2016 utilised legacy samples primarily from the vicinity of the Schaft Creek, Woodjam, and Highland Valley porphyry deposits (locations are shown on Figure 1). Additional samples were acquired from other important sites including Casino (Yukon), Coxheath (Nova Scotia), Chibougamau (Quebec), and El Teniente (Chile). In general, the deposits sampled define Cu-Mo-Au porphyry systems from island-arc settings, typical for British Columbia. For comparative purposes, samples also include those from well-defined continental-arc settings (El Tiente, Chile) and one that is likely of the same affinity (Casino, Yukon).

Research to date has included the visual examination of samples, determination of the nature of the tourmaline occurrence in each sample, estimation of modal mineralogical abundances, and in particular, noting the paragenetic relationship between tourmaline and sulphides (chalcopyrite, pyrite, molybdenite, bornite). Preliminary examination suggests that tourmaline can be classified into three groups based on occurrence and texture: vein style, disseminated, and breccia cement. Vein style and breccia tourmaline are commonly associated with sulphides, whereas disseminated tourmaline is rarely associated with sulphides. Attempts to further classify tourmaline based on colour were unsuccessful due to its consistent black colour.

Detailed petrographic analysis will be conducted on the tourmaline bedrock samples to systematically document the characteristics of tourmaline and its textural relationships. Microanalysis will include SEM-EDS, cathodoluminescence, EPMA-WDS, LA-ICP-MS, and B and Cl isotopes. Additional porphyry deposits bedrock samples will be added going forward to characterize the variations in tourmaline composition between deposits. Tourmaline in till heavy mineral concentrates collected near porphyry deposits in BC during TGI-4 will be examined in greater detail.

This report is a contribution to:
TGI 5 (2015-2020) Porphyry-style mineral systems project
Subproject 3: Mineral markers of porphyry processes
Activity P-3.2

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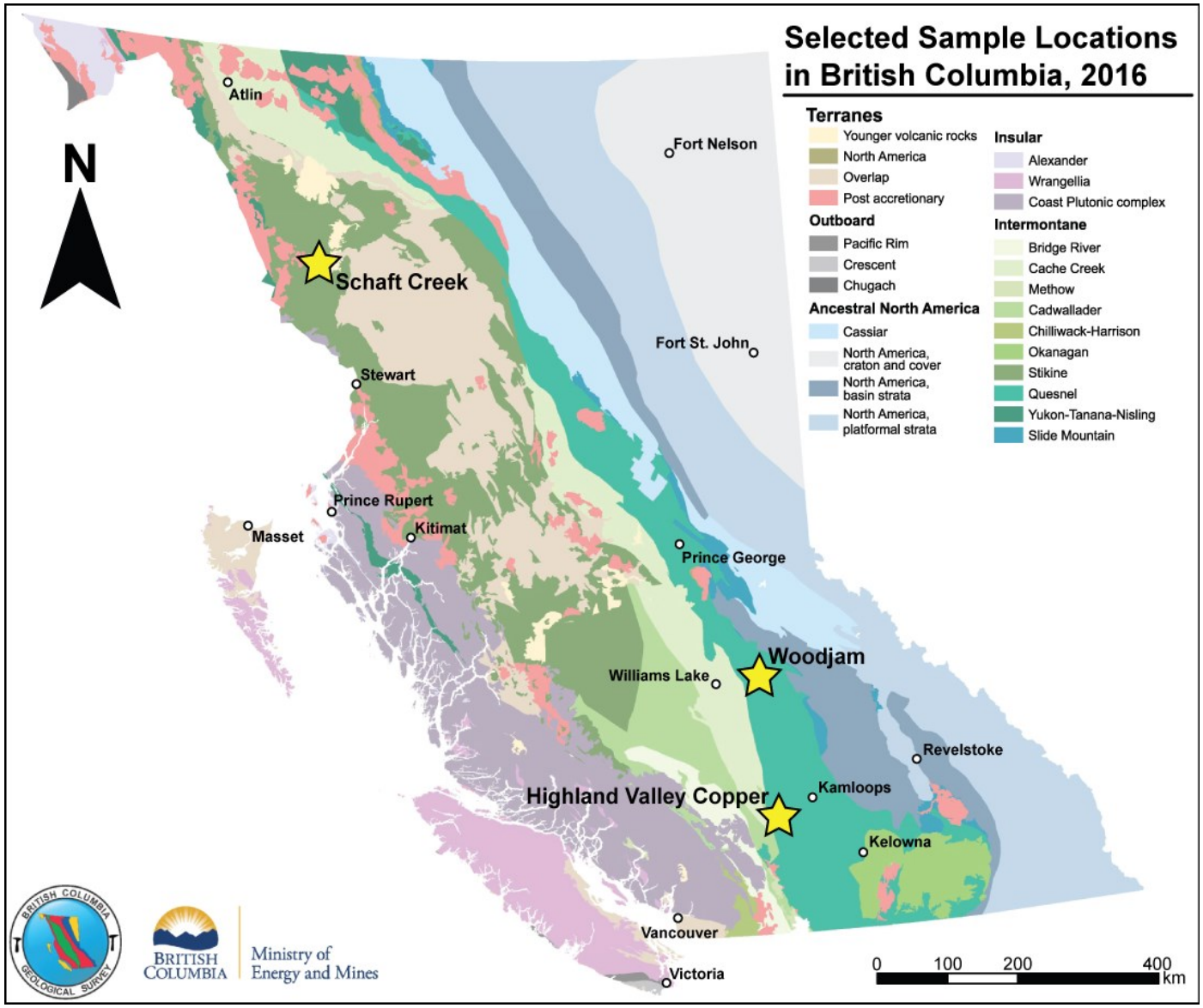


Figure 1 – Geological map of geological terranes in British Columbia showing the initial bedrock sample locations for the tourmaline study (yellow stars). Diagram modified after Clarke (2016).

2) Investigation of Indicator Minerals in the Fine Heavy Mineral Fraction

There are numerous minerals that are the product of fluid-rock interaction in porphyry deposit formation that are sufficiently robust to survive glacial erosion, transportation and weathering. Many of these minerals reside in the coarse (>0.25 mm) fraction of a heavy mineral concentrate (HMC) of glacial sediments, are visually distinct, and are routinely used in mineral exploration. More recently, workers have investigated the effectiveness of minerals in the often underutilized fine (<0.25 mm) HMC fraction (e.g., Wilton and Winter, 2012; Lehtonen et al., 2015). The published studies that use this fine fraction are reconnaissance in scope, and there is currently no consensus on optimal processing methods or commercially available facilities.

The goal of this study (led by Dan Layton-Matthews at Queen's University) is to investigate the fine heavy mineral fraction by testing various protocols on archived heavy mineral concentrates from various mineral deposit types, including porphyry deposits (e.g., Sisson W-Mo deposit), VMS (Izok Lake), and kimberlite. Methods for sieving the <0.25 mm into smaller sizes and for mounting the heavy mineral grains, as well as mineral liberation analysis (MLA) methods and protocols will be developed and documented. The developed protocols will then be applied to archived HMC from other archived deposit types. The goal is to identify any new indicator minerals in this fine fraction, and to determine the optimal size fraction, number of grain mounts per sample, and MLA procedures for examining this underutilized fraction effectively and efficiently.

Indicator mineral methods short courses

Indicator mineral methods presentations and lab exercises were given at short two courses in 2016, with two additional courses under development.

A three day modular course open to graduate and undergraduate students and industry was held at Queen's University in April. The course covers an introduction to the general principles of glacial geology and dispersal, and indicator mineral methods, including hands-on examination of indicator mineral samples and concentrates using binocular microscopes. May saw a 10 day field course run by the Prospectors and Developers Association of Canada (http://www.pdac.ca/programs/students/s-imew), which featured an indicator mineral methods module that included hands-on examinations of indicator minerals.

Future planed short courses will be held at Laurentian University in December and as part of the Exploration 2017 decennial international conference to be held in Toronto in October 2017. The Laurentian University course is available to graduate students from Ontario universities and will include a module on the application of indicator mineral methods to mineral (https://hes.laurentian.ca/programs-and-courses/modular-courses). The Exploration 2017 course "Application of Indicator Mineral Methods to Exploration using Bedrock and Sediments" (http://www.exploration17.com/About.aspx) will review principles, methods, and developments in indicator mineral methods in mineral exploration applied to bedrock and sediments, and will include presentations by 11 experienced practitioners in the field. Indicator mineral methods applied to exploration for a broad range of deposit types will be reviewed, including VMS, gold, diamonds, porphyry Cu, W-Mo. Topics to be covered will also include heavy mineral sample processing methods, quality assurance, and mineral chemistry methods.

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Fingerprinting fertile fluid corridors in the formation of unconformity-related deposits using non-traditional isotopes

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Introduction

The Athabasca and Thelon basins are the main exploration targets for uranium in Canada. Within these Proterozoic basins and surrounding basement rocks, known uranium deposits are spatially associated with structural trends and/or intersections of crustal-scale faults that are considered the main fluid conduits during formation of unconformity-related uranium deposits (Jefferson et al., 2007a). Many of these structures show evidence of multiple periods of deformation (e.g., brittle fabrics overprinting ductile fabrics) and alteration (new mineral growth - clay minerals, tourmaline, aluminum-phosphate-sulphate minerals, hematite, etc.), which is reflected in their petrophysical characteristics, and geophysical and isotopic signatures (Fig. 1).

This activity aims to advance our understanding of the role of reactivated faults in the formation of unconformity-related

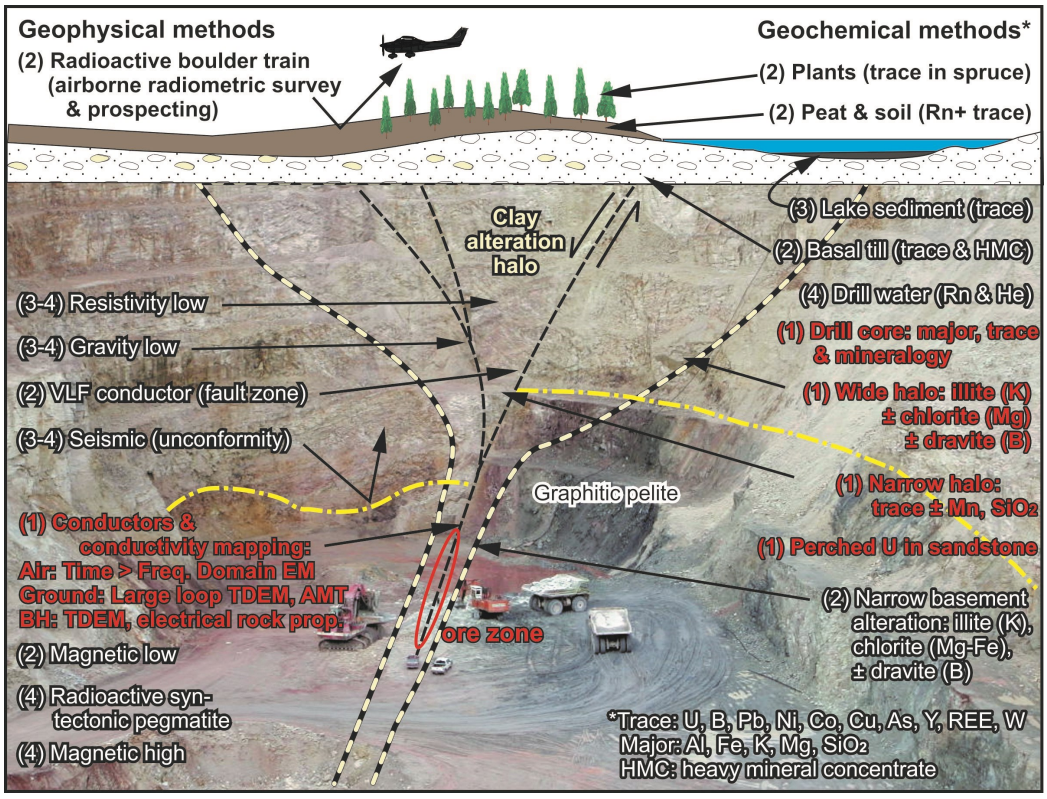


Figure 1 – Synopsis of geochemical and geophysical techniques for exploration of unconformity-related deposits, ranked in order of importance (numbers in brackets). From Potter and Wright (2015), modified after Jefferson et al. (2007b) and Tourigny et al. (2002, 2007).

This report is a contribution to:
TGI 5 (2015-2020) Uranium-rich ore systems project
Subproject 1: Uranium fluid pathways
Activity U-1.1

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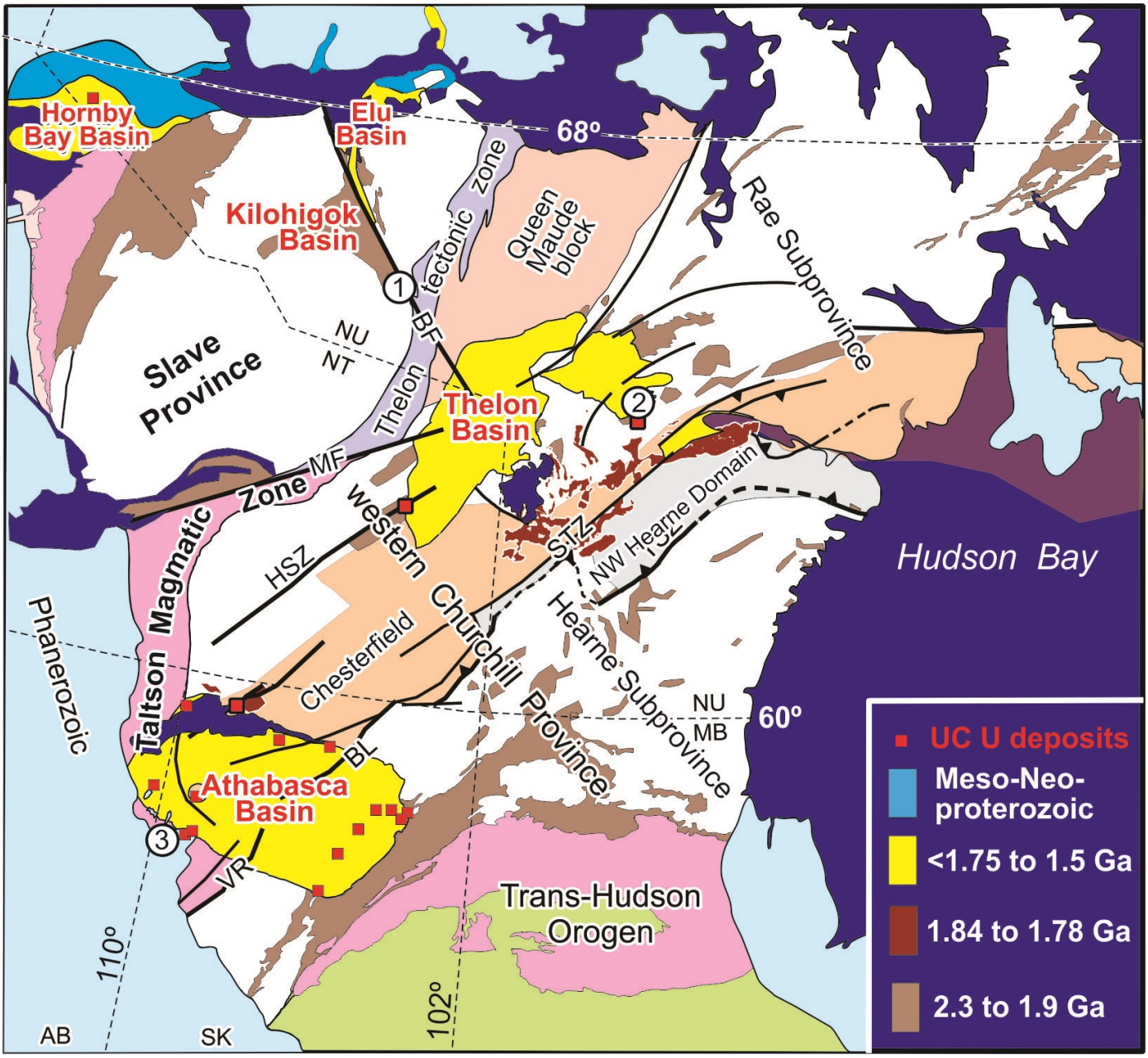


Figure 2 – Location of Proterozoic sedimentary basins in western Canada and unconformity-related uranium deposits. Numbers denote study areas discussed in text: 1 - Bathurst fault, NT; 2 - Andrew Lake - Kiggavik structural trend, NU; 3 - Patterson Lake trend, AB/SK. Faults: BL = Black Lake, BT = Bathurst, STZ = Snowbird tectonic zone, VR= Virgin River, MF = McDonald, and HSZ = Howard Lake shear zone. After Jefferson et al. (2007a).

uranium deposits and to quantify expressions of fertile alteration along such fluid pathways. Three uranium-prospective regions have been chosen for this investigation: the Bathurst fault in the Northwest Territories, key structures along the Andrew Lake - Kiggavik structural trend in Nunavut, and the Patterson Lake trend in Alberta and Saskatchewan (Fig. 2). The Bathurst Fault is a prospective crustal-scale structure that is associated with known uranium occurrences in the Proterozoic Kilohigok Basin, and also splays underneath the western margin of the Thelon Basin. The 24 km long Andrew Lake-Kiggavik trend (Fig. 2) is a northeast-southwest structural trend cross-cut by east-west faults that localized mineralization and display intense hydrothermal alteration (Riegler et al., 2014). The trend is located on the southeast margin of the Thelon Basin and hosts a number of uranium deposits (e.g. Kiggavik, Bong, Andrew Lake) and occurrences in basement rocks. The Patterson Lake trend hosts recently discovered deposits (e.g., Triple R, Arrow) in reactivated basement structures outside and

along the southwestern margin of the Athabasca Basin, with ore lenses situated well below the regional unconformity. Although hosted in reactivated fault structures, the location of these recent discoveries challenge the standard unconformity-related deposit model and thus warrant further investigation.

Activity highlights

The primary objective of the 2016 field season was to characterize the Bathurst Fault Zone deformation and collect rock samples from transects across the fault zone that preserve the ductile to brittle evolution of the Bathurst structure. The 36 samples collected will support microstructural and geochronological analyzes ($^{40}Ar/^{39}Ar$ thermochronology, U-Pb geochronology, and quartz crystallographic preferred orientation analyzes as part of a Masters-level study at Queen's University. With field observations, these data will resolve the Bathurst Fault high strain zone, the extent of fault-related brittle overprint, and older pre-Bathurst Fault regional deformation.

Bedrock mapping and sampling was conducted by the Alberta Geological Survey adjacent to the Saskatchewan border in the Marguerite River area to define the extent of basement rocks hosting the southwestern Athabasca Basin uranium deposits. These samples will be processed for $^{40}Ar/^{39}Ar$ thermochronology and U-Pb geochronology.

Existing publically available geophysical datasets were compiled for all of the three main study sites, incorporating available regional aeromagnetic, gravity and rock property measurements where available, plus enhanced derivative products and re-processing of datasets as necessary. Three dimensional geophysical analysis is initially focussed on the Andrew Lake – Kiggavik structural trend, where extensive physical property measurements, detailed ground gravity data, and high resolution industry aeromagnetic compilations provide fundamental starting datasets for reconstructing 3D rock property models of key structures to examine rock property changes related to hydrothermal alteration at depth.

Next steps

Petrographic and microstructural observations of oriented thin sections from the Bathurst Fault field work commence in fall 2016. Observations will qualitatively characterize the style and degree of deformation, and will also focus on identifying dateable minerals, such as muscovite, biotite, hornblende, monazite, and zircon, for quantitative analysis.

Detailed plans for the 2017 field season in Saskatchewan and graduate student positions are set to be developed at an interprovincial workshop during the Saskatchewan Open House in November 2016. This will serve to coordinate planned graduate student projects for summer 2017, and negotiate data sharing with industry partners.

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Role of marine brines in the formation of giant uranium deposits

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Introduction

The high-grade nature (e.g., >2.0 wt % U) of many unconformity-related uranium deposits within the Athabasca Basin are unmatched by other Canadian and global analogues (Fig. 1; Jefferson et al., 2007, Table 1). The key factor(s) controlling the high-grades characteristic of these deposits are currently undetermined. Recent work on boron isotopic analyzes of hydrothermal tourmaline has demonstrated that marine-derived fluids played a key role in the formation of the Athabasca Basin high-grade uranium deposits. In this model, highly saline and very acidic fluids transported uranium to fault zones in concentrations that were three orders of magnitude higher than common crustal fluids (Richard et al., 2012). The fluids have a diagnostic marine signature reflecting large-scale seawater evaporation and evaporite deposition coupled with fluid-rock interactions (Richard et al., 2010; Mercadier et al., 2012; Fig. 2). A pilot project under a previous phase of the Targeted Geoscience Initiative confirmed the marine signature and documented that these ore-forming fluids travelled along basement-hosted fault zones (Adlakha et al., 2015).

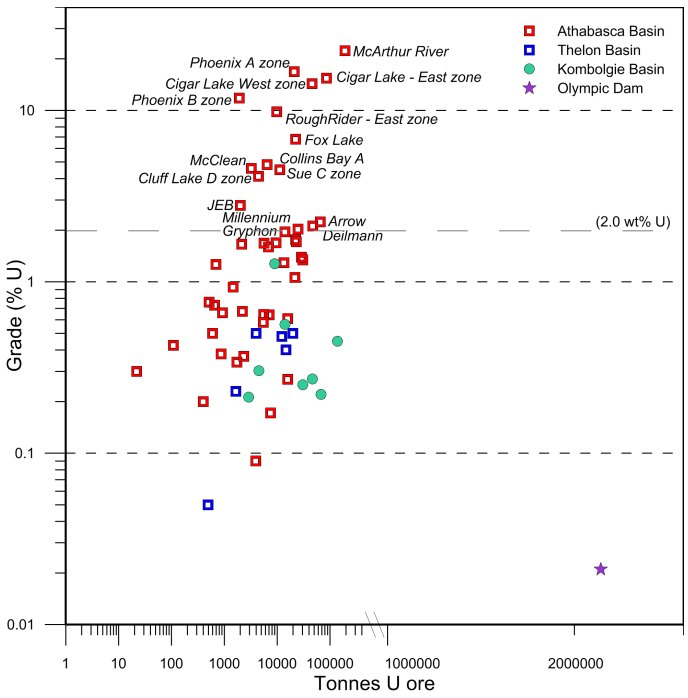


Figure 1 - Ore grade (% U) versus tonnage plot for global unconformity-related deposits. Athabasca Basin deposits are shown in red; note break in tonnage axis to account for Olympic Dam. Data from Jefferson et al. (2007), updated with recent industry technical reports for the Athabasca Basin deposits. Note: some Reserves/Resources figures reported by Jefferson et al. (2007) are historical values that are not compliant with National Instrument 43-101.

Although more contentious, marine brines have also been invoked in the formation of iron oxide-copper-gold (IOCG) deposits, some of which contain uranium (e.g., Olympic Dam; Williams, 2010a, and references therein; Fig. 3). Whereas uranium ore grades are typically low in IOCG systems (<690 ppm U globally), the overall tonnages can be vast – Olympic Dam contains the largest known recoverable uranium resource, with an estimated 2.6 Mt U_3O_8 at an average grade of 250 ppm U_3O_8 (BHP Billiton, 2016). However, geological records of evaporite rocks are not clearly recognized within the preserved stratigraphy hosting either deposit type. Variants of unconformity-related uranium deposits have also been proposed to exist in some IOCG districts (Davidson et al., 2007), highlighting the potential marine-derived fluid linkage.

To date only two IOCG deposits have been defined in Canada, both located in the Great Bear magmatic zone (NWT) – the NICO magnetite-group and the Sue Dianne magnetite-hematite deposits. However, Corriveau (2007) highlighted that there are several regions in Canada prospective for IOCG deposits, as they exhibit the regional iron oxide and alkali alteration diagnostic of these systems (e.g., East Arm Basin, NWT; Wernecke Breccia, YK; Iron Range, BC; Manitou Lake district, Bondy gneiss complex and other targets of the Grenville Province, ON-QC-LB; Rex lineament in the Superior Province, QC; Labrador Trough, QC; Mid-Continent Rift and Southern Province, ON; and the Central Mineral Belt, LB).

What remains to be tested is whether or not marine or evaporite-derived, highly saline, very acidic fluids are unique to the Athabasca Basin deposits and if so, does this, at least in part, explain their unusually high grades? It is also unclear how important marine-derived fluids are in developing economic IOCG deposits. These hypotheses can be tested through examination of deposits in other Proterozoic basins and known IOCG systems, in Canada and abroad. There is also potential to couple boron isotopes with other emerging isotopic methods (e.g., Cl, Mg, Fe, O isotopes) in alteration and ore minerals to gain further insights on the nature of the hydrothermal fluids.

This report is a contribution to:
TGI 5 (2015-2020) Uranium-rich ore systems project
Subproject 1: Uranium fluid pathways
Activity U-1.2

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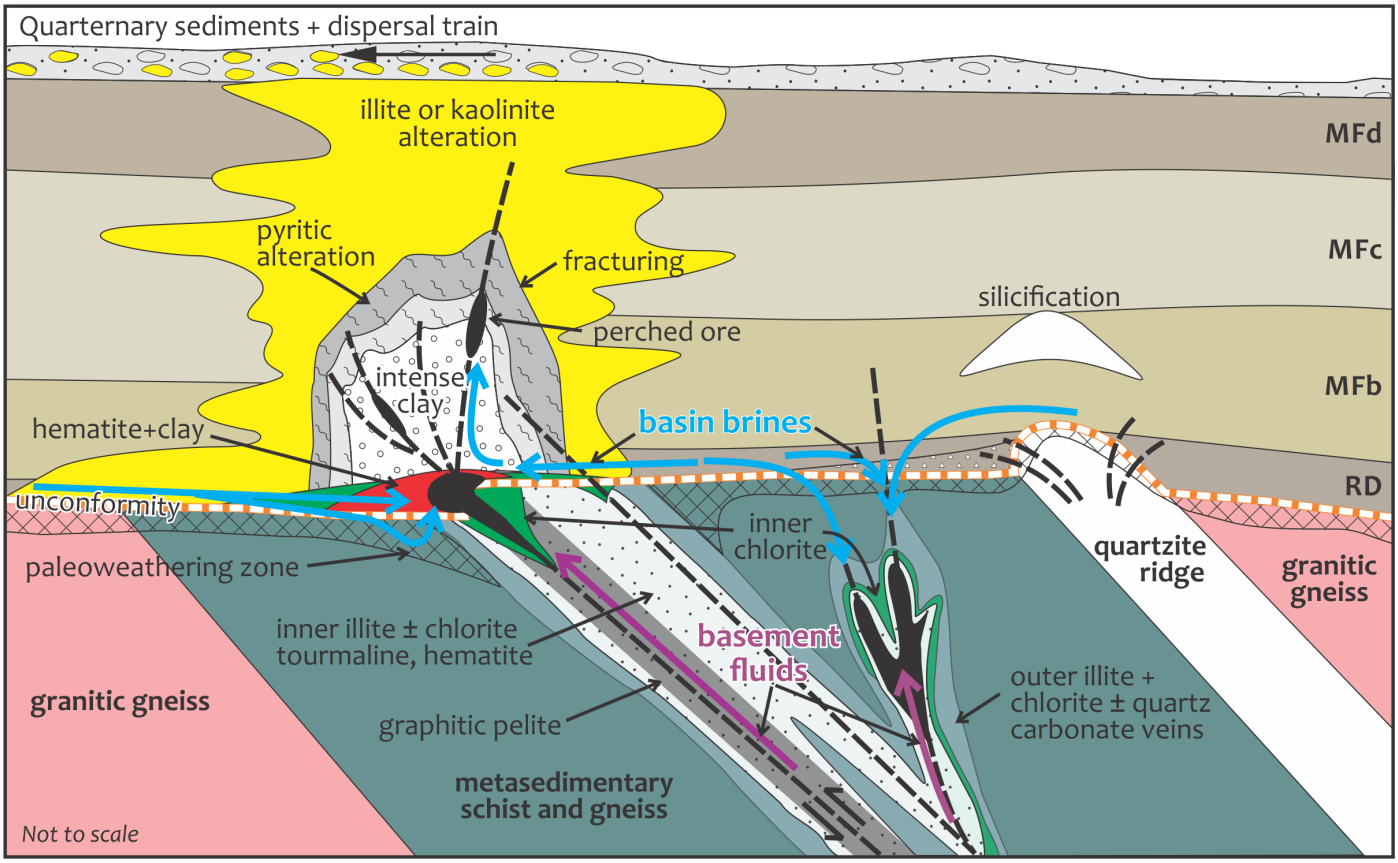


Figure 2 – Simplified Athabasca Basin unconformity-related uranium deposit models. From Potter and Wright (2015) and after Kyser and Cuney (2009). Abbreviations: RD = Read Formation; Members of the Manitou Fall Formation: MFb = Bird, MFc = Collins and MFd = Dunlop.

Activity outline

This activity will utilize the diagnostic capabilities of boron and lithium isotopic signatures of tourmaline, an accessory mineral in both ore deposit types, to constrain the role of marine brines in leaching and transporting metals to form large tonnage, unconformity-related and IOCG ± uranium deposits (e.g., MacArthur River and Olympic Dam). Analytical methods will focus on in-situ procedures to determine the paragenetic setting and composition of tourmaline. Such analyzes will include: scanning electron microscopy, electron microprobe analyzes (major elements), secondary ion microprobe analyzes (B and Li isotopes) and laser-ablation inductively coupled plasma mass spectrometry (trace elements). Samples will be selected to cover a range of deposits and to characterize systems at the deposit and district scale. Documentation of a significant marine or evaporate-derived fluid signature associated with large tonnage mineralization may provide a first-order evaluation of the fertility of a basin or IOCG system to host significant uranium deposits. The results will also contribute insights into the genesis of both ore deposit types (fluid sources and metal pathways) and influence current exploration models.

Two research streams are projected: 1) unconformity-related deposits from Proterozoic basins in Canada (e.g., Athabasca, Thelon, Hornby Bay, Elu and Otish basins), and 2) uranium-bearing IOCG deposits from the Great Bear magmatic zone, NWT, and the Central Mineral Belt, LB.

Science impact

The underlying hypothesis being tested in this activity is that marine brines are critical to the formation of high-grade unconformity-related deposits and large tonnage, uranium-bearing IOCG systems. Boron isotopes are a diagnostic geochemical tool to identify marine sources within hydrothermal brines. With recent analytical advances and better understanding of boron isotope systematics, marine signatures in the ore and alteration mineral assemblages can be examined in uranium-bearing systems with differing ore grades and tonnages. Uranium-bearing systems are intimately associated with fertile source rocks, but the critical factors in controlling uranium grades and tonnage are unknown.

Next steps

A graduate student position at the University of Manitoba and a post-doctoral fellowship at the Geological Survey of Canada are in development. Meanwhile, suitable samples from archival collections are being identified to provide polished sections for microanalytical techniques, which will form the basis of the study.

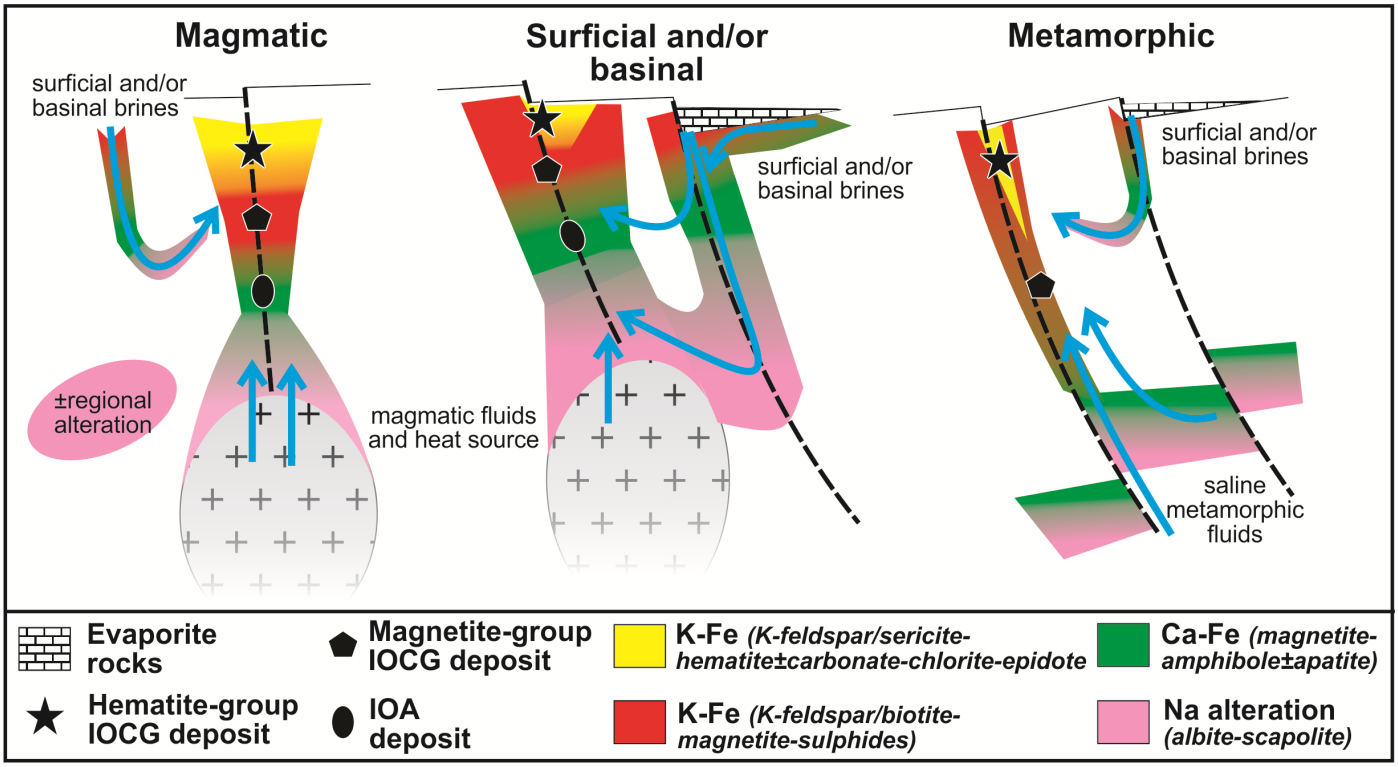


Figure 3 – Fluid source models for IOCG systems highlighting the spectrum of potential fluid and metal sources. Magmatic and evaporitic models invoke magmatic heat ± fluids, derived from calc-alkaline to shoshonitic, high-temperature magma chambers that evolved to A-type magmas within a crustal architecture characterized by deeply-seated faults. All three models involve some component of near-surface fluids. Modified from Barton and Johnson (2004) and Barton (2014), taking into consideration the alteration-zoning model of Corriveau et al. (2010; in press).

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Metal pathways and traps in polymetallic (U ± Fe, Cu, Au, REE) metasomatic ore systems

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Introduction

Iron oxide-alkali alteration systems frequently occur above large, calc-alkaline to shoshonitic, high-temperature magma chambers that evolve to A-type magmas within a crustal architecture characterized by deep-seated faults. Active tectonics and interaction with voluminous saline fluids trigger a chain of metasomatic reactions across the upper crust that lead to systematic alteration facies and to the most extreme, directly observable physico-chemical gradients. Extreme fluid disequilibrium with the country rocks causes early, extensive and pervasive sodic metasomatism and recharge of out-going fluids in most elements and metals, leaving a porous albitite residue along major fault zones that serve as preferential fluid pathways for subsequent alteration and mineralization. Renewed disequilibrium of out-going fluids with the country rocks triggers precipitation of calcium, iron and specialised metals to form iron oxide-apatite (IOA) deposits, some of which can become enriched in rare-earth elements (REE). The fluid column charged in base, precious, and actinide metals continues to rise, mixing with oxidized fluids to precipitate potassium, iron, base, precious and specialized metals in iron oxide-copper-gold (IOCG) deposits (Fig. 1; Corriveau et al., in press). Additionally, active tectonics can telescope deep albitites into the field of lower-temperature and more oxidized environments leading to

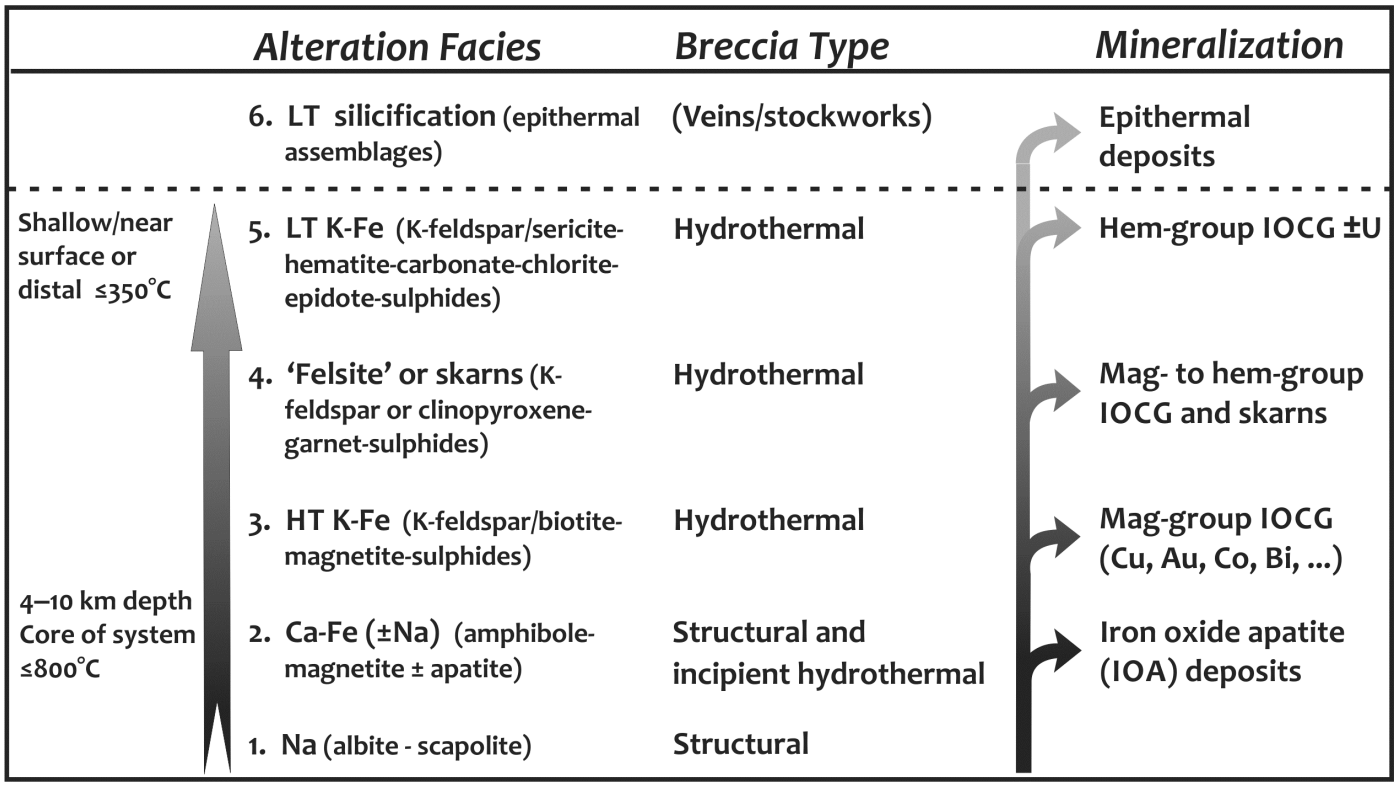


Figure 1 – Iron oxide-alkali alteration zoning model and potential ore deposits formed in response to the evolving metasomatic fronts. After Corriveau et al. (2010a, b, in press).

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TGI 5 (2015-2020) Uranium-rich ore systems project
Subproject 2: Uranium-rich deep metasomatic processes
Activity U-2.1

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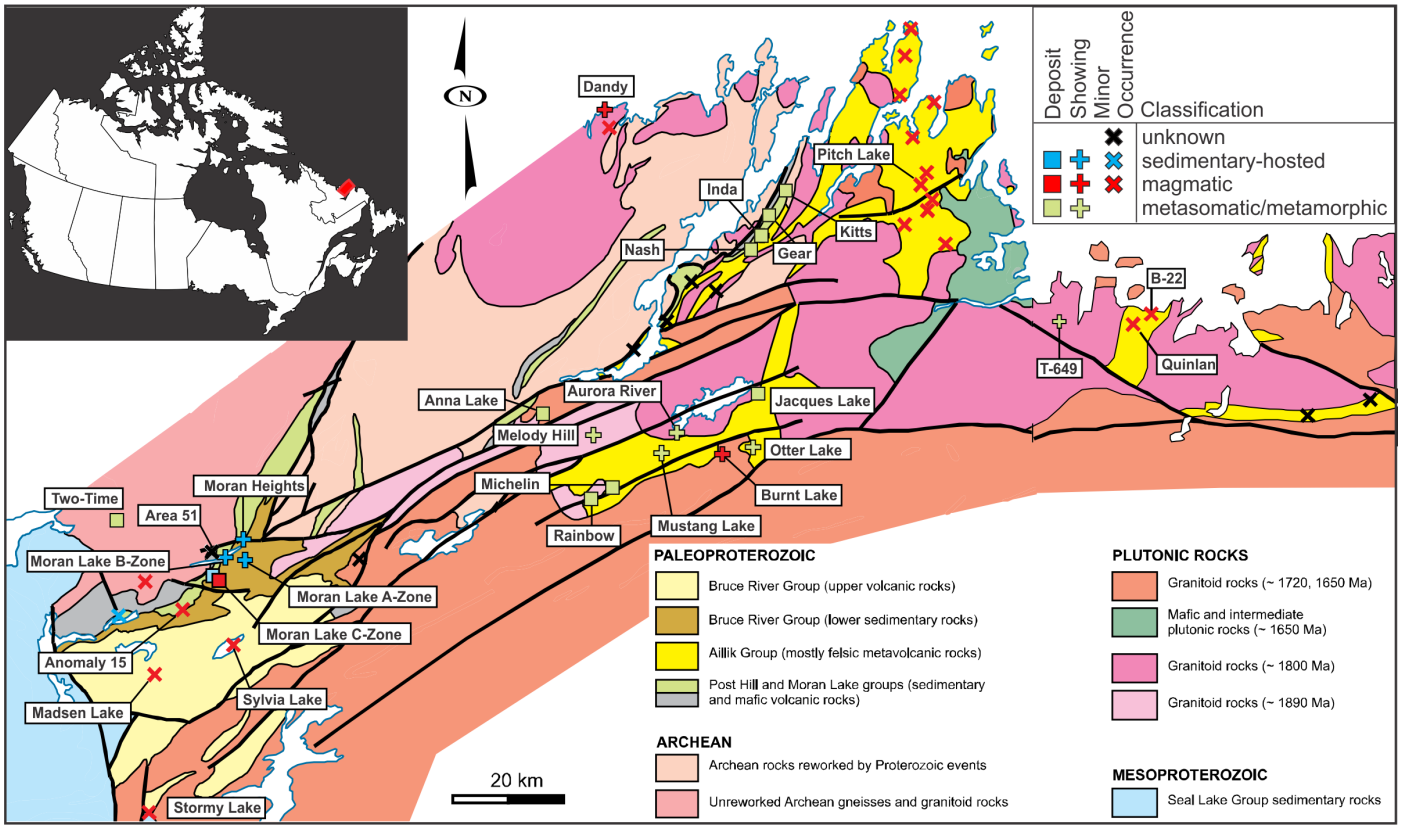


Figure 2 – Generalized geology and uranium mineral occurrences from the Central Mineral Belt of Labrador. After Sparkes and Kerr (2008).

albitite-hosted uranium deposits (Montreuil et al., 2015). Post-mineralization magmatism, deformation and metamorphism may drive remobilization of metals to form albitite-hosted, 'orogenic' gold or Au-U (e.g., Romanet Horst, QC) and REE occurrences (e.g., Kwyjibo deposit, QC), or metamorphosed analogs to IOA and IOCG deposits (Bondy gneiss complex, QC).

Many Canadian settings with IOCG potential remain to be validated but the Geological Survey of Canada, in collaboration with industry, academia and Provincial and Territorial geological surveys, have identified key geological and geophysical exploration criteria and characterized the array of potential deposit types hosted by the regional-scale, iron oxide-alkali alteration systems (summarized in Corriveau et al., 2010b, in press; Blein and Corriveau, in press; Montreuil et al., in press). Among these criteria are polymetallic uranium prospects that are easily recognized in the field and commonly reflect remobilization, and thus record the presence of deeper components of the systems such as IOA and IOCG deposits. The Central Mineral Belt of Labrador is one of these districts (Fig. 2), with well-known and widespread uranium ± iron, copper and gold occurrences, but few integrated overviews of these deposits and their metasomatic footprints across the belt.

The metal pathways and traps in polymetallic (U ± Fe, Cu, Au, REE) metasomatic ore systems activity will examine the sources and processes of uranium enrichment in IOCG deposits that are hosted within broader iron oxide-alkali alteration systems. These systems can host an extraordinary range of deposit types each with economic quantities of base, precious, specialty and/or actinide metals in IOCG, IOA, albitite-hosted uranium, certain skarns and certain intrusion-related deposits (Hitzman et al., 1992; Williams et al., 2005; Corriveau, 2007; Corriveau et al., 2010b, in press; Porter, 2010; Montreuil et al., 2014, in press a, b). It has also been proposed that the silica-undersaturation of iron oxide-alkali alteration systems generates silica-rich, acidic fluids that can lead to epithermal-type mineralization, such as quartz-vein or when syn-metasomatism deformation occurs, orogenic gold (including Au-U) occurrences (Mumin et al., 2010; Corriveau et al., 2010a, b, 2014). Each of these deposit types form as a consequence of the systematic depth-to-surface development of metasomatic-hydrothermal alteration facies across very high-temperature geothermal gradients within the upper crust. Evolving chemical affinities of magma chambers is also observed as metasomatism proceeds and geodynamic conditions change regionally (Montreuil et al., in press a). Such changes may play a role in liberating key volatiles and ligands such as H_2O, CO_2, Li, B, F, P, and Cl and imparting to cogenetic igneous rocks a non-"CHARAC" (CHArge-and-RAdius-Controlled) trace element signature that may help define the prospectivity of magmatic belt for IOCG deposits (Blein and Corriveau, in press). The formation of the deposits also provide fertile metal sources during later deformation or metamorphism.

Current state of knowledge

The Central Mineral Belt (Fig. 2) has both syngenetic mineralization (pegmatite or intrusive-related) and apparent epigenetic mineralization (i.e., IOCG, sodic metasomatite, sandstone - and volcanic-hosted, unconformity-related uranium systems; Sparkes and Kerr, 2008; Sparkes and Dunning, 2015; Sparkes et al., 2016). Recent research and exploration in the district has highlighted regional- to deposit-scale sodic, calcic, potassic and iron hydrothermal alteration and local breccias characteristic of polymetallic iron oxide-alkali alteration systems worldwide (Fig. 3; Corriveau et al., 2010a). In particular, recent mapping and geochronology by Sparkes and Dunning (2015) and Sparkes et al. (2016) on deposits exhibiting iron oxide and alkali alteration has reinforced the temporal association of uranium mineralization and iron oxide-alkali metasomatism along the belt from 1.88 – 1.66 Ga. Hence the seemingly disparate U-Fe, REE, Mo, Cu, Ag, U or Au-U occurrences in the Central Mineral Belt may be united, explained, predicted and explored for under the iron oxide-alkali alteration system model.

Current activities and next steps

Geochemical and geophysical data submitted to the Newfoundland and Labrador Geological Survey as industry assessment files are being compiled into digital databases and archival rock collections are being surveyed for relevant materials.

Using industry drill core stored in Happy Valley-Goose Bay, the research team will undertake targeted drill core sampling from key mineral occurrences in 2017. The goal is to target alteration and ore assemblages from specific mineral occurrences for isotopic and trace element geochemistry. The geochemical and geophysical compilations will be used to guide sampling and subsequent field visits.

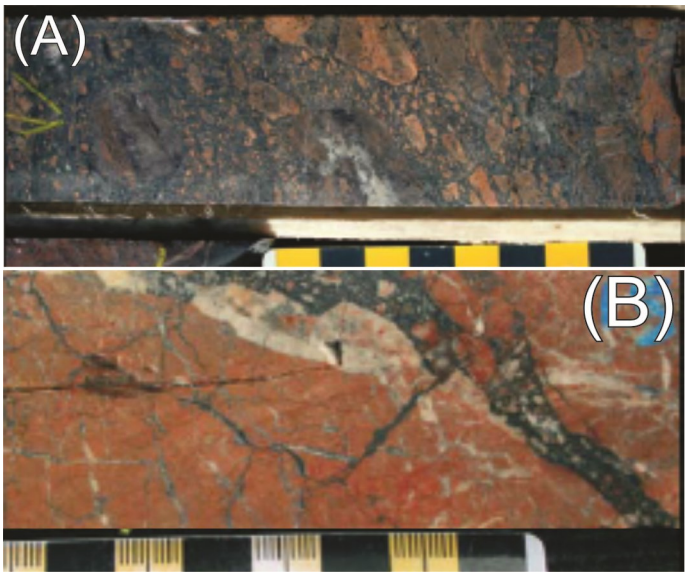


Figure 3 - (A) Hydrothermal breccia with sodic and carbonate altered clasts set in a hematite-rich cement from the Moran Lake C Zone, DDH-ML-3, ca. 105 m. (B) Sodic, carbonate, iron oxide-altered host rocks cut by hematite-rich breccia. Both figures from Sparkes et al. (2016).

Science impact

Recently Montreuil et al. (2013) have proposed an iron oxide-alkali alteration discrimination plot based on whole rock geochemistry. Blein and Corriveau (in press) and Blein et al. (in press) are testing the implications of non-CHARAC behaviour on igneous rocks hosting IOCG deposits and their metamorphic analogues, while Hayward (2013) developed a geophysical modelling process that highlights potential IOCG targets through gravity and magnetic data. In combination with the evolving IOA – IOCG ore deposit model (Corriveau et al., in press; Montreuil et al., in press a, b), the geochemical and geophysical compilations produced in this activity will assist in targeting key mineral occurrences that exhibit diagnostic iron oxide and/or alkali alteration and ore assemblages for further examination.

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Role of anoxia, euxinia and microbes in seafloor hydrothermal sulphide (VMS and SEDEX) deposit formation

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Introduction

This activity aims to understand the role(s) of anoxia (no oxygen in the water column), euxinia (H_2S in the water column), and organic matter in the formation of seafloor sulphide systems in sediment-covered settings. Anoxia or euxinia, and fixation of metals by microbes have been implicated as critical controls on the formation of SEDimentary EXhalative (SEDEX) and volcanic-sediment-hosted massive sulphide (VSMS) deposits (i.e., those in volcanosedimentary sequences). However, others suggest that anoxia or euxinia played only a passive/casual role in the formation of SEDEX and VSMS deposits, and that anoxia has only influenced the compositions of the deposits, or their preservation. The long-standing exploration model for SEDEX and VSMS deposits is that reduced (organic matter-rich and pyritic) sediments are a key requisite (as an inhibitor of destructive seafloor oxidation in the case of VSMS), as is the involvement of microbes in the water column (as the sole source of sulphur for the deposits via BSR, in the case of SEDEX). Recent research, conducted during an earlier phase of the Targeted Geoscience Initiative, revealed micro-scale variability in sulfur isotope compositions of different pyrite morphologies (Fig. 1) from key SEDEX districts in Selwyn Basin (Howard's Pass, Gadd et al., 2016; MacMillan Pass, Magnall et al., 2016). Because of the distinct isotope compositions of pyrite, these studies suggest that anoxia or euxinia are not imperative to the SEDEX mineralizing processes in these districts (Gadd et al., 2016; Magnall et al., 2016). This finding is in stark contrast to the commonly accepted genetic model for SEDEX deposits (Goodfellow et al., 1993); thus, the geological environment(s) of SEDEX formation dictated by prevailing models are too restrictive.

Activity highlights

Paleo-redox indicators based on bulk geochemical parameters typically contradict each other and remain equivocal. For this reason, other independent, more robust indicators must be sought. Therefore, to gain a clearer understanding of paleoredox, we will employ modern, state-of-the-art analytical methods, together with established methods to critically assess the role(s) of anoxia, euxinia, organic matter, and microbes in the genesis of SEDEX and VSMS deposits. Methods will include:

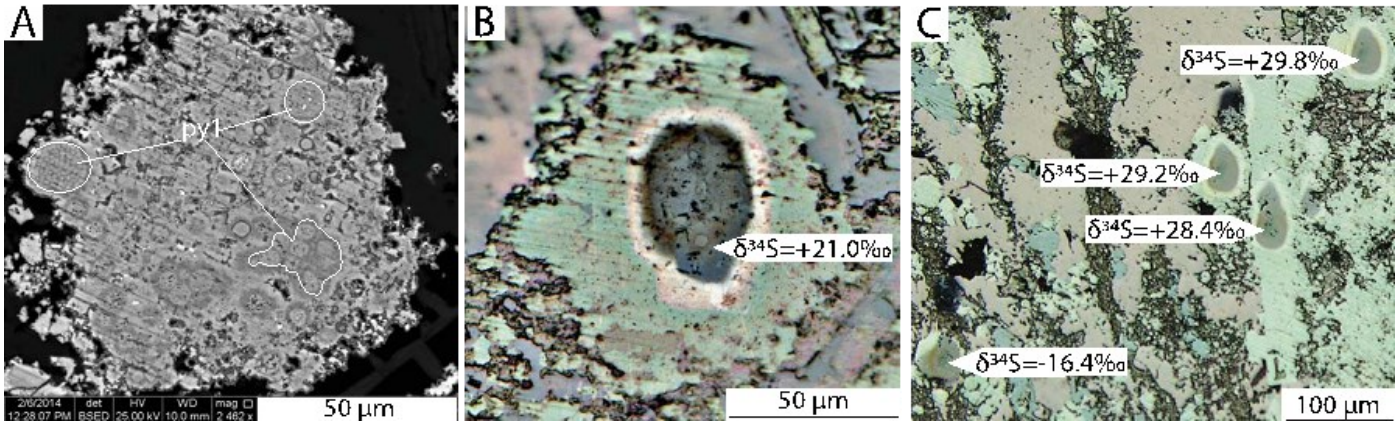


Figure 1 – An example of framboidal and diagenetic pyrite from XY Zn-Pb SEDEX deposit of the Howard's Pass District (sample XY- Adit-386.2). A) BSE image of diagenetic pyrite replacing and overgrowing framboids, which are outlined in white. B) Reflected light photomicrograph of pyrite showing the location of SIMS analysis and the corresponding $\delta^{34}S$ value. C) Reflected light photomicrograph of framboidal and diagenetic pyrite showing the locations of SIMS analyzes and the corresponding $\delta^{34}S$ values.

This report is a contribution to:
TGI 5 (2015-2020) Volcanic- and sedimentary-hosted base metal mineralization project
Subproject 1: Seafloor ore deposition through space and time
Activity VS-1.1

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bulk lithogeochemistry, laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS), conventional microscopy, scanning electron microscopy and cathodoluminescence, electron microprobe, mineral liberation analyzer; organic geochemistry, including biomarkers; conventional and multiple sulphur isotopes (^{32}S, ^{33}S, ^{34}S, ^{36}S) of sulphides; carbon, oxygen and strontium isotopes of ore and host rock carbonates and phosphates in concretions, matrix, laminae, etc.; and non-traditional metal isotopes in host rocks, sulphides, carbonates and phosphates.

These studies will use existing samples from the Howard's Pass and MacMillan Pass districts, Selwyn Basin; Duddar, Pakistan (its Jurassic age making it the youngest and least deformed/metamorphosed example); Bathurst Mining Camp; Finlayson Lake District; and Iberian Pyrite Belt. These will be supplemented by limited, additional new sampling, from the Selwyn Basin, Finlayson Lake District and Bathurst Mining Camp.

Since the activity commenced, a postdoctoral research fellow has been hired, and a M.Sc. student is presently being selected who will be based at Queen's University to work on metal isotope systematics. Much legacy geological, geochemical, mineralogical information and samples have been assembled for analysis. Analyzes will be done both in-house (e.g., SEM, EMP, LA-ICP-MS), and by commercial laboratories or academic institutions.

Science impacts

Because SEDEX and VSMS deposits are far larger than VMS deposit in volcanic settings (no sediments in host sequence), they are mainstay and highly desirable exploration targets in Canada and abroad. This activity is particularly topical, as there are serious shortfalls in world Zn production with the closure of key mines, and no new supply. In the coming years, Zn demand and prices are expected to rise, placing greater exploration focus on seafloor base metal deposits, the key source of Zn. Corroborating or discounting the role of anoxia and/or euxinia in these deposits has the strong likelihood of revolutionizing the genetic and exploration models for SEDEX and VSMS deposits.

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Development of genetic and exploration models for hyper-enriched black shale (HEBS) deposits

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Introduction

Hyper-enriched black shales (HEBS; Fig. 1), also referred to as polymetallic metalliferous shales, are an important global resource for Zn, Ni, Cu, Mo, Se, U, V, ± Cr, Co, Ag, Au, PGE and REE (e.g., Jowitt and Keays, 2011). These deposits are thin (<10 to 40 cm) and laterally widespread, covering 100s of km2 (e.g., the Cambrian Yangtze Platform, China, and the Devonian Mackenzie Platform, Yukon). Canada hosts some of the best examples (e.g., Nick deposit, Yukon; Hulbert et al., 1992) and there is significant potential for the further discovery and development of such deposits. However, exploration is currently hindered by an incomplete model of how these deposits formed. Current genetic models are myriad, and interpreted sources of metals include seafloor hydrothermal, ambient seawater/phosphogenesis/high organic productivity, and extra-terrestrial (e.g., Hulbert et al., 1992; Lehmann et al., 2007; Goodfellow et al., 2010). Recent work has shown that HEBS formed at periods of peak atmosphere-ocean oxygenation, and that reduction by organic matter may have been key in drawing down trace metals and depositing them at the seafloor (Large et al., 2015).

Activity highlights

In order to advance our understanding of HEBS formational processes, this activity is investigating the chemistry of these systems at a much finer resolution than has previous been attempted. Data from micro-analytical techniques will be integrated into large-scale processes (i.e., operating at the basin/plate tectonic scale) to develop a cohesive and utilitarian exploration model for HEBS mineralization. This activity will determine the genetic controls on HEBS deposits, and develop an exploration model by using existing legacy samples and datasets, together with limited new (micro-scale) well-constrained sampling from key deposits.

Samples will be analyzed using micro-scale analytical techniques (e.g., LA-ICP-MS, SIMS), with an emphasis on trace metal and metalloid geochemistry and stable and radiogenic isotopes. Traditional and metal isotopic systems will be used, including S, multiple S and metal isotopes, and Re-Os dating of sulphide minerals. The LA-ICP-MS work will focus on the geochemical redox indicators (e.g., Mo, Se, Re, As, Fe, Mn, Ce, Eu, Tl, Cu) of sulphides, sulphates and phosphates. In order to constrain the involvement of organic matter in the redox cycling and sequestration of metals, organic geochemical and isotopic analyzes will also be done.

Since the activity commenced, a postdoctoral research fellow has been hired, and a master's-level studentship, based at Queen's University, initiated. The focus of this student project is to characterize the HEBS horizon underlying the Cardiac Creek Zn-Pb-Ag-Ba sedimentary exhalative (SEDEX) deposit, northern B.C., and compare these data with other localities in northern Canada. An additional master's-level studentship on metal isotope systematics of HEBS is in development.

Historical datasets including: samples, geological, geochemical, mineralogical information have been assembled and compiled for analysis. Analyzes will be done both in-house (e.g., SEM, EMP, LA-ICPMS), and by commercial laboratories or academic institutions. To date, optical mineralogy and SEM analysis have been completed on a subset of samples, and one sample has been processed for mineral separations, in preparation for additional targeted further analyzes. Select samples are currently undergoing paleontological assessment to



Figure 1 – Photograph of HEBS layer (thin, dark-coloured layer) from the Nick Deposit, Yukon (photograph courtesy of Wayne D. Goodfellow).

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TGI 5 (2015-2020) Volcanic- and sedimentary-hosted base metal mineralization project
Subproject 1: Seafloor ore deposition through space and time
Activity VS-1.2

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Peter, J.M., Gadd, M.G., Layton-Matthews, D., Goodfellow, W.D., Jackson, S.E., Taylor, B.E., and Johnson, N., 2017. Development of genetic and exploration models for hyper-enriched black shale (HEBS) deposits; in Targeted Geoscience Initiative – 2016 Report of Activities, (ed.) N. Rogers; Geological Survey of Canada, Open File 8199, p. 105-106. doi:10.4095/299573

improve age determinations. Additionally, organic matter in select samples is being extracted for analysis and characterization.

Science impacts

This activity will improve our understanding of the genetic processes responsible for northern Canadian HEBS deposits, permitting a refined exploration model for this style of mineralization. The findings may be applicable to sedimentary (and volcano-sedimentary) basins elsewhere in Canada. Currently, two of the most widely accepted models for their formation are seafloor hydrothermal activity and hydrogenous synsedimentary deposition. The working premise is that ambient paleoredox state (and importance thereof to the mineralizing process) of the depositional environment of these deposits (organic-rich systems with metals that form strong complexes with organic matter) is likely a critical controlling factor. Except for a select number of recent studies on Chinese examples, HEBS deposits have not been studied using modern micro-analytical methods.

Due to their polymetallic nature, this deposit type represents a source of not only base metals (Zn, Ni, Cu), but also other rare and strategic metals (as by-products). Consequently, they may represent attractive exploration targets that, to some extent, are resistant to the effects of cyclical metal prices, particularly if they become a resource of metals that are currently in high demand for electronics, energy, military, and other high-tech applications. Finally, the economic feasibility of mineralization in other deposit types that is spatially close to HEBS mineralization may be positively impacted by the metal enrichments and tenors within the latter (i.e., HEBS may be an ore "sweetener").

Next steps

Analysis and interpretation of legacy samples and data is ongoing. Fieldwork will be conducted in north-eastern BC, and elsewhere in Yukon in 2017. Scientific partnerships will also be key to the success of the activity with agreements in place or development with Queen's University, Laurentian University, Memorial University of Newfoundland, Acadia University, University of Alberta, Yukon Geological Survey, Centre For Astrobiology – Spanish National Research Council, and University of Tasmania.

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Is there a genetic link between the SEDEX and MVT deposits of the Canadian Cordillera?

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Introduction

The concept of a possible genetic relationship between Mississippi Valley-type (MVT) and sedimentary exhalative (SEDEX) deposits has been alleged by numerous scientists but never well documented and proven. Both deposit-types appear to have been generated by processes operating in large sedimentary basins in the absence of significant contributions from magmatic sources. The fundamental objective of this activity is to verify if there is a genetic link between SEDEX and MVT deposits of the "shale and carbonate corridors". The physical and geochemical parameters, depositional conditions, age of formation, and origin of metals and sulphur in SEDEX and MVT deposits will be documented and compared. This will enable us to finally conclude if there is a genetic and/or temporal links between these deposit types.

This paper summarizes the initial results of the 2016 field program that focussed on select carbonate-hosted mineralization in south-eastern British Columbia, including Mississippi Valley-type (MVT), REE-fluorite, and magnesite deposits (Fig. 1). This component of the activity is being conducted collaboratively with the TGI 5 Specialty Metal Ore System Project.

All of the studied deposits (Fig. 1) are located within a "carbonate corridor" that extends from north-east to south-east in the Rocky Mountain Fold and Thrust Belt of the Canadian Cordillera. Future fieldwork will target: i) the north-east section of the "carbonate corridor" (Mackenzie and Macdonald carbonate platforms of the northern Canadian Cordillera) that contains numerous MVT deposits; and ii) a parallel "shale corridor" represented by the Selwyn Basin and the Kechika Trough (a southward extension of the Selwyn Basin), which contains significant SEDEX Zn-Pb (±Ba, ±Ag) deposits and numerous barite occurrences. This architecture provides an exceptional opportunity to examine the possible genetic and temporal links between MVT and SEDEX deposits.

Fieldwork in 2016 examined the south-eastern portion of the "carbonate corridor", where fertile segments of the corridor host MVT, polymetallic veins, REE-fluorite, fluorite and barite -bearing deposits. The objective here was to test a potential genetic link between MVT, specialty metals (fluorite REE-bearing), and magnesite mineralization. On a more regional scale, these deposit-types may be also structurally linked with deep-seated structures that acted as conduits for some of alkaline intrusive breccia diatreme, kimberlite and the Ice River alkaline complex that are located along the same regional carbonate trend.

This fieldwork indicates that the above working hypothesis appears to hold true. Lithological, textural, mineralogical and geochemical parameters, depositional conditions, age of formation, provenance of metals and sulphur, tectonic and structural controls, variations in the C and O isotopes in carbonates in proximity of MVT, magnesite and fluorite (±REE) deposits will need to be documented and compared. Later this data will be merged with existing and newly acquired information on SEDEX deposits to complete the metallogenic story.

Activity highlights

During the summer of 2016, field work concentrated in the Canadian Cordillera of south-eastern British Columbia (Fig. 1). Studies focussed on a range of MVT deposits (Shag, Monarch, Kicking Horse, Munroe), the REE-fluorite bearing Rock Canyon Creek deposit, and a magnesite deposit (Mount Brussilof). Field work at the MVT Zn-Pb deposits comprised of documenting and sampling individual sites, and acquiring samples directly from the mining and exploration industry.

For the most part, two types of sulphide mineralization were observed: i) stratabound replacement of host dolostone by sphalerite and galena (±pyrite); and ii) open-space filling of fractures, breccias, and vugs. Mineralization is exclusively hosted by locally brecciated dolostone, which was associated with hydrothermal sparry and saddle dolomite. Hydrothermal dolomite occurs as cement in intergranular porosity and open-space fill and replacement of the host dolostone. Sparry dolomite forms a variety of textures including zebra textures and fracture fillings. Examples of various mineralized textures are shown in Figures 2 to 5.

The Rock Canyon Creek deposit, hosting REE and fluorite mineralization, is of special interest because unlike most REE-bearing deposits in British Columbia, it is not spatially associated with currently recognized, outcropping carbonatite or alkaline rocks. Furthermore, this deposit was discovered as a result of geochemical exploration for MVT Zn-Pb deposits. The work done at Rock Canyon Creek involved two days of helicopter-supported reconnaissance studies, in combination with core-logging and sampling of five drill holes stored at the Vine Core Library. Mineralization is predominantly fracture-controlled occurring as purple fluorite (±calcite and ±barite)

This report is a contribution to:
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Subproject 2: Base metal sources and mineralizing processes
Activity VS-2.1

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Paradis, S. and Simandl, G.J., 2017. Is there a genetic link between the SEDEX and MVT deposits of the Canadian Cordillera?; *in* Targeted Geoscience Initiative – 2016 Report of Activities, (ed.) N. Rogers; Geological Survey of Canada, Open File 8199, p. 107-113. doi:10.4095/299573

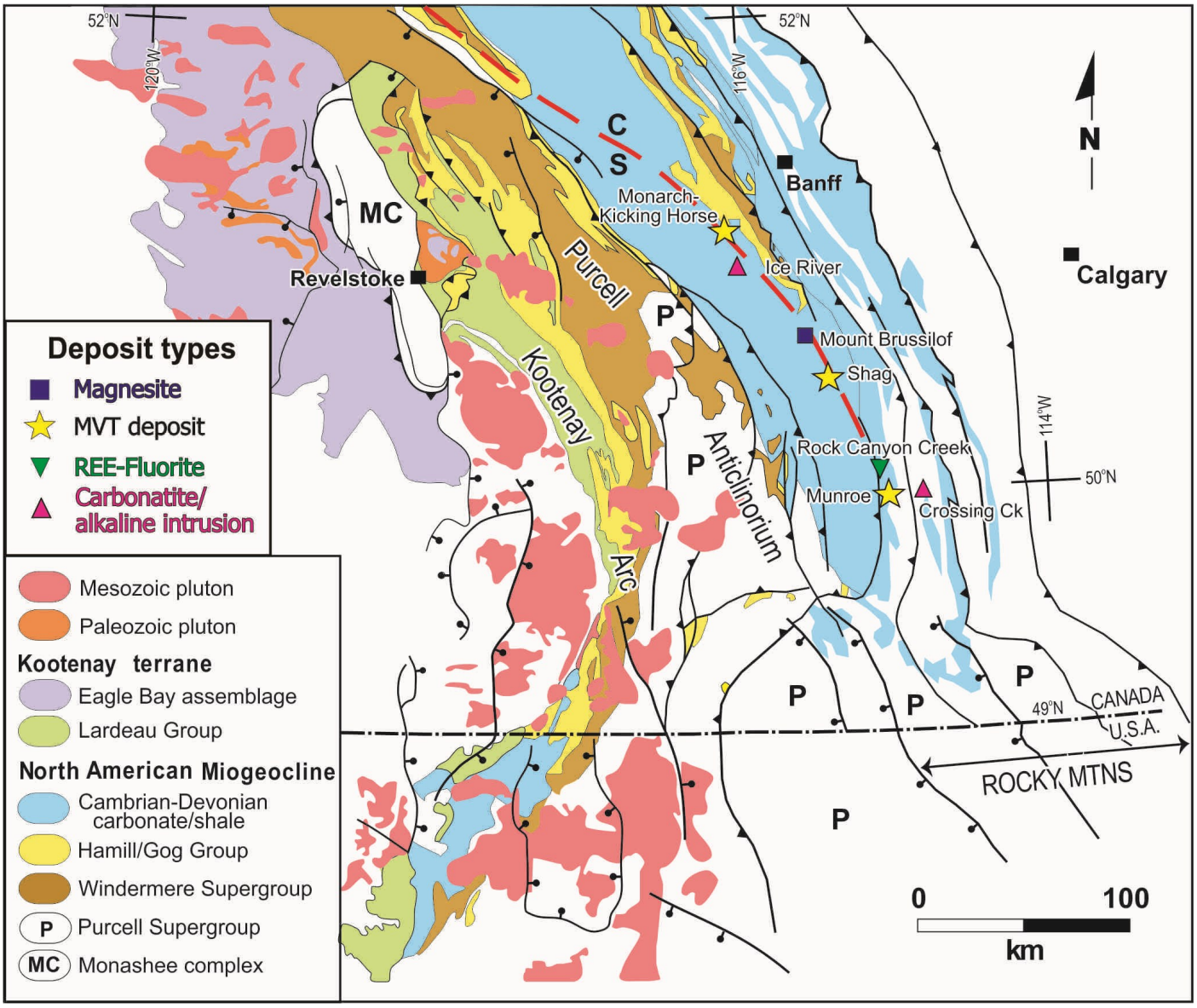


Figure 1 – Simplified geological map of the southeastern Canadian Cordillera (modified after Wheeler and McFeely, 1991; and Logan and Colpron, 2006) with location of deposits that were the focus of the 2016 field program. It includes MVT deposits (Shag, Monarch, Kicking Horse, Munroe), REE-fluorite bearing Rock Canyon Creek deposit, and magnesite deposit (Mount Brussilof). The location of the Ice River complex and Crossing Creek Kimberlite is shown for reference. The thick red line indicates the middle Cambrian carbonate (c) to shale (s) transition.

veinlets crosscutting dolostone of the Devonian Burnais Formation.

Science impacts

In the study area, the MVT Zn-Pb and magnesite deposits are concentrated exclusively within the carbonate belt of the Canadian Cordillera, and more specifically located within the Kicking Horse paleo-bathymetric Cambrian high. All of the carbonate-hosted deposits, including the Rock Canyon Creek REE-fluorite deposit, are associated with sparry (hydrothermal) carbonate and breccia zones. None of these deposits are located in proximity to a known intrusion.

Establishing the spatial, tectonic, structural, stratigraphic, lithologic, geochemical, and temporal setting of these deposits will enable us to verify if there are genetic links between MVT, some specialty metal (e.g., Rock Canyon Creek), and magnesite deposits (e.g., Mount Brussilof) in south-eastern BC. The apparent spatial coexistence (i.e., same trend) of these deposits with intrusive breccia diatremes, which were described by Helmstaedt et al. (1988) and Pell (1994), suggests the presence of deep-seated faults.

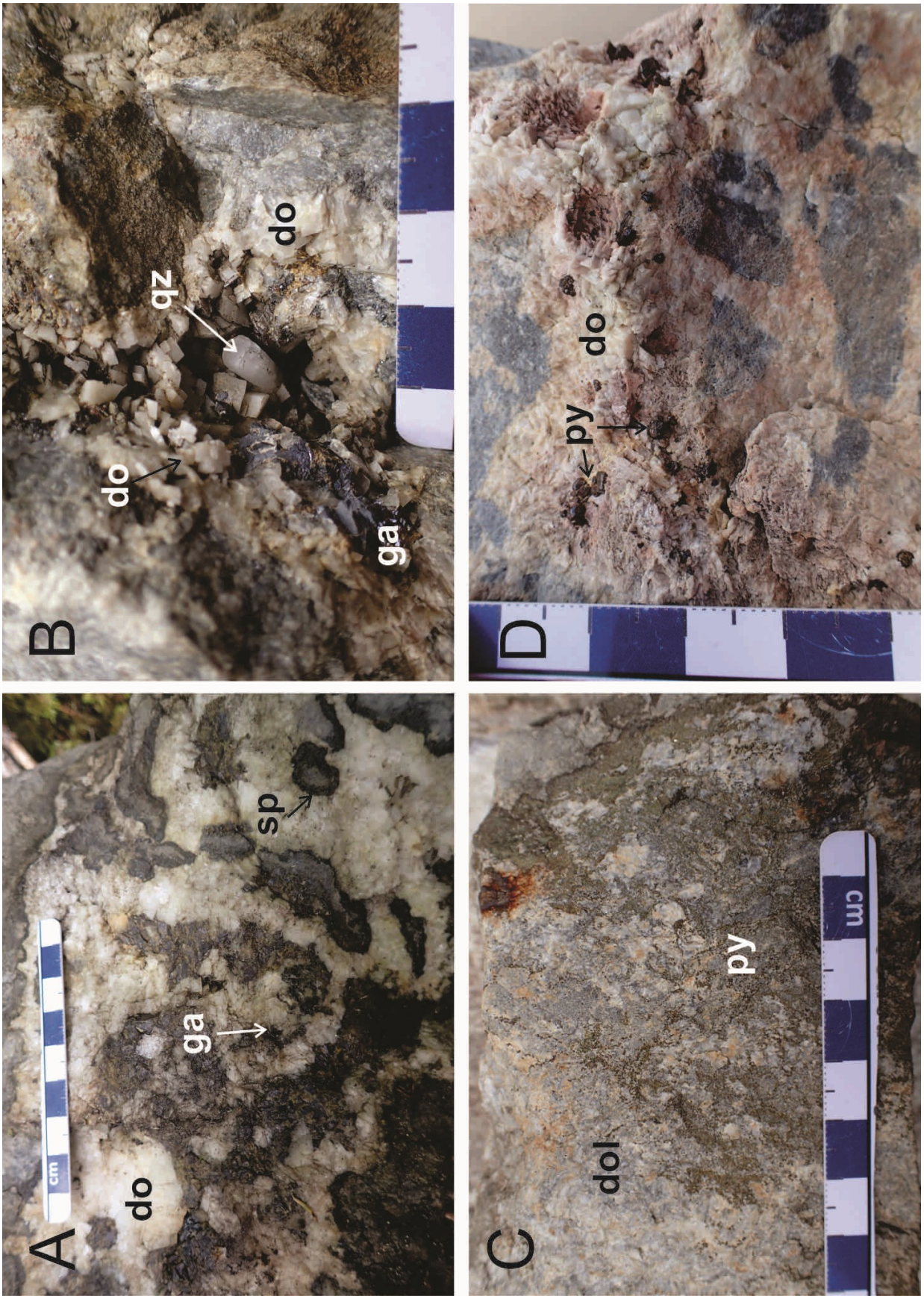


Figure 2 – Monarch-Kicking Horse MVT Zn-Pb deposits. A) Aggregates of sphalerite (sp) and galena (ga) in white sparry dolomite (do) cement. Note that sphalerite completely or partially rim dolostone fragments. B) Cavity filled by galena (ga) and late dolomite (do) and quartz (qz) crystals. C) Fine- to coarse-grained pyrite (py) disseminated and fracture-filled in dolostone (dol). D) Late disseminated euhedral pyrite crystals in cavity and fracture-filled dolomite.

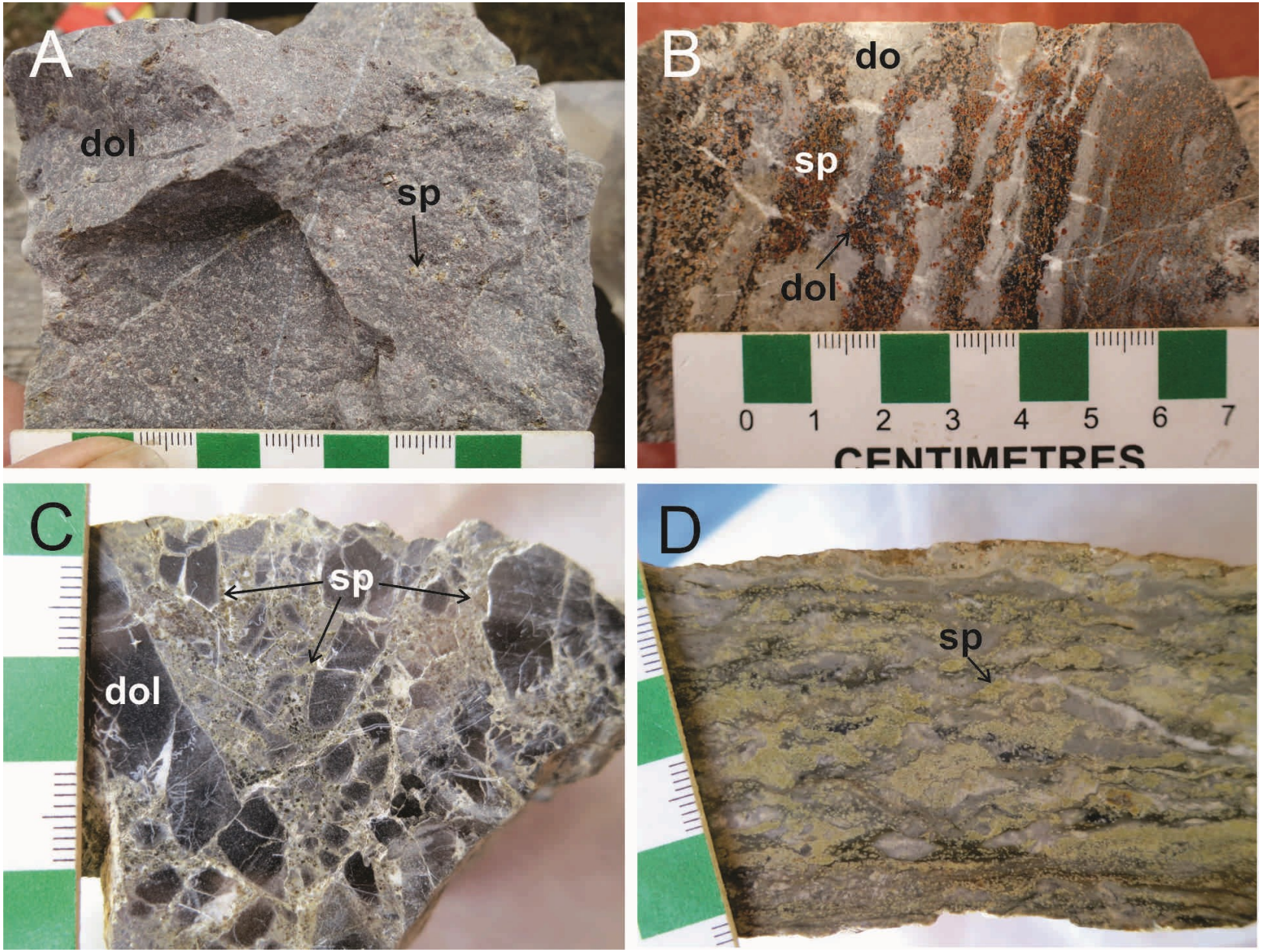


Figure 3 – Shag MVT Zn-Pb deposit. A) Disseminated and recrystallized red and yellow colored sphalerite (sp) in crystalline dolostone (dol) of the Middle Cambrian Cathedral Formation, BM showing. B) Replacement-type red sphalerite mineralization at the Red Bed showing; note that red and yellow colored sphalerite preferentially replaced the grey dolostone (dol) beds. C) Green to yellowish green granular sphalerite fills the fractures in the dolostone breccia, C-3 showing. D) Mottled sphalerite replacement texture within siliceous dolostone, C-4 showing.

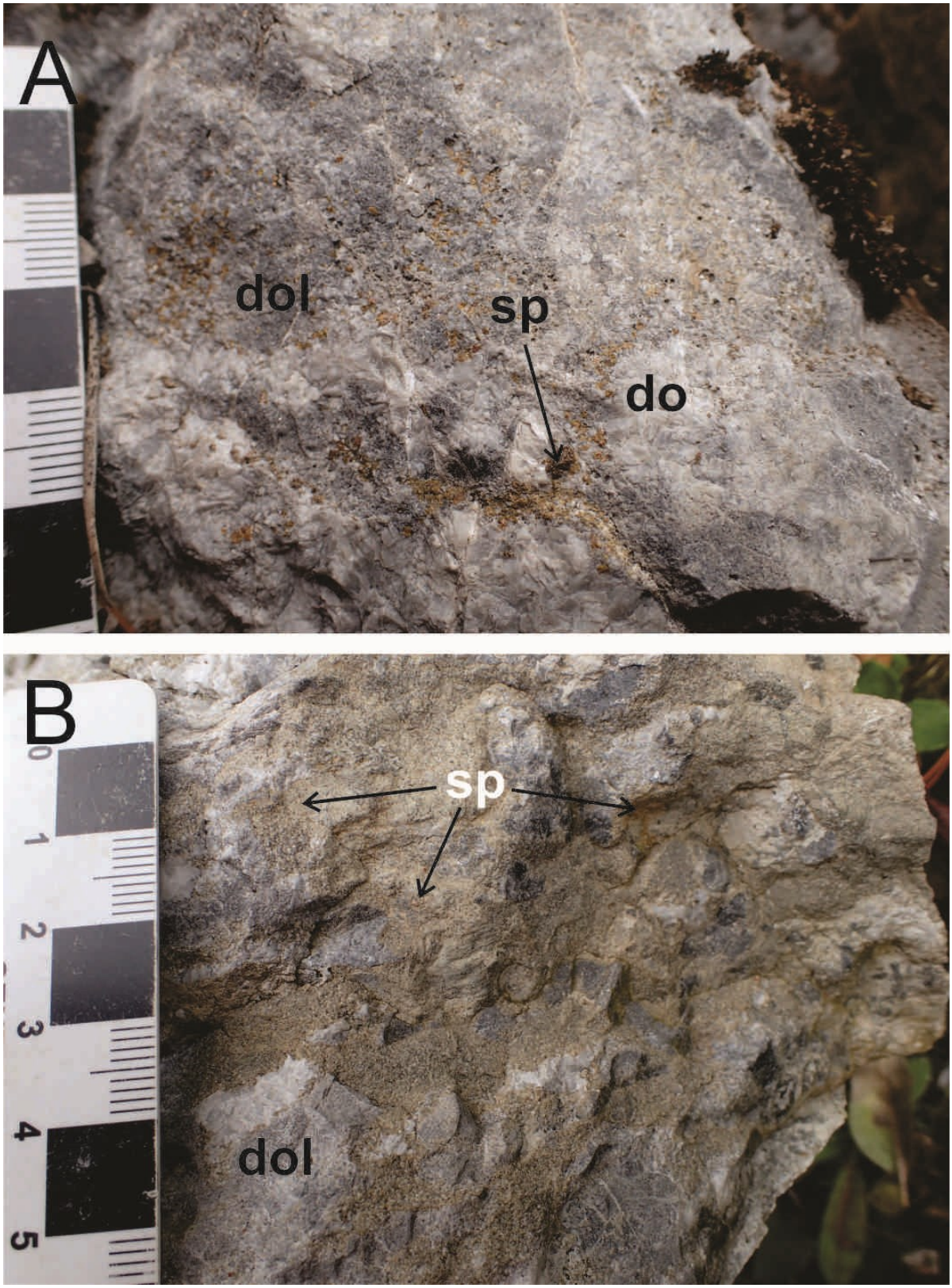


Figure 4 – Munroe MVT Zn-Pb deposit. A) Recrystallized yellow to red colored sphalerite (sp) disseminated in dolostone (dol), concentrated along the periphery of spar dolomite (do) patches. B) Pale yellow to almost clear sphalerite (sp) replacing dolostone (dol) of the Upper Devonian Palliser Formation.

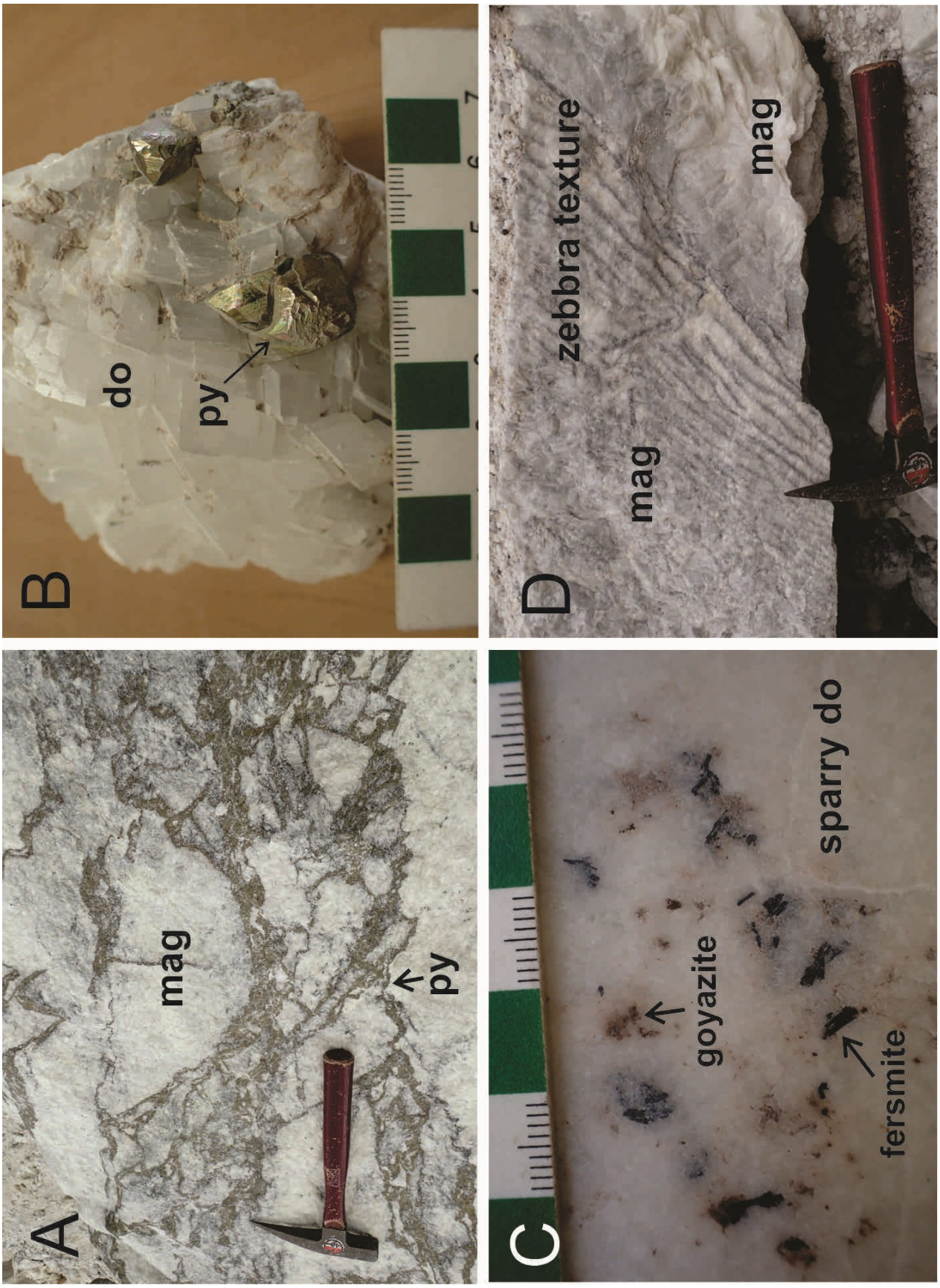


Figure 5 – Mount Brussilof magnesite deposit. A) Fine-grained fracture-filled pyrite (py) in magnesite (mag), Cambrian Cathedral Formation, Baymag Mine. B) Coarse-grained euhedral pyrite (py) crystals in coarse-grained sparry dolomite (do). C) Pseudo-cubic, euhedral crystals of goyazite (red-orange), fersmite (steel-gray) within sparry dolomite (do). D) Magnesite (mag) ore displaying a "zebra texture", commonly observed at Mount Brussilof mine and characteristic of MVT deposits.

Next steps

The samples collected in 2016 are being prepared for the following analytical studies:

- Detailed petrography, mineral chemistry using the scanning electron microscope (SEM) and electron microprobe, and where appropriate, in-situ trace element analysis using laser ablation ICP-MS. Specialty metal content (e.g., Ge, Ga, In) of sulphides in MVT deposits will be investigated.
- Documenting Nb, REE and possibly Be-bearing minerals from fractures and vugs within magnesite ore at Mount Brussilof.
- S-isotopes of pyrite (and other sulphides) and barite, and O, C and Sr isotopes of carbonates.
- Age dating of pyrite mineralization using Re-Os isotope system (assuming that the Re-Os concentration is suitable for dating).

In 2017, fieldwork in northern British Columbia will be initiated. The work in south-eastern British Columbia will continue in conjunction with the Specialty Metals component of TGI, the British Columbia Geological Survey and the Japan Geological Survey.

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Magmatism and relationships to sediment-hosted Zn-Pb deposits

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Introduction

The Northern Canadian Cordilleran continental margin developed and rifted intermittently during the early Palaeozoic. Periods of rifting were accompanied by alkalic and ultrapotassic volcanic and intrusive rocks that are distributed discontinuously along the entire continental margin. These rocks are spatially, and possibly temporally and genetically, associated with clastic sediment-hosted Zn-Pb (±Ag, ±Ba) deposits (SEDEX) and other deposit types (e.g., VHMS, veins). However, despite local spatial association of magmatic rocks to these deposit types, the nature of the genetic relationship between them is poorly documented and understood.

Our objectives are to resolve the following questions: i) Is the relationship between SEDEX mineralization and magmatism causal (i.e., partial heat engine) or casual (i.e., purely spatial)? ii) What are the precise ages and geochemical signatures of the magmatic rocks associated with sediment- and volcanic-hosted Zn-Pb mineralization? iii) What tectonic processes are associated with the magmatic rocks? iv) Do the magmatic rocks reflect specific structural and heat corridors, and does their emplacement reflect the utilization of long-lived lithospheric structures that also potentially controlled hydrothermal activity? v) What are the temporal and spatial variations in the physical and chemical volcanology and mineralization? And finally, vi) can these questions and answers be used to predict the presence or absence of mineralization in a given basin?

During the summer of 2016, four weeks of preliminary field work (including travel time) were carried out in the Keno-Mayo (105M/13, M/14), Anvil (105K/3, K/6), and MacMillan Pass (105O/1, O/2) districts of the Selwyn Basin, central Yukon (Fig. 1). The aim was to constrain the geology, document the styles of volcanism, and systematically sample the volcanic rocks for future geochemical studies.

These three districts are host to important Zn-Pb-Ag (±Ba) deposits (SEDEX, vein-type, and rare VHMS). The Anvil district hosts Zn-Pb-Ag (Ba) SEDEX deposits (Faro, Vangorda, Swim, Grum, and Dy), and one VHMS occurrence (Rebel KD). The Keno-Mayo contains numerous Ag-Pb-Zn vein deposits (BelleKeno, Hector-Calument, Lucky Queen, Elsa, etc.), and the MacMillan Pass district is well known for its Zn -Pb-Ag (Ba) SEDEX deposits (Tom and Jason). Below is a brief summary of our field observations for each district.

Activity highlights

Keno Hill-Mayo district:

The Keno Hill mining district in central Yukon was the second largest silver producer in Canada with mines operating from 1913 to 1989 on more than 65 Ag-Pb-Zn vein deposits. Volcanic rocks of the Devonian-Mississippian Earn Group (DMEV) form a layer several metres to hundreds of metres thick at the top or near the top of the Earn Group strata (Roots, 1997). These rocks are exposed on the north-facing slope of Mount Haldane (105M/13) and around Keno Hill (105M/14).

The Earn Group is overlain by the Mississippian Keno Hill quartzite, which hosts the Ag-Pb-Zn vein deposits. The Earn Group volcanic rocks consist of foliated greenish-white to green-grey quartz-sericite-chlorite phyllite and schist (Fig. 2) that are inferred to be felsic metavolcanic rocks, some of which are possibly meta-tuffs and lapilli tuffs. On occasion feldspar and quartz phenocrysts are observable.

The volcanic rocks and sediments are crosscut by fine- to medium-grained Triassic meta-diorite to meta-gabbro intrusions. The intrusive rocks are concordant to discordant bodies of fine- to coarse-grained amphibole-chlorite-plagioclase meta-diorite or meta-gabbro (medium to dark green-gray in color; massive texture). According to Roots (1997), the intrusions range from augite diorite to less common feldspar-phyric pyroxene gabbro. These intrusions show a spatial relationship to the Ag-Pb-Zn mineralization; however their temporal relationship is unknown because the age of the Ag-Pb-Zn veins has not yet been determined.

Anvil district:

The Zn-Pb-Ag (Ba) SEDEX deposits (Faro, Vangorda, Swim, Grum, and Dy) of the district occur within a 150-metre stratigraphic interval straddling the contact between the metasedimentary Mount Mye and Vangorda formations in the ancestral North American succession of the Selwyn Basin. A thick, resistant, grey-weathering, basaltic volcanic unit, informally named the Menzie Creek formation (Jennings and Jilson, 1986), conformably overlies the Vangorda formation (Fig. 3). The Menzie Creek volcanic rocks (OSM), which host the Rebel KD VHMS occurrence (Yukon MINFILE 105K 083, Deklerk, 2003) and other unclassified deposits, are exposed south and north of the Anvil Batholith.

This report is a contribution to:
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Subproject 2: Base metal sources and mineralizing processes
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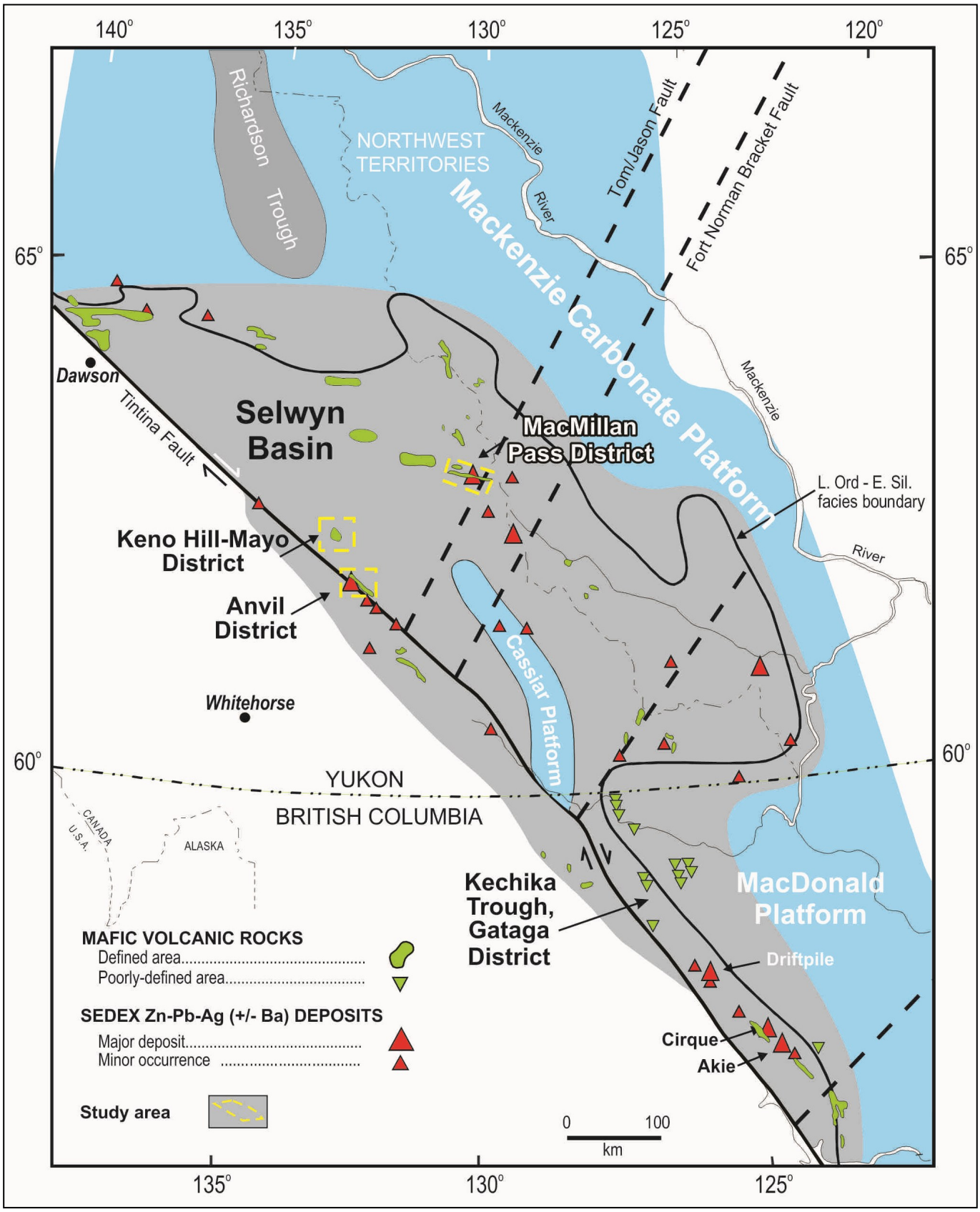


Figure 1 – Location of field study areas in 2016. Modified from Goodfellow et al. (1993).

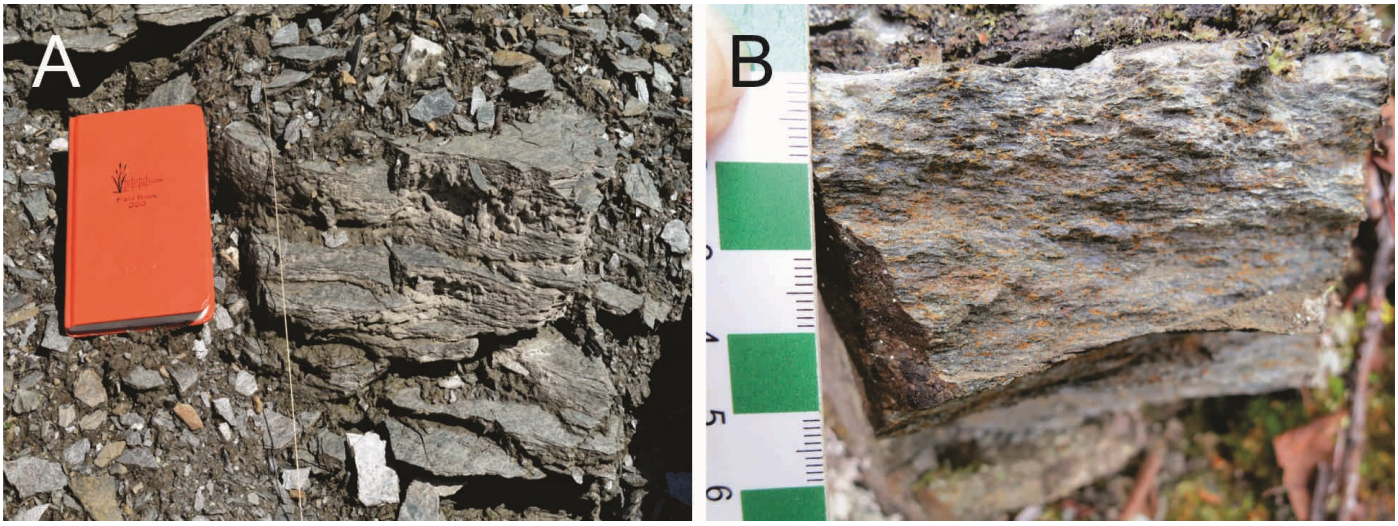


Figure 2 – A) Greenish to green-grey quartz-sericite-chlorite schist inferred to be felsic metavolcanic rocks, Devonian-Mississippian Earn Group (DMEV) in the Keno Hill-Mayo district, central Yukon. B) Close-up of metavolcanic rock of the Earn Group. Note the foliation and abundant Fe-carbonate spots throughout the sample.

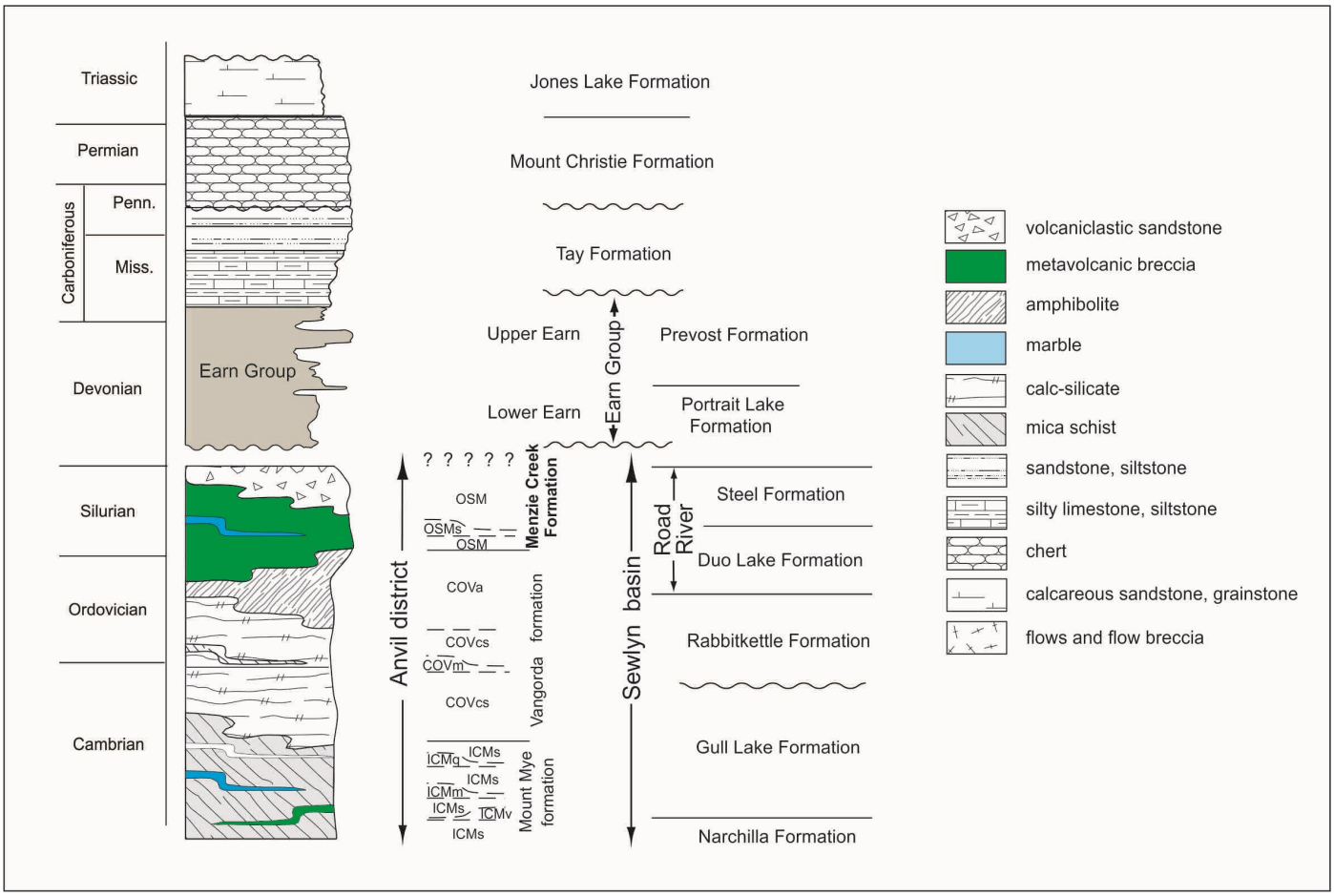


Figure 3 – Stratigraphy of the Anvil district, central Yukon. The terminology of the Anvil mine district is shown on the left column and is used in this paper. The regionally equivalent Selwyn basin stratigraphy is shown on the right. Modified from Cobbett (2016).

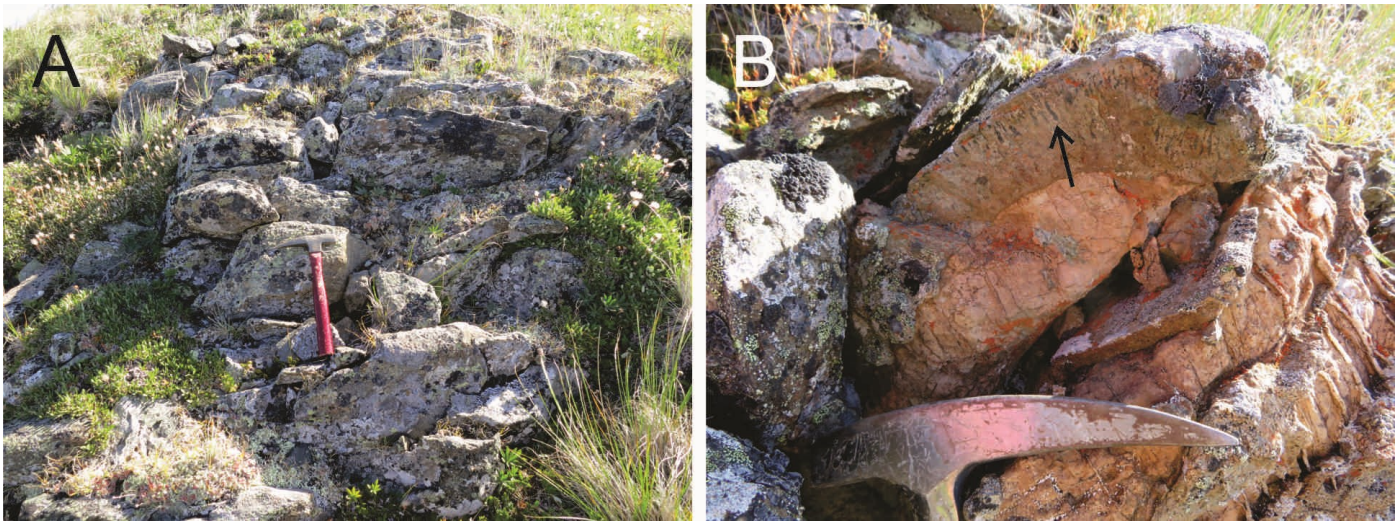


Figure 4 – Menzie Creek formation, south of the Anvil Batholith. A) Typical outcrop of deformed pillow basalt. B) Deformed and altered pillow basalt. Note the elongated pipe vesicles at the margin of pillow (arrow).

South of the Anvil Batholith, the Menzie Creek volcanic rocks consist of a medium green, pervasively foliated, noncalcareous to slightly calcareous chloritic phyllite/schist. Occasionally, primary volcanic textures are visible, such as amygdaloidal pillow flows with up to 20% vesicles (Fig. 4) and minor flow breccias.

North of the batholith, primary depositional textures are well preserved and thick exposures of variably amygdaloidal massive basalt, amygdaloical pillow basalt, monolithic matrix- and fragment-supported breccia, pillow flow breccia, and tuff are observable (Fig. 5). Dark green weathered and fresh, Ordovician-Silurian gabbro and pyroxenite appear to be conformable to slightly cross-cutting with the volcanic rocks. In summary, the Menzie Creek volcanic rocks are mafic in composition and the observed primary depositional textures are consistent with submarine to potentially subaerial depositional environments.

MacMillan Pass district:

All of the known SEDEX deposits of the MacMillan Pass district are hosted within the clastic sedimentary rocks of the middle to upper Devonian Portrait Lake Formation (DMsh) of the Lower Earn Group, and occur adjacent to NE-trending extensional synsedimentary faults. Discontinuous occurrences of presumed middle Devonian volcanic and intrusive rocks are interlayered with the clastic sedimentary rocks. The MacMillan Pass volcanic rocks include orange weathering, carbonate-rich mafic to felsic flows, minor coarse-grained gabbroic sills and dikes, and a variety of pyroclastic monolithic to heterolithic tuff, lapilli tuff and tuff breccia, along with amygdaloidal flow breccia, hyaloclastite, and epiclastic volcanic rocks. The primarily monolithic pyroclastic units commonly contain an abundance of pumaceous or scoriaceous clasts (Fig. 6A, B). Beds are commonly massive, but well-bedded to vaguely graded beds, and cross bedding are locally present (Fig. 6C). Other structures include bomb sags and gas escape pipes. Heterolitic tuff contains lapilli-size fragments of chert, siltstone, and mudstone that are rounded to angular, with variable percentages of magmatic fragments (Fig. 6D). Epiclastic volcanic units include lahars, and volcanogenic turbiditic deposits associated with radiolarian chert.

According to Rhodes and Matthew (1993) and Goodfellow et al. (1995), basaltic flows and volcaniclastic deposits overlap in time with the formation of the Tom, Jason, and Boundary Creek SEDEX deposits, and they are spatially associated with the Boundary Creek and Jason deposits. Variety in the nature and type of volcanism seem to be the norm, however its change through time and relationships to SEDEX deposits are unknown and need to be better defined.

Work in this area in the 2016 field season was reconnaissance in nature. As a result of the variety of the pyroclastic rocks and nature of the outcrops, it is possible to map volcanic facies toward a better understanding of the nature of volcanism, how it changed through time, and its relationship to mineralization.

Science impacts

Reconnaissance field investigation of volcanic rocks in the Selwyn Basin outlined various styles and types of volcanism associated with base-metal mineralization at different times in the geological history of the basin. As a result of these investigations we are able to identify specific styles of volcanism and volcanic facies, and describe the characteristics of volcanism at each of the study areas. Based on these field observations, samples were identified for further studies of the physical and chemical nature of volcanism, along with age dating. These studies are in progress and will inform planning for subsequent field work.

There is an abundance of mafic volcanism that occurred intermittently during the lower Cambrian, upper Cambrian-early Silurian, and Late Devonian. The abundance, distribution, and nature of felsic volcanism are unknown and needs to

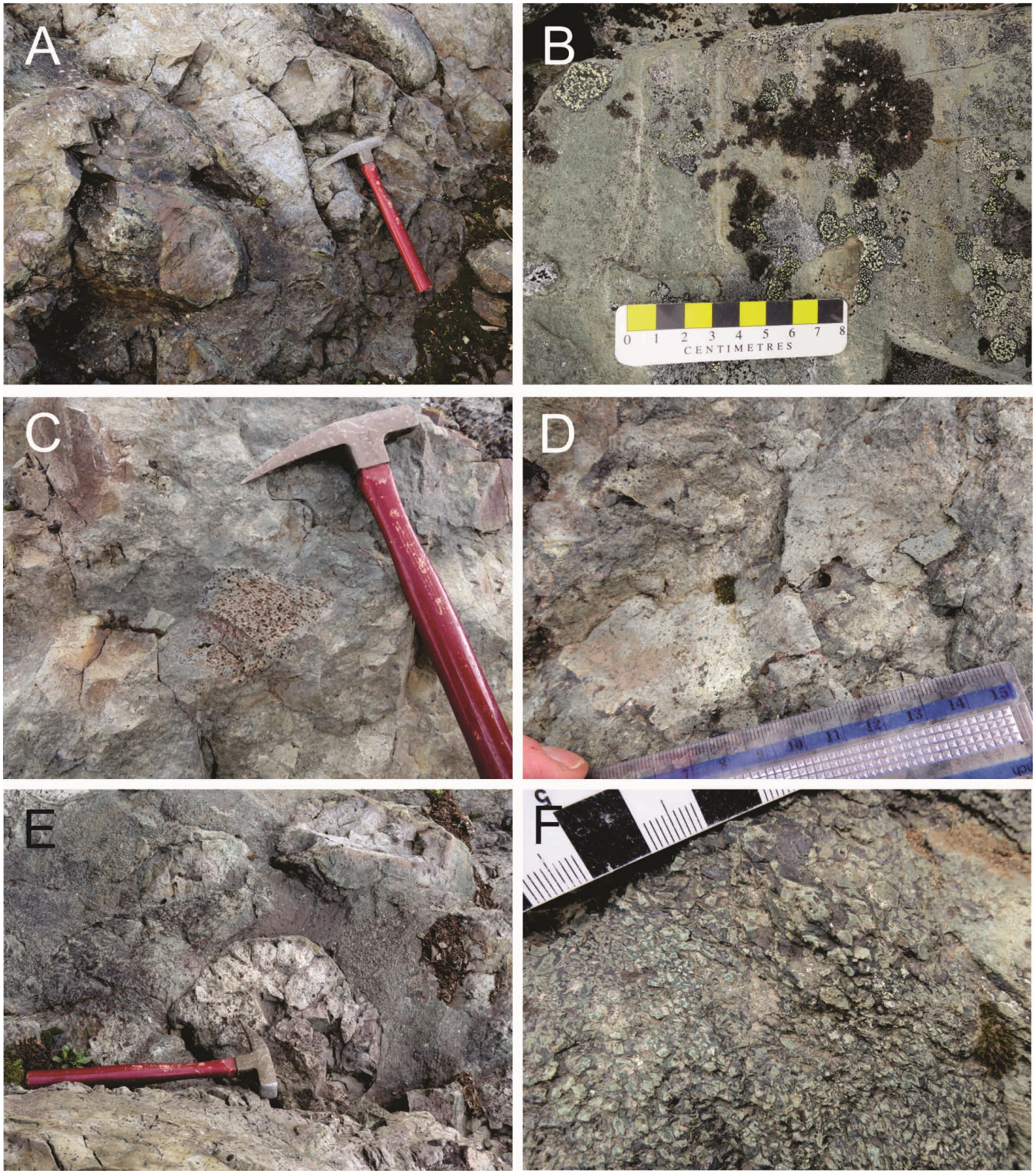


Figure 5 – Menzie Creek formation, north of the Anvil Batholith. A) Pillow tubes. B) Bedded tuff. C) Clast-supported monolithic, basalt breccia. Note the highly vesicular scoriaceous fragment in the middle of the photo. D) Clast-supported monolithic, basalt breccia. The fragments have wispy and ragged margins. E) Isolated pillows and pillow fragments in hyaloclastite matrix. F) Close-up of hyaloclastite matrix between pillow fragments of photo E.

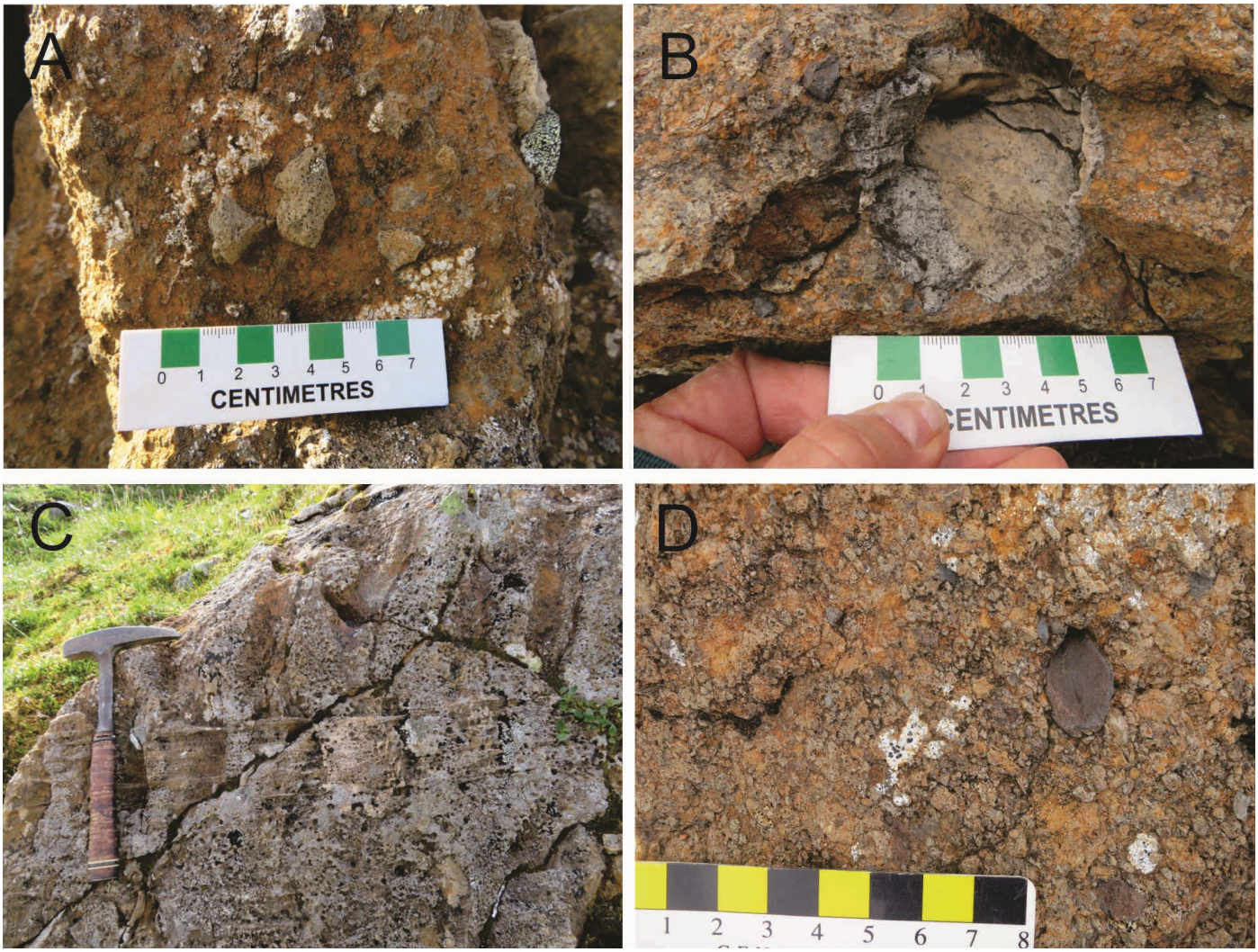


Figure 6 – MacMillan Pass volcanics, Middle Devonian Earn Group. A) Heterolithic lapilli tuff to tuff breccia comprising pumaceous fragments (whitish) in a matrix of fine ash. The larger clasts (white) are angular and highly vesicular (tiny vesicles). The pumaceous clasts are more resistant to weathering giving this lithology a knobby appearance. B) Pumice fragment with irregular vesicles in heterolithic lapilli tuff. C) Bedded ash and lapilli tuff breccia. Cross-beds are locally visible (arrow). D) Heterolithic lapilli tuff breccia comprising pumaceous fragments (whitish), pyrite-rich fragment (brown), and chert fragments (black) in a matrix of fine ash.

be defined along with determining which one(s) characterize the genesis of base-metal deposits.

Next steps

The collected samples will be further analyzed using the following techniques:

- Lithogeochemistry (major, trace, REE), radiogenic isotope (Nd-Hf), and mineralogy of magmatic rocks to understand their primary and secondary (alteration) signatures, and define their petrogenesis and tectonic affinity.
- U-Pb geochronology of key units to constrain timing of magmatism using coarse mafic products (e.g., baddelyite in gabbros) and/or associated felsic rocks.
- Basic mineralogy and mineral chemistry (where appropriate) of units for primary and secondary mineralogy using SEM and electron microprobe; and where appropriate in-situ trace element analysis and/or dating of phases using LA-ICP-MS.

This study will form the basis of a doctoral thesis at Laurentian University.

In 2017, approximately four weeks of fieldwork is projected at various sites in the Yukon and Northwest Territories.

Acknowledgements

This study is done in collaboration with Rosie Cobbett and Maurice Colpron of the Yukon Geological Survey. Lee Pigage

(retired geologist of the YGS) and Charlie Roots (YGS, deceased) provided geological information on the Faro and Keno-Mayo districts, respectively.

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Elucidating VMS mineralizing fluid pathways from the geophysical responses to hydrothermal alteration

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Introduction

The identification, classification and zoning of hydrothermally altered rocks play a prominent role in vectoring towards volcanogenic massive sulphide (VMS) deposits. Although hydrothermal alteration zones of VMS deposits may widely vary in scale, geometry and prevalent alteration mineral assemblages, they typically share characteristic zoning in alteration minerals, particularly in proximal up flow zones in the footwall of the deposit. Mineralogical and geochemical analytical methods have proven to be effective in mapping hydrothermal alteration and reconstructing the PT and chemical conditions of hydrothermal fluid flow. Access via outcrop or drill hole sampling, however, is strongly localized so that conduits are only accessible for a minor fraction of the source-to-trap pathway, hence interpretation of mineralizing fluid flow processes are limited in scale. This activity aims to add to the knowledgebase of hydrothermal conduit architecture by developing an integrated model of lithogeochemical, physical rock property and geophysical data. By incorporating interpretations of geophysical surveys calibrated by co-located drill hole physical rock property and lithogeochemical data, inferences on hydrothermal fluid flow can be made at more regional scales and at greater depths than is possible from sample analysis alone. This is based on the premise that hydrothermal alteration induces contrasts in physical rock properties so that the fluid conduits can be imaged in the subsurface.

From an ore vectoring perspective, identifying hydrothermal alteration zoning and interpreting their relative proximity to associated ore deposits can be difficult because many ancient VMS ore settings are affected by a complex history of polyphase tectonic deformation (e.g., van Staal and Williams, 1984; Lentz and van Staal, 1995). The relative simple model-derived zonal arrangement of alteration mineral assemblages is commonly modified and obliterated by subsequent tectonic processes. Moreover, due to the relative high ductility of sulphide ore and phyllosilicate-rich altered volcanic rocks, shear zones preferentially localize in the ore and footwall hydrothermal alteration zones (Castroviejo et al., 2011). As a result, the heterogeneous distribution of high finite strains accommodated within these incompetent zones can deform the VMS ore system to the extent that the ore horizon becomes dismembered into detached shear lenses that discordantly trend from the hydrothermal feeder system (Franklin, 1997). Hence, an in depth three-dimensional understanding of how VMS deposits were modified by tectonic deformation is important for interpreting the complexity of the hydrothermal fluid pathways and associated structural, magmatic and lithological permeability controls. Although virtually all VMS ore systems are affected by tectonic deformation, the topological relationships between hydrothermal alteration and volcanogenic lithofacies, metal grade and intrusions are commonly left intact providing important insight in the ascent of mineralizing fluids, the complexity of hydrothermal conduit networks and associated structural, magmatic and lithological permeability controls.

This activity was inspired by the discovery that the effects of hydrothermal alteration in the footwall of the Lalor VMS deposit (Snow Lake, Manitoba) are detectable in physical rock property measurements and can be traced on 3D seismic data. The Lalor deposit is, to our knowledge, the only VMS deposit in Canada where the sampling of borehole physical rock properties is dense enough to support integrated reconciliation of geophysical survey data with geological and lithogeochemical drillhole data on the scale of the deposit.

Iron Mask Batholith Complex and the New Afton Mine

The Lalor volcanogenic massive sulphide deposit is located near Snow Lake, Manitoba, about 700 km north of Winnipeg and is hosted in volcanic and volcaniclastic rocks of the Snow Lake arc assemblage in the eastern Paleoproterozoic Flin Flon greenstone belt. The 1.89 Ga Snow Lake arc assemblage is a ≥6 km-thick section that comprises three volcanic sequences displaying a geodynamic evolution from a primitive arc (Anderson sequence) to a mature arc (Chisel sequence) followed by an arc-rift setting (Snow Creek sequence) (Bailes and Galley, 1999). The Snow Lake arc assemblage is affected by at least four episodes of deformation (Galley et al., 1993). The deformation events are related to fold-and-thrust–style stacking and interleaving of volcanic assemblages and younger sedimentary rocks during the Trans-Hudson orogeny (Kraus and Williams, 1999).

The Lalor VMS deposit is hosted in the Chisel Sequence (Fig. 1) and consists of 12 mineralized zones starting at a vertical depth of 570 m below surface and extending down to approximately 1,160 m. As of January 2014, the Lalor deposit has a proven and probable reserve estimate of 15 Mt grading 6.7% Zn, 0.63% Cu, 2.01 g/t Au and 23 g/t Ag, and an inferred resource estimate of 10 Mt with 2.5% Zn, 1.03% Cu, 4.23 g/t Au and 28 g/t Ag. The mineralization zones trend to

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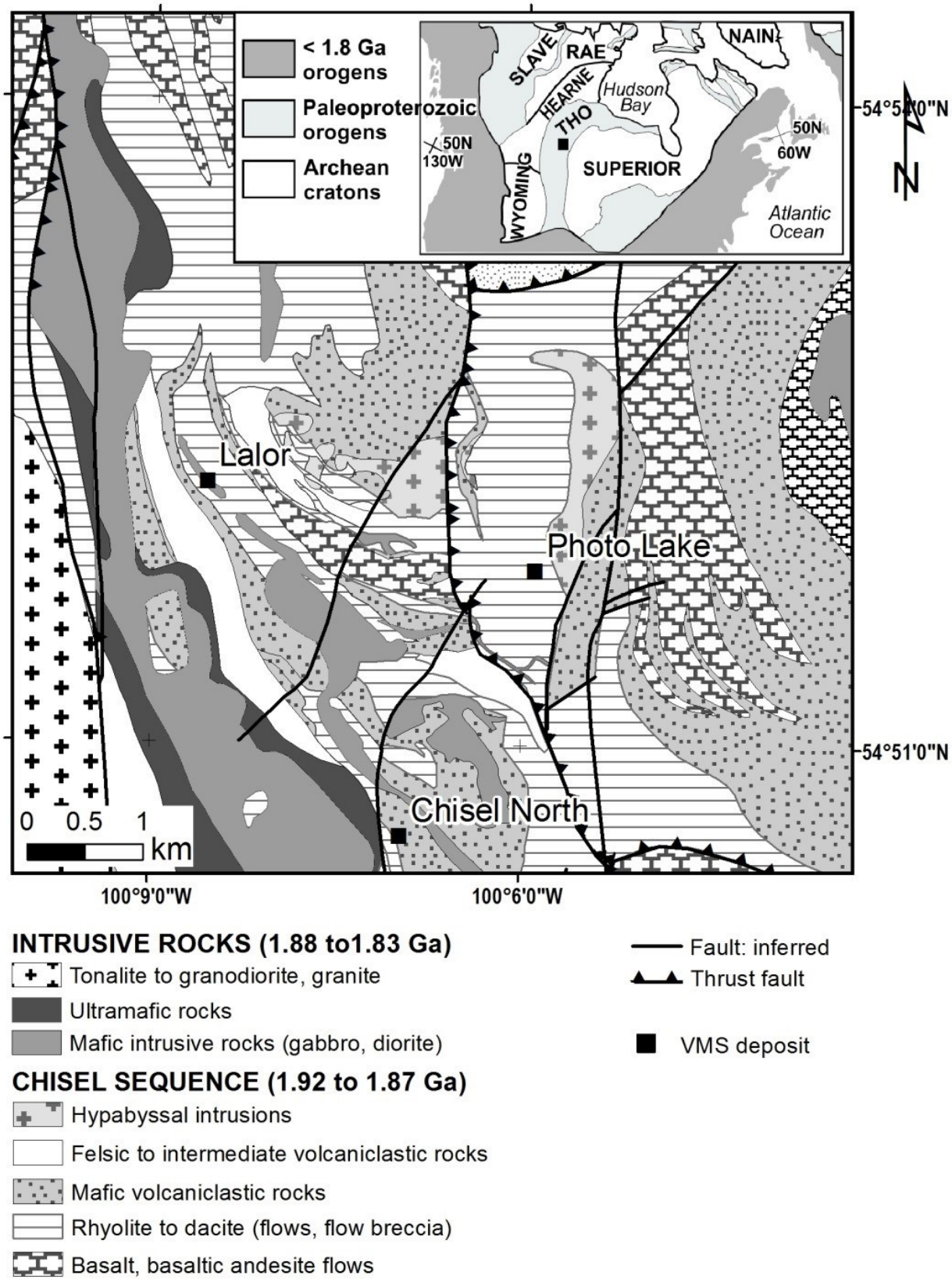


Figure 1 - Geological map of the Chisel basin (after Bailes and Galley, 2007) showing the location of the Lalor VMS deposit. Inset shows the tectonic map of the Canadian Shield, (THO = Paleoproterozoic Trans-Hudson orogeny).

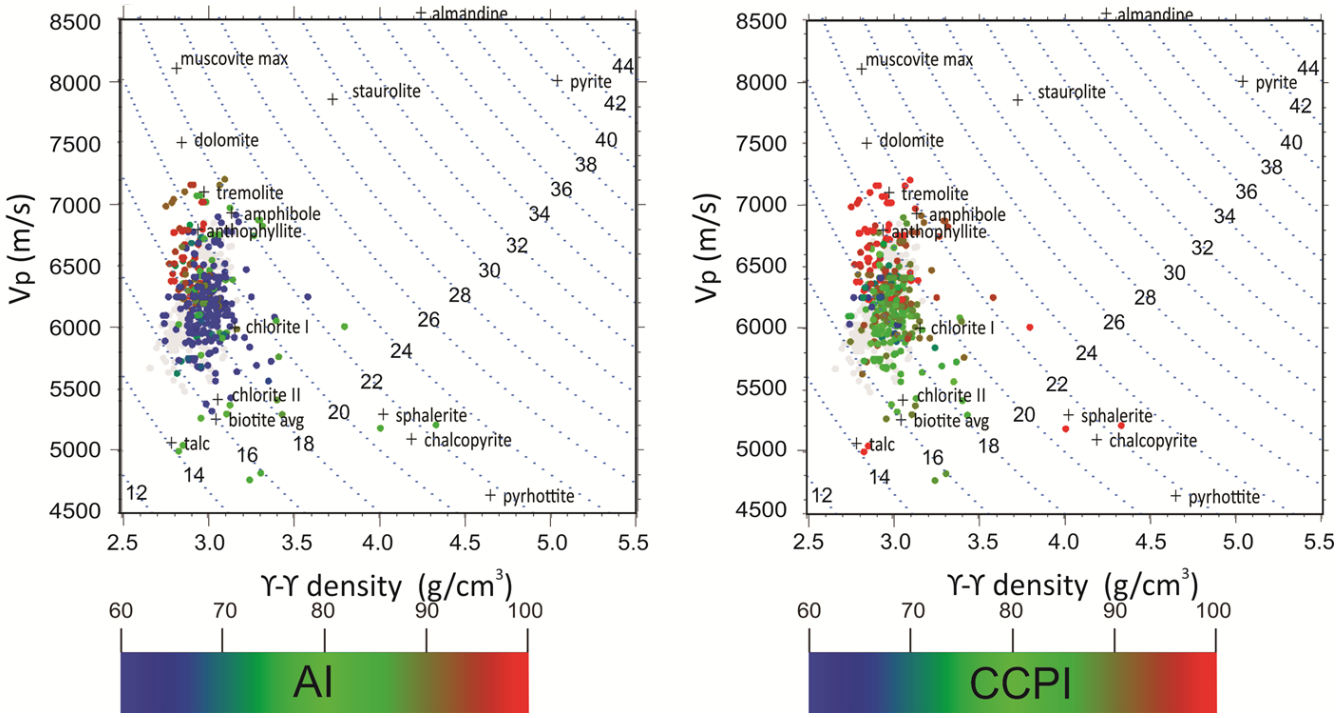


Figure 2 - Vp-density plots of collocated lithogeochemical analysis and physical rock property wireline log samples. The continuous hue range annotation of the samples is proportional to the intensity of alteration computed from: Hashimoto (= AI) index (left) and Carbonate-Chorite-Pyrite (= CCPI) index (right). Labelled Vp-density values of silicate, carbonate and sulphide minerals are from Carmichael (1989).

the northwest and have dips between 10° and 30° to the NNE. The ore lenses are relatively thin (average thickness is less than 12 m) and vary in size and grade. The deposit comprises seven zinc-rich and five gold-rich zones (Duff et al., 2015). The upper zinc-rich zones account for approximately 15 Mt of the 25 Mt of the deposit and comprise near-massive to massive sulphide mineralization. Sulphides in the zinc-rich zones dominantly consist of sphalerite interstitial to pyrite crystals. The gold-rich zones are generally found below the zinc zones in the footwall rocks. However, some of the gold zones overlap and cut through the zinc zones (Caté et al., 2015; Duff et al., 2015). The gold zones (including 8.8 Mt at 4.6 g/t Au: Caté et al., 2015; Duff et al., 2015) tend to be disseminated with some stringers of sulphide mineralization. These zones contain a low amount of iron sulphide, typically less that 4-5%. One of the gold zones (zone 27) is also associated with higher copper grades (average grade of 4.64% Cu) and is referred to as the gold-copper zone. The continuation of the strongly transposed gold-copper mineralization found in the deeper part of the deposit remains an active and open exploration target at greater depths.

A large subconcordant hydrothermal alteration system developed in the footwall of the Zn-rich VMS deposits of the Chisel sequence, with the nearby Richards subvolcanic intrusion considered the possible heat source (Bailes et al., 2016, Fig. 1). Discordant alteration zones that can be traced upsection to the Chisel, Chisel North and the Lalor deposits are rooted within the intrusion (Bailes et al., 2013). The footwall hydrothermal alteration below the Lalor VMS deposit evolved in two stages. The first alteration stage produced a semi-conformable zone of albitization, silicification and epidotization 1-2 km below the deposits that is spatially associated with synvolcanic dykes and intrusions (Bailes et al., 2013). The second stage produced sub-concordant to discordant zones of intense hydrothermal alteration in the immediate footwall of the massive sulphide deposits (Bailes et al., 2013). These hydrothermal alteration zones were overprinted by amphibolite facies metamorphism that caused major recrystallization and transformed volcanic and volcaniclastic rocks of mafic to felsic composition into granoblastic assemblages colloquially called “schists” and “gneisses”. These rocks are rich in large alumino-silicate porphyroblasts, including garnet, staurolite, cordierite, kyanite and anthophyllite-cummingtonite (Caté et al., 2013; 2015). Alteration in close proximity to the sulphide ore zones at Lalor also includes pervasive zones of finely disseminated sulphides (pyrite, pyrrhotite, sphalerite, chalcopyrite and galena) associated with carbonate, tremolite, anthophyllite, talc and chlorite-rich rocks (Bailes et al., 2013; Caté et al., 2013; 2015). Five chemical associations, each corresponding to distinct metamorphic mineral assemblages can be distinguished in the proximal hydrothermal alteration system associated with the Lalor deposit ore lenses, reflecting both primary (protolith) and secondary (hydrothermal alteration metamorphic metasomatism and lithogeochemical variations.

Physical rock properties of alteration minerals

In hard rock seismic exploration the primary focus has typically been the direct detection of sulphide ore zones based on

their anomalously high seismic impedance. Accordingly, the analysis of physical rock properties in these studies, usually report densities and seismic velocities of sulphide minerals (e.g., Salisbury et al. 2000). P-wave velocity - density plots from wireline log and drill core samples from the Lalor VMS deposit are consistent with these studies. The Vp-density plot shows a typical mixed response between the fast high-density trend of pyrite and the slow high-density trend of chalcopyrite, sphalerite and pyrrhotite.

In contrast, relatively little work has been done on the seismic properties of alteration mineral assemblages in metamorphosed VMS deposits. This is important for geophysical detection and delineation of alteration zones. Considering that alteration zones are orders of magnitude larger in size than the ores themselves, they should provide favourable geophysical targets.

Our initial studies, in which proxies for the intensity of alteration (e.g., Hashimoto (AI) and carbonate-chlorite-pyrite (CCPI) indices) were analyzed in Vp-density plots, show that they correlate with the Vp-density wireline measurements (Fig. 2). More specifically, both the AI and CCPI indices appear to increase with increasing Vp and decreasing density. A comparison with representative Vp and density mineral values from the literature, suggests that these trends are likely associated with an increase in abundance of Fe-Mg carbonates and the amphibole anthophyllite (Fig. 2). In addition, high seismic impedances appeared to be correlated in the alteration box plot with the highest intensities of alteration in both the Fe-Mg carbonate and Fe-Mg silicate trendsl.

Next steps

Based on this exploratory analysis of co-located physical rock properties and alteration proxies we intend to model the 3D distribution and intensity of hydrothermal alteration. The method that we are currently testing is based on interpolating the measured physical rock properties on a curvilinear grid that is conformable to the overall geological structure and employs more densely-sampled major and trace elements as secondary variables. These geological-knowledge physical rock property models will be subjected to forward and inverse modelling routines to characterize the hydrothermal conduit system and map the effects of alteration beyond the extent of drilling.

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Fingerprinting fluid source regions and pathways of volcanogenic massive sulphide deposits

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Introduction

This activity has two main aims: i) to evaluate the direct magmatic contributions (if any) of metals and volatiles in volcanic massive sulphide (VMS) deposits; and ii) to evaluate the mineralogical and mineral chemical variability of non-traditional indicator minerals in VMS as a record of fluid-rock interaction and their potential use in exploration.

With respect to the first aim, one of the central tenets of the VMS genetic model is that the mineralizing fluids are modified seawater. However, fluid inclusion data for the vast majority of VMS deposits indicate fluid salinities that are substantially greater than seawater (i.e., >3.2 eq. wt. % NaCl), with most >2X the salinity of seawater (e.g., Bodnar et al., 2014). Some of these data can likely be attributed to secondary (e.g., metamorphic) fluids (Manning and Aranovich, 2014), but most are likely primary VMS mineralizing fluids. Various mechanisms have been proposed to explain these values, including: phase separation and boiling; hydration of rocks in the subsurface; presence of ephemeral chlorine-bearing phases in the subsurface; dissolution of evaporites; and direct contribution of a saline magmatic fluid (de Ronde, 1995). For some deposits, there are other indicators (e.g., "magmatic suite" trace metals such as Hg, As, Sb, Bi, Te; S, H, O stable isotopic; radiogenic Pb isotopic; aluminous alteration assemblages) that provide supporting evidence of a magmatic contribution, yet their quantification remains problematic.

For the second aim, there are numerous minerals that are the product of fluid-rock interaction and VMS deposit formation that are sufficiently robust that they survive glacial erosion and weathering. Most of these minerals reside in the coarse fractions of a heavy mineral separate and these are routinely used in mineral exploration. More recently, workers have investigated the utility of minerals in the fine fraction (e.g., Wilton and Winter, 2012; Lehtonen et al., 2015). These studies are of a reconnaissance nature only; there currently is no consensus on optimal methods and no methods are commercially available.

Activity highlights

In order to disambiguate the magmatic signature from the purely hydrothermal (modified seawater) signature, detailed analyzes of pristine ore-forming fluids are required. In the past, bulk leach or decrepitation methods were employed to extract sufficient liquid and vapour from fluid inclusions for analysis. However, this method was fraught with complications due to the almost invariable presence of both primary (mineralizing fluid) and secondary (metamorphic, tectonic, or other fluid) inclusions within a single sample and resulting mixed population analyzes. Over the last few years the application of LA-ICPMS, PIXE, Synchrotron XRF, Gas Chromatography, Ion Chromatography, decrepitate analysis has allowed the direct analysis of a wide range of cations and anions, including stable and radiogenic isotope ratios, in individual fluid inclusions (e.g., Wilkinson et al., 2009). We will analyze fluid inclusions using microanalytical methods (primarily by LA-ICPMS) within existing samples from a number of VMS deposits that have enigmatically high salinities and for which a leached evaporite origin is not plausible (e.g., Windy Craggy, BC; Mattagami, QC; Iberian Pyrite Belt, Portugal). The element enrichment suites, together with anion contents will allow for the recognition of magmatic input. We will also compare these analyzes with melt inclusions from footwall and hanging-wall volcanic rocks (where available) that host the VMS deposits to fingerprint magmatic trace metal and metalloid budgets. The goal is to fingerprint the constituent components (element enrichment suites, together with anion contents) of the mineralizing fluids. Ancillary work will also involve detailed multiple sulphur isotopic analysis of an Archean VMS system (Izok Lake, NU; Fig. 1). This will allow for the evaluation of the role of atmospherically cycled sulphur via subducted sediments in VMS deposits; the reader is referred to Taylor et al. (2015) for further explanation. The Izok Lake deposit was chosen for the multiple sulphur (and lead) isotope study as there is a vast body of information, and there exists an excellent, well-characterized sample set.

The second aim focuses on minerals dispersed from VMS deposits to take advantage of recent technological innovations in microscopy and visualization, particularly the development of Mineral Liberation Analysis (MLA). With MLA rapid quantitative mineralogy of individual, <0.25 mm diameter mineral grains is possible. We will characterize the mineralogy and mineral chemistry of the fine fraction of till samples from se-

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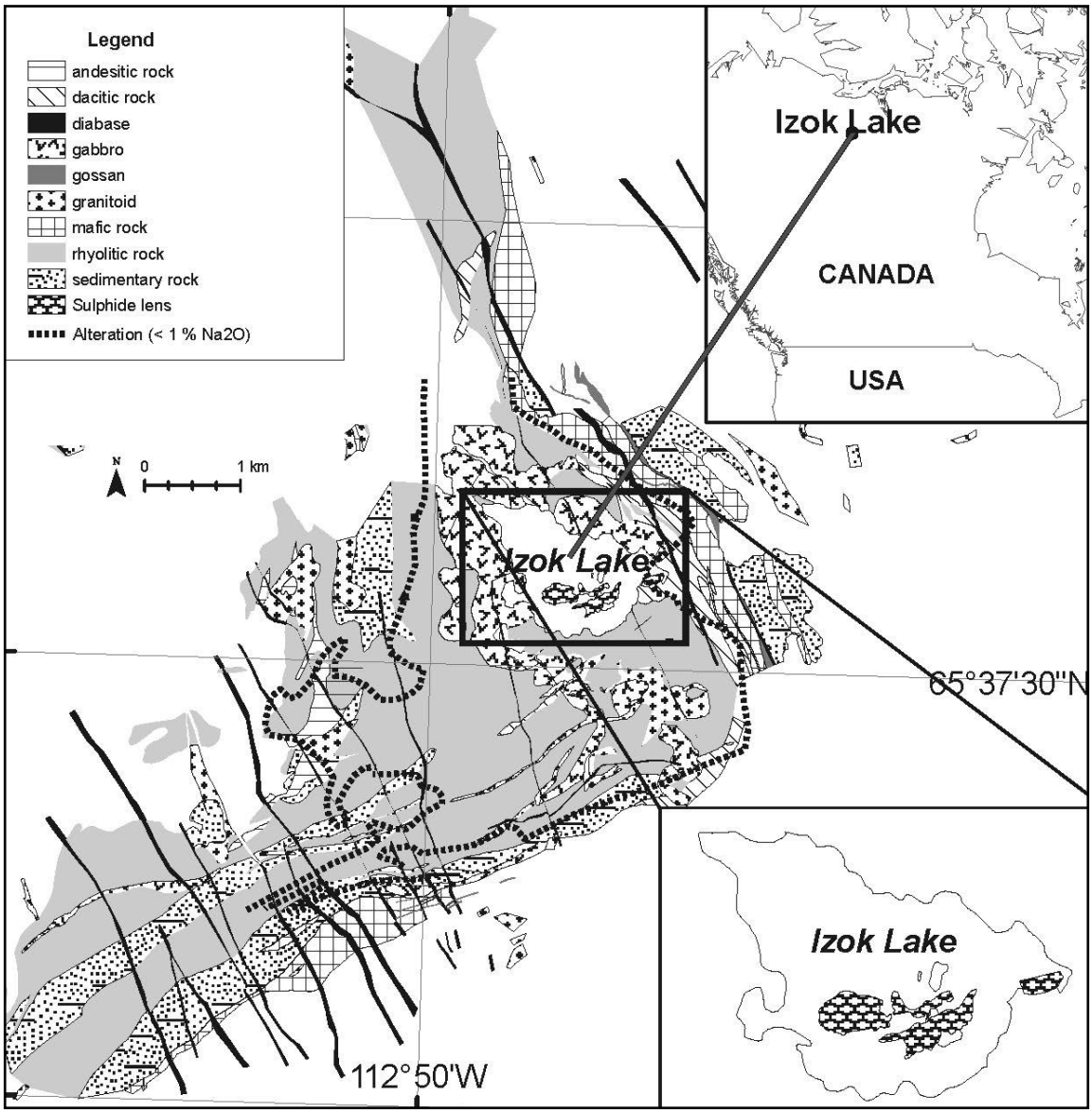


Figure 1 - Geologic map of the Izok Lake VMS deposit area. Modified from Laakso et al. (2015).

lected VMS deposits (Izok Lake, NU; Halfmile Lake, NB) utilizing specialized microsieving and splitting, and the subsequent analysis by LA-ICPMS, ESEM, EMP, MLA, and optical spectroscopic methods of selected minerals (e.g., gahnite, staurolite, axinite).

Two master's level studentships have been instigated. The first is based at Laurentian University, and will assess the contribution of metals via magmatic input to seafloor massive sulphide deposits. The second is based at Queen's University, and will develop methods to characterize and evaluate the efficacy of fine fraction indicator mineral signatures of VMS and porphyry deposits. For both studies legacy geological, geochemical, mineralogical information and samples have been assembled for analysis. For the first project, LA-ICP-MS method development will be done prior to analysis of samples from a test deposit (Windy Craggy VMS deposit, northwest British Columbia). For the second project, very fine gold grains from the Halfmile Lake VMS deposit, New Brunswick, test site were submitted to a commercial laboratory for grain mounting, ahead of analysis at Queen's University.

Science impacts

The analysis of single fluid inclusions from selected VMS deposits may effectively test the topical hypothesis that magmatic fluids are critical to the formation of large and/or high-grade (either base metals and/or precious metals) VMS deposits. Detailed multiple sulphur isotope analyzes of a single VMS deposit may unambiguously show the role of atmospherically cycled sulphur (e.g., subducted versus magmatic contribution) in deposit formation and influence the genetic and exploration models. By elucidating the contributions of various

fluid sources (e.g., magmatic, seawater) and processes (e.g., phase separation) to the metal budget of seafloor hydrothermal ore deposits, we will strengthen the link between genetic ore deposit models and interpretations of the tectonic setting of VMS systems (e.g., arc, back-arc, mid-ocean ridge, hot-spot, etc.). The single fluid inclusion micro-analytical work is acknowledged to be "high risk, but potentially high reward". Problems that may be encountered include: limitations of the analytical method (fluids too dilute to give adequate signal-to-background); sample limitations (primary inclusions not preserved; significant component of magmatic input not detectable). At a minimum, the work will enhance our knowledge-base, and optimally, it may provide unambiguous fingerprinting of metal sources in VMS. If successful, this information will inform and strengthen the VMS genetic and exploration models, and may result in improved exploration efficiencies for VMS deposits of atypically large size or of atypical base- and precious-metal grades in Canada and globally.

The study of potential indicator minerals recovered from the fine fraction (<0.25 mm) of tills associated with VMS deposits, and the development of optimal methods for their separation and study, will facilitate the use of this underutilized/ neglected fraction. MLA techniques are automated and thus could save time over the visual grain picking process employed currently and complement the information provided by the conventional coarser fraction. Since smaller grains are potentially transported greater distances, their utilization could greatly increase the footprint of glacial dispersal trains, and thus present a larger exploration target for exploration programs. These methods have the added advantage of being able to identify all mineral grains within a sample, and not only the traditional visually distinct indicator minerals. As a result, new indicator mineral species may be identified. Furthermore, an increased understanding of these minerals in VMS formation and their behaviour during glacial dispersal will ultimately lead to increased VMS exploration efficiency and success across Canada.

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