TGI 4 – Intrusion Related Mineralisation Project: A synthesis

Neil Rogers

Geological Survey of Canada, 601 Booth St., Ottawa, Ontario

Abstract: The Targeted Geoscience Initiative 4 (TGI 4) was a 2010-15 Government of Canada research program to conduct thematic, knowledge-driven ore systems studies aimed at assisting in the discovery of future resources through more effective targeting of buried mineral deposits.

Intrusion related (e.g., porphyry) deposits are the world's most important sources for Cu, Mo, W and Sn, as well as being a major contributor of Au, Ag, and PGEs. Porphyry deposits are typically large, low- to medium-grade deposits in which mineralisation is hosted within and immediately surrounding distinctive intrusive phases within larger intrusive complexes that commonly have prolonged emplacement histories. To develop more effective exploration criteria to identify and evaluate deeply buried and/or hidden fertile intrusive mineralising systems, studies into Cu-Mo/Au and W-Mo-Sn systems are aimed at answering the following questions: i) are there distinctive proximal and distal footprints for deposit types that will allow identification of, and vectoring towards hidden economically viable deposits?; and ii) what are the triggering conditions and indicators of an hydrothermal-magmatic system of size and duration sufficient to develop a large porphyry deposit? To help answer these questions studies are being undertaken at sites associated with the Triassic-Jurassic porphyry deposits of the British Columbia interior and for the array of mineralised Devonian intrusions developed in the Canadian Appalachians.

A common problem facing Cordilleran and Appalachian exploration is how to detect intrusion-related mineralization through the extensive glacial sediment cover. Consequently, research activities are focussing at identifying key geochemical and mineral indicators in till near known mineralisation and their detrital dispersal down-ice. Indicators are being developed for the detection of mineralisation, but also the alteration halos and vein systems associated with mineralization, which represent much larger exploration targets than the actual economic orebody itself. Once identified in till, these indicators can be traced to their bedrock source using reconstructed ice movement vectors.

Structural relationships indicate that Sn-W-Mo mineralised intrusive systems can form due to extension associated with far removed non-orthogonal accretion. Deposits within these bodies form along fluid pathways such as the intersection of high-angle syntectonic breaks. Mineral potential can also be resolved through trace element fingerprinting. Subtle compositional changes in commonly occurring minerals (i.e., biotite) and fluid inclusions provide evidence of chemical variations related to magma fertility and vectors to mineralisation.

Introduction

The Targeted Geoscience Initiative 4 (TGI 4) was a five year (2010-15) collaborative research program instigated by the Government of Canada to develop geoscience knowledge to support enhanced effectiveness of deep exploration. The underlying objectives of the program are to: 1) develop more robust measures of whether a geological system may contain deeply buried ore in order to reduce exploration risk; 2) develop new geoscience knowledge and innovative techniques to model and detect Canada's major mineral systems; and 3) train and mentor students to increase the number of highly-qualified personnel available to the mineral industry. To achieve these objectives the program was constructed to conduct thematic research that was targeted at resolving specific geoscientific problems that inhibit development of effective mineral exploration programs, as opposed to providing additional data to known mineral districts. The intension being that the resulting exploration models will be exportable to new regions and thus facilitate the discovery of the next generation of mineral deposits. In particular that these models will help in the discovery of deeply buried and/or hidden ore (whether it be by a thick sequence of country-rock or a thin veneer of surficial materials) that have defied identification using standard exploration methods.

Research themes within TGI 4 were constructed within "ore systems", which is an approach that focuses of the processes of ore formation, as opposed to the characteristics of specific deposits. The ore system concept is broken down into four parts, namely what terrane to look in, where to look in a terrane, vectors towards ore and detection methods (Fig. 1). 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 recognise 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?

Corresponding author: Neil Rogers (nrogers@nrcan.gc.ca)

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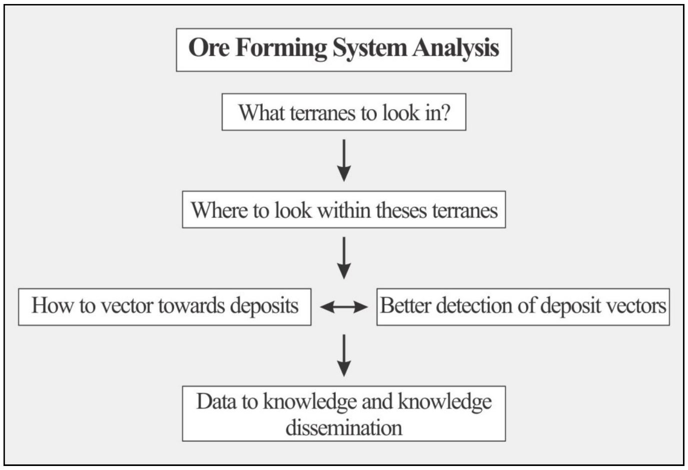

Figure 1 – Ore system conceptual model.

- Are there regional-scale structural controls that focus the ore system?

The third part of the ore system concept is related to vectoring towards ore, which breaks down the individual component parts of how an ore deposit is formed. These aspects are examined to determine whether there are distinctive features that can characterise the potential of or 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 and fluids?
- 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 ore fluids? 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 remobilisation 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 controls of mineralisation can be adapted into enhanced exploration tools and models.

Intrusion related ore system

The term intrusion related ore system is somewhat of a misnomer as it includes two distinct deposit types and does not include all ores generated by intrusive processes. The deposit types under investigation are Cu- and Cu-Mo(-Au) porphyries and post-accretionary granitoid Sn-W-Mo-In deposits. Although these types of mineral deposit form in different tectonic environments and are associated with unrelated varieties of granitoid intrusive rocks, they do share common traits within the mechanisms associated with ore formation that correspond to a single ore system. In a broad sense the common mechanism can be considered as porphyry-style mineralisation, which can be generally envisioned as hydrothermal system driven by intrusive magmatism where the ore metals are temporally and genetically related to the intrusion. Detailed descriptions of porphyry-style mineralisation processes are provided by Sinclair (2007), Sillitoe (2010) and Richards (2011).

The empirical model for porphyry-style mineralisation described by Sinclair (2007) consists of large, low- to medium-grade deposits that are formed in response to extensive, polyphase magmatic-hydrothermal systems developed within and above genetically-related intrusions. Meteoric fluids play a major role in this generic model, as they are typically considered to be largely responsible, though not essential in all cases, for features such as phreatic brecciation that can provide a trap for ore and large-scale alteration (i.e., sericitic alteration) halos (see Sillitoe (2010) and references therein). A modification of the general model has been referred to as the "orthomagmatic" model (Burnham, 1967, 1979; Phillips, 1973; Whitney, 1975, 1984; Sinclair, 2007) where crystallisation produces a volatile phase that transports and concentrates ore metals toward the carapace of the magma chamber (Christiansen et al., 1983; Candela and Holland, 1986; Manning and Pichavant, 1988; Candela, 1989; Cline and Bodnar, 1991; Heinrich et al., 1992). The induced fluid pressure may result in fracturing and rapid escape of the ore bearing fluids into the space provided. The sudden drop in pressure following fracturing causing adiabatic cooling of the fluid phase, which in turn can result in ore precipitation. An addendum to this model has the magmatic processes related to volatile phase generation and transport/ concentration of ore metals causing the upper reaches of a magma chamber to remain largely liquid through-out much of the ore forming process (Shannon et al., 1982; Carten et al., 1988; Kirkham and Sinclair, 1988; Shinohara et al., 1995; Sinclair, 2007).

Porphyry-style mineralisation constitutes the world's most important source for Cu, Mo, W and Sn, as well as representing a major supplier of Au, Ag, and PGEs. Porphyry deposits are typically large generally ranging in size from tens of millions to billions of tonnes of ore (Sinclair, 2007). The grades for economic metals are highly variable between specific deposit types, but are typically low- to medium-grade with ore constituting less than one percent of the mineralised rock (Sinclair, 2007). Porphyry-style mineralisation occurs throughout the world in association with relatively narrow orogenic belts. In Canada the primary terranes correspond to the Triassic and younger orogens of Western Canada (porphyry Cu and Cu-Mo/Au deposits), Devonian sequences of the Canadian Appalachians (Sn-W-Mo-In deposits) and the Archean Superior Provence (porphyry Au). For this project activities have been focussed on the Gibraltar, Highland Valley, Mount Polley and Woodjam deposits of south-central British Columbia (Fig. 2; Plouffe and Ferbey, 2015) and in the Canadian Appalachians the Acadian Plutonic Suite (central New Brunswick), South Mountain Batholith (Nova Scotia) and Connaigre Peninsula (Newfoundland and Labrador) (Fig. 3; Goeddeke et al., 2015; McClenaghan et al., 2015; Rogers et al., 2015a, b; Tweedale et al., 2015; van Staal et al., 2015). Archean porphyry Au deposits were investigated under the auspices of the TGI 4 – Gold project (e.g., De Souza et al., 2014; Gao et al., 2014; Katz et al., 2015).

Sillitoe (2010) argued that porphyry Cu deposits are amongst the most studied and best understood ore deposit type that have enabled advanced exploration programs to be applied (e.g., Kelley et al., 2006; Holliday and Cooke, 2007). Whereas he identified a number of outstanding issues requiring resolution to fully understand the formation and distribution of porphyry Cu deposits, the overall arc tectonic setting (both continental and mature island arc) are well established (e.g., Richards, 2009, 2011). The tectonic setting for post-accretionary Sn-W-Mo-In deposits are far less constrained with several distinct tectonic processes identified as possibly causing such deposits (Richards, 2011), none of which definitively explain the temporal and spatial distribution of such Canadian Appalachian deposits (cf. van Staal et al., 2009, 2014, 2015; Rogers et al., 2014, 2015a, b).

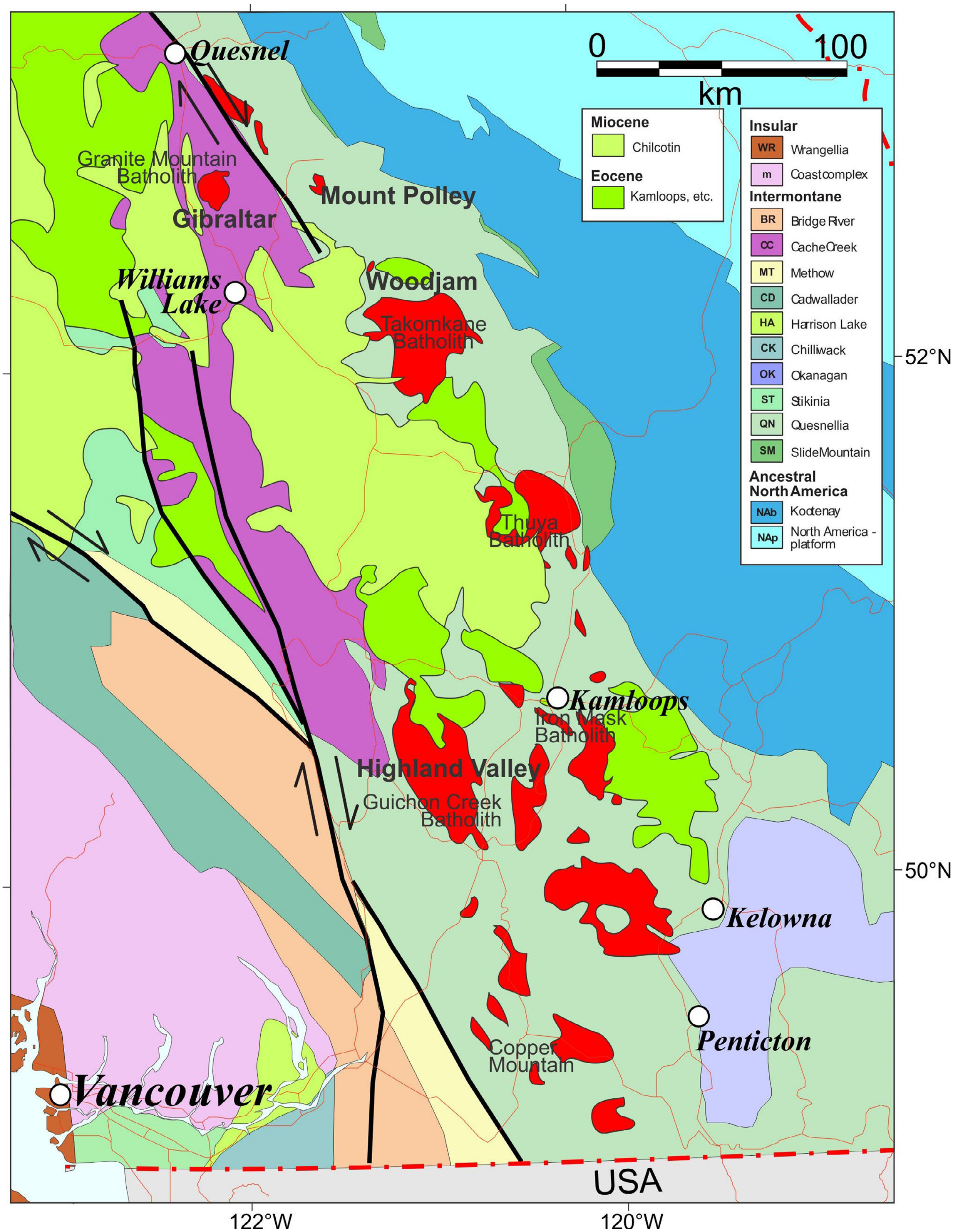

Figure 2 – Simplified bedrock geology map of south-central BC highlighting the location of the Gibraltar, Highland Valley, Mount Polley and Woodjam deposits. Bedrock geology modified after Massey et al. (2005), Erdmer and Cui (2009) and Logan et al. (2010).

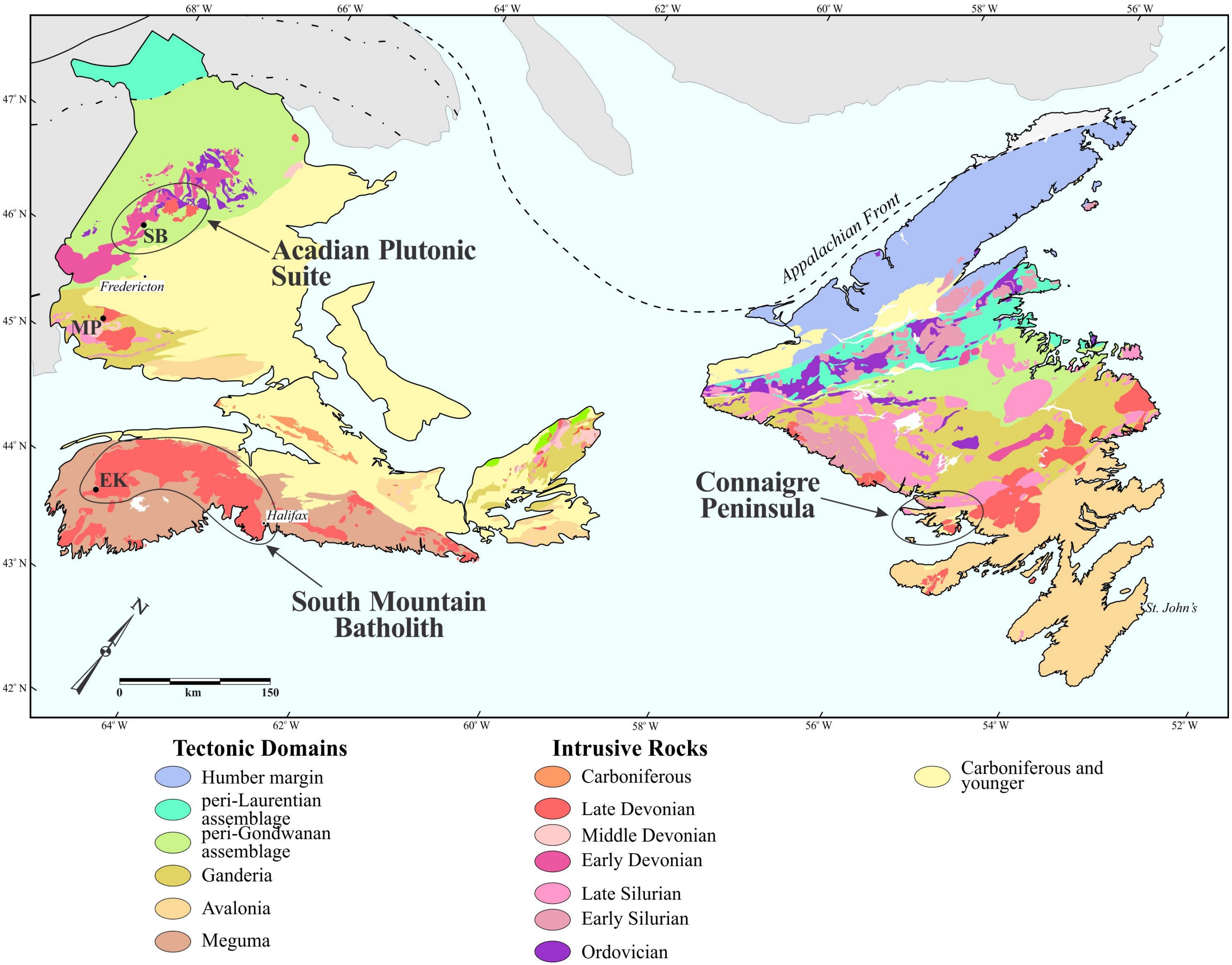

Figure 3 – Distribution of Palaeozoic granitoids and interpreted tectonic subdivisions of the Appalachian Orogen in Newfoundland, New Brunswick and Nova Scotia, highlighting the Acadian Plutonic Suite, South Mountain Batholith and the Connaigre Peninsula. Bedrock geology modified after Hibbard et al. (2006), van Staal et al. (2009), Rogers et al. (2014) and references therein). EK - East Kemptville Mine; MP - Mount Pleasant Mine; SB - Sisson Brook deposit.

Table 1 – Hierarchical hypotheses tested within the TGI 4 - Intrusion Related Mineralisation Project

Primary Hypothesis	Secondary Hypothesis	Tertiary Hypothesis
Tectonic setting, crustal structures and source composition dictate type, metal budget and where porphyry style mineralisation occurs and thus can predict buried/hidden systems	Stratigraphic and structural relations within the country rock are key determinants on the localisation of porphyry-style mineralisation	Intersecting crustal structures present mineralising fluid pathways and thus define high mineral prospectivity zones for deep seated and hidden ore
	W-Mo-Sn mineralization associated with peraluminous granite are oriented by regional stress fields	Sn-W-Mo bearing granite can form by within-plate melting in translational jogs related to oblique subduction
	Barren versus fertile intrusive suites and phases can be differentiated and large mineral systems pinpointed through characterization of late melt and fluid phases	Fertile Sn-W systems contain characteristic fluid inclusions that provide a link to ore potential
		Indium rich systems develop distinctly from typical W-Mo systems and thus late melt charachteristics correlate to In potential
Distinctive geological, mineralogical and geochemical characteristics exist that can differentiate and vector to not only deposit sub-types but also the degree of fertility of hidden/deep mineralization	Geochemical, petrologic and strucural indicators are present that determine whether near surface low grade porphyry-style deposits represent a carapace to higher grade mineralized cores	
	The composition of surficial materials are affected by underlying porphyry deposits such that they provide robust, large-scale and effective exploration vectors to economically viable deposits	Certain elements and minerals are anomalously enriched in glacial materials near porphyry deposits and are indicative of ore fertility
		Epidote abundance within till directly corresponds to entrainment from a mineralised zone
	Indicator mineral profiles are effective economic potential indicators of and vectors towards Sn-W-Mo systems	Scheelite fluorescence under ultraviolet light is an effective pre-screening tool for indicator mineral profiling of till
		On-site portable XRF analysis of till corresponds with indicator mineral vector profiles

Given the objectives behind TGI 4 (above) and the relative knowledge bases for the two types of porphyry-style mineralisation under investigation, activities supported within this project were designed to advance effective exploration for hidden deposits. To that end a hierarchical series of hypotheses were developed for testing (Table 1) that if resolved could reasonably be expected to facilitate advanced exploration models. Within the ore system concept this hypothesis testing largely focussed studies on the source control/system fertility (i.e., distribution and setting of mineralisation) for the post-accretionary deposits across the Canadian Appalachians and on enhanced methods for detecting/vectoring towards buried porphyry deposits (both south-central BC porphyry Cu and Cu-Mo/Au deposits and Appalachian post-accretionary Sn-W-Mo-In deposits). It should be noted that polymetallic, post-accretionary deposits also formed in association with the Western Canadian orogens, and likewise porphyry Cu mineralisation is present within Canadian Appalachian terranes. Although activities were not directed at examples of these specific types of mineralisation within these particular regions, the thematic nature of the ore system concept should enable resulting exploration models to be applicable and exportable to other domains.

Advancements to the intrusion related ore system

Structural and tectonic controls on porphyry-style mineralisation

Studies related to the structural and tectonic controls on porphyry-style mineralisation were primarily aimed at testing the primary hypothesis that "tectonic setting, crustal structures and source composition dictate type, metal budget and where porphyry style mineralisation occurs and thus can predict buried/hidden systems" (Table 1). In the ore system model this relates to helping resolve which terranes are the most prospective and where within these terranes exploration should be focussed.

Spatial and temporal relationships for post-accretionary Sn-W-Mo-In deposits

Although the multiple Palaeozoic accretionary orogens that constitute the Canadian Appalachian resulted in voluminous and widely distributed granitoid magmatism, the bodies that host porphyry-style mineralisation are spatially and temporally restricted (Fig. 3; Kellett et al., 2014; Rogers et al., 2014). These spatial and temporal restrictions closely correspond with pre-existing structures and far removed accretionary orogenic events that the standard tectonic models for post-accretionary polymetallic porphyry development do not readily predict (Rogers et al., 2014). Consequently, a modified tectonic model was proposed that incorporates magma genesis with external orogenic accretionary processes. The first requirement for this model is for the region to have been through at least one orogenic cycle in order to prepare the crust (concentrate ore metals) prior to melting and magma genesis. Crustal melting in the hinterland to an active accretionary margin is subsequently induced in response to non-orthogonal collision causing stress within the upper plate that is dissipated through reactivation of suitably orientated crustal breaks (faults). Depending on the orientation of the accretionary margin, particularly where embayments and promontories are involved, transpressive shear may require crustal scale translational jog to accommodate strain. Such effects can be manifested by crustal thinning and localised extensional basin development such as within the Connaigre Peninsula (Rogers et al., 2015a; van Staal et al., 2015). In this modified model associated pressure and temperature (P-T) transitions in the lower crust, along with potential asthenospheric upwelling, are the drivers for crustal melting, as per standard models for post-collisional granitoid genesis (cf. Richards, 2011). The difference being that the temporal and spatial distributions of mineralised intrusions are explained, and thus the potential prospectivity of a region can be assessed by analysis of the regional tectonic framework.

At a more local scale a spatial association is noted between mineralisation and syn-magmatic faults or lineaments (along which only minor displacements are present) that intersect at a high angle (Rogers et al., 2014, 2015a, b). The implication is that the intersecting structures provide convenient pathways for ore-bearing fluids, and that motion along them can cause rapid P-T changes which result in ore precipitation due to adiabatic cooling. Essential components of this model are that the syn-magmatic breaks (minor faults, lineaments or well developed joints) be orientated in the extensional field and that associated displacements are minor to facilitate protracted mineralisation/increased ore grade.

Further constraints on the distribution of mineralisation were investigated on the Connaigre Peninsula, south-central Newfoundland (Rogers et al., 2015a; van Staal et al., 2015). This area contains two post-accretionary plutons that were emplaced in the ca. 380 Ma period that corresponds with most of the polymetallic granitoid mineralisation known in Newfoundland (Tuach et al., 1986; Kerr et al., 1993, 1995; Lynch et al., 2009, 2012; Kerr and McNicoll, 2012; Kellett et al., 2014; Kerr, 2014) and where one body hosts several well-developed ore deposits and the other one apparently largely barren (O'Brien et al., 1995; O'Brien, 1998; Rogers et al., 2015a). Although the "barren" intrusion is petrographically distinctive, Rogers et al. (2015a) suggest that the primary factor influencing apparent mineral potential is depth of intrusion. In this case the body that does not contain significant known Mo mineralisation was mostly emplaced virtually at the surface. Notably minor mineralisation does occur within this granite, but its distribution is limited to marginal sections were the emplacement depth (based on the relative stratigraphic position of country-rock) corresponds to the emplacement depth of the adjacent intrusion that hosts multiple ore bodies. The underlying mechanism for this emplacement depth – mineralisation association is interpreted to be related to ore-bearing fluids transgressing a P-T threshold as they migrate upwards, at which point ore minerals are precipitated. The observed spatial association of fluorite with the Mo deposits suggests that ore metals were mostly transported intimately associated with F, either HF complex or redox buffer. Consequently, where P-T conditions are met for fluorite precipitation, ore metals also likely to come out of solution.

Another implication of the above model is that intrusive bodies that evolve by distinct pulses of magma being emplaced at different levels (cf. Vry et al., 2010) can develop zones of mineralisation well within the main granite body in response to changing P-T conditions over time, as opposed to the standard interpretations where ores are restricted towards the top of a pluton (e.g., Tuach et al., 1986). Furthermore, were ore-bearing fluids are transporting metals derived from younger pulses of magma into older granitoid phases, then it is unnecessary for the host granitic rock to be in chemical equilibrium or directly genetically related to ore. An example of this situation is developed within the Acadian Plutonic Suite, central New Brunswick, where the Tin Hill deposit occurs within the Buttermilk Cupola (Rogers et al., 2015b). However, the mineralisation at this site occurs within thick quartz veins that are effectively macroscopic tension gashes accommodating regional strain and competency differences between the granite and adjacent Cambrian to Ordovician clastic sedimentary rocks. Thus, although Sn-W mineralisation is developed within a granitic cupola, this is not an example of idealised orthomagmatic porphyry-style mineralisation (e.g., Sinclair, 2007) as the ore metals are derived from a buried, younger intrusion that is responsible for numerous exogranitic (intrusion related mineralisation not hosted by granitoid rocks) deposits (e.g., Burnt Hill Mine and Two and a Half Mile Brook deposit) within the same structural trend (Rogers et al., 2014, 2015b).

Timing of Cu-Mo mineralisation the Gibraltar Mine, BC

The Gibraltar Mine is one of British Columbia's largest Cu-Mo deposits (Oliver et al., 2009; Anderson et al., 2012). The six ore zones which make up the deposit are hosted by the composite, peraluminous Late Triassic Granite Mountain batholith (Fig. 2; Drummond et al., 1973; Bysouth et al., 1995; Ash et al., 1999a, b; Ash, 2001; Oliver et al., 2009; Schiarizza, 2015). There has been a longstanding debate on the nature of mineralisation at the Gibraltar Mine as the hosting Granite Lake batholith had been interpreted as a part of the Cache Creek terrane (Drummond et al., 1973; Bysouth et al., 1995), in contrast to other Triassic to Jurassic granitoid associated Cu-Mo deposits of south-central BC that form part of the Quesnel terrane (Logan et al., 2010; Nelson et al., 2013). Ash et al. (1999a, b) presented an alternate interpretation that the Granite Mountain batholith was indeed formed within the Quesnel terrane, but was subsequently (inferred as 20 to 30 m.y. after magmatism) juxtaposed by faulting into Cache Creek terrane. Their interpretation was that the structures observed within the Granite Mountain batholith, and associated with ore distribution in the Gibraltar Mine (Fig. 4), were formed by tectonic displacement and thus mineralisation would be unrelated to granite formation (i.e., not a porphyry Cu-Mo deposit). To this end Ash et al. (1999b) stated that for the "cataclastic and mylonitic shear fabrics characterised by retrograde greenschist grade metamorphic assemblages occurred during crystallisation of a magma body is difficult to rationalise", as opposed to the "porphyry with a difference" description of Sutherland Brown (1974).

To test which interpretation of the Cu-Mo mineralisation is correct Re-Os molybdenum age dates from within the Gibraltar Mine were obtained that gave the timing of mineralisation as 215.0 ± 1.0, 212.7 ± 0.9 and 210.1 ± 0.9 Ma (R.G. Anderson, pers. comm., 2012). These ages for the mineralisation are consistent with various crystallisation ages determined for the Granite Lake batholith (217 ± 0.20 Ma – U-Pb zircon TIMS, R. Friedman reported in Schiarizza, 2015; 215 ± 0.8, 212 ± 0.4 Ma – U-Pb zircon(?) reported in Ash and Riveros, 2001; 211.9 ± 4.3, 209.6 ± 6.3 Ma – laser ablation ICP-MS U-Pb zircon, Olivier et al. 2009). Notably these dates are also broadly consistent with those observed for the Guichon Creek batholith that hosts the Highland Valley Cu-Mo porphyry deposits (Fig. 2; McMillan, 1985; McMillan et al., 2009; B. Davis, pers. comm., 2011). These data

Figure 4 – Syn-magmatic ductile deformation of ore rocks within the Gibraltar Mine, BC.

strongly suggest that the mineralisation is syn-magmatic (and by extension so is the deformation, as mineralisation is distributed along both pervasive ductile and later brittle structures), hence this is a porphyry Cu-Mo deposit. It also suggests a genetic correlation between the Gibraltar and Highland Valley deposits. Subsequent mapping (Schiarizza, 2015) has determined that the Granite Mountain batholith does intrude Nicola Group rocks and therefore was emplaced within the Quesnel terrane.

Although the terrane identification for the Gibraltar deposit is important regionally, in the ore system context the recognition of the extent of syn-magmatic deformation that is possible within a porphyry system is of primary importance. These rocks suggest a variation from the standard model for porphyry development is possible whereby a relatively long-lived intrusion can source and transport ore fluid from younger magma phases to older phases that are variably solidified. Concurrent with this, stress can induce pervasive syn-magmatic ductile deformation in portions of the intrusive body that have not crystallised completely and so plastically deform (i.e., act as "soft solid"). As crystallisation continues these phases within the pluton become more rigid and if mineralising fluids are still being produced by deeper and younger magmatic phases then ores are liable to be developed along brittle fractures.

Granitoid ore fertility indicators and vectors to mineralisation

The following studies have focussed on developing new methodologies to chemically test the mineral potential (fertility) and/or divine chemical gradients to (vector towards) mineralisation. In the ore system concept these relate to resolving if there are distinctive chemical markers that indicate that substantive mineralising processes have occurred within an intrusive body, and if so are there directional indicators to an ore body. The standard model for porphyry systems incorporate ore metals being redistributed from a magmatic source and deposited/concentrated elsewhere whether it is within the granitic body (endogranitic) or external to it (exogranitic). Hence, except for circumstances where mineralisation is associated with intense metasomatic alteration, there is no guarantee that the ore component of the system would be in chemical equilibrium to the host (endogranitic) or nearest (exogranitic) granitoid rock. Consequently focus has been on direct measurements of fluid evolution through fluid inclusion decrepitation (Tweedale et al., 2015) or on mineral phases that have low closure temperatures and so act as a proxy for magmatic evolution (Azadbakht, 2015a, b, c). A related study has also been conducted specifically aimed at helping resolve the distinct characteristics that control indium content within certain polymetallic post-accretionary granitoid mineralisation (Goeddeke et al., 2015).

Fluid inclusion utility as a mineral fertility indicator and/or vector to ore

The inherent hydrothermal nature of porphyry-style mineralization means it is only reasonable to expect that a geochemical fingerprint of the mineralizing fluids might be preserved both petrographically and as secondary fluid inclusions in the associated intrusive bodies on a scale equal to or larger than the mineralized zones. A commonly applied technique to investigate fluid inclusion chemistry is microthermometry based on freezing and homogenisation temperature to determine fluid inclusion salinity. However, this technique reports results qualitatively as NaCl equivalent concentration which does not account for other cation and anion solutes that may be significant in porphyry-style mineralising systems. An alternative technique of crush-leach fluid extraction followed by LA-ICP-MS analysis is also potentially inadequate for resolving the evolution of a porphyry system as the results of crush-leach analysis may combine multiple generations of fluids (Chi et al., 2003), and the electronegativity of fluorine, a potentially ore-forming ligand in magmatic-hydrothermal settings (Muecke and Clarke, 1981; Thomas et al., 2006; McPhie et al., 2011) prevents its detection by standard LA-ICP-MS analysis. Given the potential shortfalls of these methods, Tweedale et al. (2015) examined whether fluid inclusion decrepitate analysis techniques (Eadington, 1974; Haynes and Kesler, 1987) can be applied as a cost-effective and time-efficient exploration tool to regionally assess granitoid ore fertility. This method determines semi-quantitatively the composition of solute ions, such as Na, K, Ca, Cl, and F, via scanning electron microscopy/ energy dispersive X-ray spectroscopy analysis of precipitate mounds formed by thermal decrepitation of fluid-inclusions.

Exploration tool potential testing and development was conducted on the South Mountain Batholith of southwestern Nova Scotia (Tweedale et al., 2015). The ca. 380 Ma South Mountain Batholith at ca. 7,300 km^2 is the largest Appalachian batholith and hosts a variety of polymetallic deposits (e.g., East Kemptville and New Ross). Previous detailed mapping has identified 260 discrete granitic bodies that were grouped into 49 map units based on field relations and composition (Keppie, 1979; MacDonald, 2001). These units were assigned to 13 plutons, which in turn are designated as being Stage I (early) or Stage II (later) plutons (MacDonald, 2001). A fundamental aspect of this study was determining if methods can be applied for reconnaissance exploration in such a complex environment (Tweedale et al., 2015). Initial results indicate that reconnaissance studies can efficiently summarise a complex, multi-phase batholith through element distribution maps and identify target areas for detailed follow-up (Tweedale et al., 2014, 2015). In particular the prevalence of F-rich fluids is noteworthy, as this element likely plays a significant role in the potential of fluids to partition, transport and precipitate ore metals (McPhie et al., 2011). The precise role of F in the hydrothermal processes involved in porphyry-style mineralisation remains equivocal, in part due to the most prevalent methods of fluid inclusion analysis not resolving F directly (e.g., Ulrich, 2004; Klemm et al., 2008; Ulrich and Mavrogenes, 2008; Audétat, 2010). Experimental data (e.g., Jackson and Helgeson, 1985; Candela and Holland, 1986; Candela and Bouton, 1990; Keppler and Wyllie, 1991; Hu et al., 2008; Rempel et al., 2008) suggests that Cl-complexes (especially for Cu and Sn), pH and temperature are the main factors on the initial melt-fluid partitioning of metals and their deposition. An indication of the role of F in ore systems developed within the South Mountain Batholith is provided F distribution maps that show a decoupling between the fluid inclusion composition and whole-rock data at fluorite-bearing deposits (Tweedale et al., 2014). The implication here is that fluorite formation depletes the F (and Ca) from the fluid phase, which in turn changes the pH and thus the solubility of ore metals.

In situ mineral analysis and ore system fertility

The Devonian granites of New Brunswick display a wide range of settings from pre-, syn-, late-, to post-tectonic related to the Acadian and Neoacadian orogenies, with affinities from primitive to highly evolved A-, S-, and I-types granitoids and are associated with Sn, Ta, Li, Sb, W, Mo, Cu, and Au, as well as base-metals and U mineralisation (Whalen, 1993; van Staal et al., 2009). To determine whether in situ mineral analysis can differentiate between barren and mineralised granitic systems 42 of New Brunswick's Devonian granitoid intrusions were investigated for the compositional variations in biotite (Azadbakht et al., 2015a, b, c). The choice of biotite for analysis is because it is a common phase to many granitic rocks, is highly sensitive to physico-chemical changes of its host, and continuously reequilibrates with host and derivative fluids (Lentz, 1992; Lofersji and Ayuso, 1995; Siahcheshm et al., 2012; Wang et al., 2013). Furthermore biotite is a suitable proxy for the overall magma composition as: 1) it is the most important reservoir of any excess aluminium in granites that do not contain modal garnet, cordierite, or the Al_2SiO_5 polymorphs; therefore, it directly reflects the peraluminosity of the host magma in such rocks; 2) it is the most readily available indicator of oxidation state; and 3) it can provide information about the F and Cl content of the magma. Analyses conducted by electron microprobe and laser ablation ICP-MS have shown major elements are typically constant within biotite grains from core to rim, but can show remarkable trace element zoning. To investigate this zoning further laser ablation ICP-MS trace element maps were also produced where permitted by the size of the biotite, frequency of the mineral inclusions, degree of alteration, and the laser spot size required to achieve sub-ppm detection limits.

Results of this study showed large-ion lithophile element zoning, including Cs, Ba, and Rb, for most of the biotite grains. As these elements are highly incompatible, any zoning can be a result of the magma evolution history recorded within the biotite crystalline structure. For example, biotite grains from the Pleasant Ridge granite show an increase from core to rim for Cs and Sn and a decrease for W and Sc (Fig. 5). Copper is also high along the cleavages where biotite is weakly altered to chlorite. These observations indicate a direct link between the fractional crystallisation of this granite and Sn mineralisation (Azadbakht et al., 2015b). Such correlations indicate that biotite composition can be correlated with magma fertility, but more work needs to be done to define characteristics of different magmatic processes.

Indium is a minor component of some post-accretionary mineralised granitoids in the Canadian Appalachians, but is potentially economically very significant due to high demand for a variety of industrial and technology applications, particularly in electronics (e.g., touch screens). However, indium distribution between deposits is highly uneven, and whereas some deposits contain hundreds of kilograms of the metal at grades sufficient to justify recovery, others are near-barren. At almost 1,000 tonnes combined indicated and inferred contained metal (McCutcheon et al., 2010, 2013), the Mount Pleasant Mine represents possibly the largest documented global indium reserve (Sinclair et al., 2006). In order to investigate the fundamental temperature, mineralogical, spatial and chemical controls on indium mineralisation in the district, a study was undertaken on samples from indium rich and poor occurrences at 10 drilled prospects in southern New Brunswick and southwest Nova Scotia, as well as from the past-producing East Kemptville Mine in Nova Scotia (Goeddeke et al., 2015).

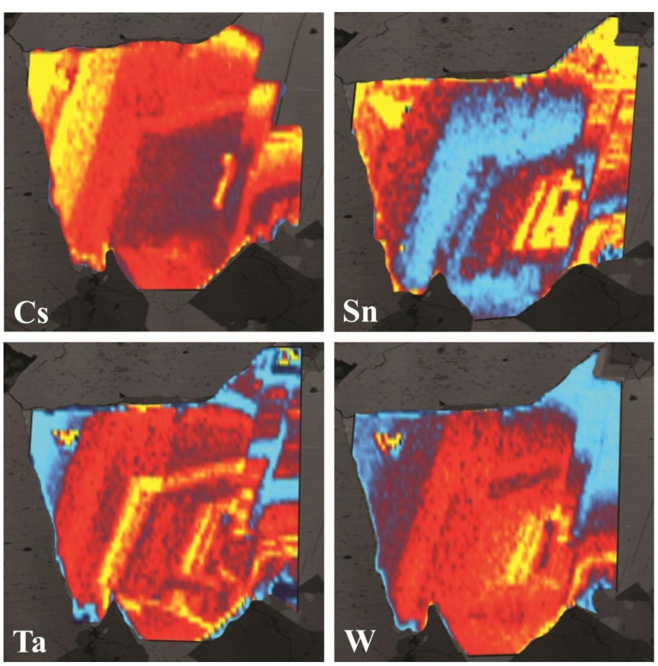

Figure 5 – Laser ablation ICP-MS trace element maps of a biotite crystal from the Pleasant Ridge granite (sample WX-NB-187). After Azadbakht et al. (2015b).

Detailed mineralogical characterization of these materials has shown that, contrary to existing models, within this district, indium is commonly introduced early in the deposit paragenesis, presumably as a component of the initial, high-temperature magmatic-hydrothermal fluids. During this phase of mineralisation, indium is dominantly precipitated within Cu-rich sphalerite, and it is the distribution of this mineral phase that primarily governs the presence or absence of indium within a mineralised body. During later cooling of the deposit a proportion of the indium is exsolved forming lamellae in sphalerite cores zones (Goeddeke et al., 2015).

Surficial vectors towards intrusion related mineralisation

Extensive glacial sedimentation covers many of the prospective regions for porphyry-style mineralisation in Canada. Although these sediments may obscure or completely mask direct bedrock observation of deposits, glacial detrital processes can disperse products associated with ores such that they form a much larger target that can be traced back (vectored) to mineralisation. To develop efficient methodologies and exploration protocols for glaciated terrains, studies were conducted in the vicinity of several major deposits in south-central British Columbia (Plouffe and Ferbey, 2015) and New Brunswick (McClenaghan et al., 2015). These studies were directed towards testing the primary hypothesis of whether “distinctive geological, mineralogical and geochemical characteristics exist that can differentiate and vector to not only deposit sub-types but also the degree of fertility of hidden/deep mineralization” (Table 1). In the ore system concept these activities relate to detection methods and techniques for enhanced exploration.

The utility of till composition in identifying Cu-Mo/Au porphyry deposits buried by glacial sediments was tested in the vicinity of the Gibraltar, Highland Valley and Mount Polley mines and the Woodjam prospect (Fig. 2). The primary objective of this study was to confirm that geochemical and mineralogical indicators of Cu porphyry mineralisation are resolvable in an efficient and cost-effective manor given the typical low to medium ore metal grades of the deposits in question, such that these methods are exportable to the exploration industry. The methods employed involved sampling till and measuring ice-flow indicators from bedrock outcrops following procedures outlined in Spirito et al. (2011) to resolve glacial dispersal patterns and record any chemical or mineral enrichment that could vector to the known deposits (Plouffe and Ferbey, 2015, and references therein).

Key results from this study are that products of porphyry-style mineralisation can be detected over several kilometres both as multi-element chemical enrichment in the clay-sized fraction of till and as identifiable grains of ore related minerals within silt/sand-sized fractions of till (Plouffe and Ferbey, 2015). Comparisons between the various study sites indicates that the actual chemical concentrations or number of grains that define the dispersal trains are not important, merely that they are anomalous relative to the regional background values. Similarly the areal extent and shape of dispersal trains varies between deposits. In part these features reflect the extent of mineralised bedrock that subject to glacial erosion within individual deposits (Plouffe et al., 2012). The recognition of high abundances of alteration minerals (e.g., epidote) in till down-ice from Cu porphyry deposits can thus be significant, as the alteration zones associated with these types of deposit are much larger than the ore zone itself. Hence, alteration minerals are more likely to be incorporated into till than direct ore products and can potentially represent a larger exploration target (Plouffe and Ferbey, 2015).

Notable ore minerals (e.g., chalcopyrite) are present within the till dispersal trains (Plouffe and Ferbey, 2015). This is significant as other studies elsewhere (e.g., the giant Pebble porphyry Cu-Au-Mo deposit in Alaska – Kelley et al., 2011) have not identified sulphide minerals in tills despite their presence within the ore. The interpretation has been that the absence of chalcopyrite in till reflects sulphide-destructive processes within the surficial environment (Kelley et al., 2011). An alternative explanation for why ore minerals may be precluded from tills is suggested by the observation of ore bodies that are at least partially covered by pre-glacial sedimentation (i.e., the Valley deposit at the Highland Valley Mine). Such relationships would protect mineralised zones from glacial erosion and so impact the potential for ore minerals to be incorporated into till (Fig. 6; Plouffe et al., 2012; Plouffe and Ferbey, 2015). Furthermore, lacustrine deposits can accumulate above ore zones prior to glaciation because the alteration associated with ore generation tends to "weaken" the ore zone relative to its margins, and thus these areas are susceptible to forming palaeotopographic depressions within which sediments may collect.

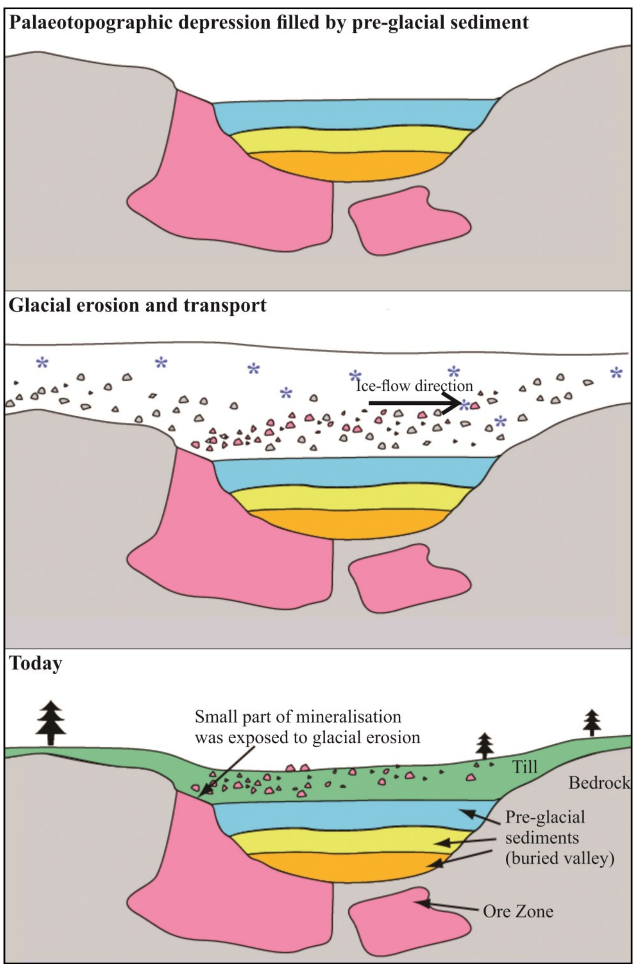

Figure 6 – Diagrammatic representation of how pre-glacial sediments deposited in palaeotopographic depressions can shield Cu porphyry mineralised zones from glacial processes and limit the incorporation of ore into down-ice dispersal trains. Modified from Plouffe et al. (2012).

Surficial signatures for polymetallic, post-accretionary granitoid related mineralisation was examined in the vicinity of the Sisson W-Mo and Mount Pleasant Sn-W-Mo-Bi-In deposits, New Brunswick (McClenaghan et al., 2015 and references therein). Indicator minerals were studied by heavy mineral concentrates from till and stream sediment samples, with chemical analysis (partial and total digestion) were obtained from the silt fraction of till. Indicator/pathfinder trace elements in till includes Sn, W, Mo, Cu, Zn, Pb, Ag, Bi, In, As, Cd, Re, Te, Tl, and Zn. The range of indicator elements reflects the polymetallic nature of the deposits and the broad suite of elements readily available by commercial ICP-MS analysis. The Mount Pleasant deposit contains a significant In resource (Sinclair et al., 2006) and till down-ice from the deposit contains some of the highest In values (13 ppm) ever reported for till, indicating that till geochemistry can be an important exploration tool for In-bearing deposits (McClenaghan et al., 2015). In addition to full chemical analyses, small samples were also examined using a portable XRF. Although the data obtained by portable XRF is not directly comparable in quality or range of elements determined in relation to ICP-MS analysis, its immediacy and potential to analyse many samples make it a valuable tool for directing exploration and reducing the number of samples required to undergo full analysis.

Indicator minerals identified in the medium grain size fraction (0.25-0.5 mm) of till and stream sediment near the Sisson W-Mo deposit include scheelite, wolframite, molybdenite, chalcopyrite, joseite, native Bi, bismutite, bismuthinite, galena, sphalerite, arsenopyrite, spessartine, pyrrhotite, and pyrite. At the Mount Pleasant Sn-W-Mo-In deposit indicator minerals include cassiterite, wolframite, molybdenite, topaz, fluorite, galena, sphalerite, chalcopyrite, galena, arsenopyrite, pyrite, and loellingite. Additional (but rare) secondary indicator minerals at the Mount Pleasant deposit include beudantite, anglesite, and plumbogummite. Indicator minerals present in the coarse (0.5-2.0 mm) heavy mineral fraction of till indicate proximity to the mineralised source. A process to systematically determine scheelite ($CaWO_4$) within heavy mineral concentrates using its short wave ultraviolet light fluorescence was developed and is now commercially available (McClenaghan et al., 2015).

Conclusions

All of the hypotheses listed in Table 1 that underpinned the suite of activities conducted within the auspices of the TGI 4 – Intrusion Related Mineralisation Project have at least partially been confirmed. The resulting advancements to the associated ore system model provide several potential avenues for the application of innovative exploration models for hidden or buried porphyry-style mineralisation. Currently, the improved surficial methods for the detection of intrusion related ore bodies (McClenaghan et al., 2015; Plouffe and Ferbey, 2015) are the most advanced and thus are suitable for immediate adoption by industry as part of a mineral exploration strategy.

Overall the results outlined above provide the basis for predictive models from the regional level of which terrane is most prospective down (tectonic setting/structure) to the small scale with effective vectors to ore (mineral analysis/till composition). A recurring theme within the bedrock related studies has been the significance within the ore system model of the transport of metals via fluid from source to deposition. Granitoid intrusions often develop as a relatively long lived system through multiple intrusive phases and pulses of magma over timescales that can be significantly longer than individual mineralising events. Consequently, there is no inherent reason why host granitoid rocks to a deposit are directly genetically linked (other than by metasomatic alteration) with the ore. In this sense for exploration purposes all porphyry-style deposits should be explored for as if they are exogranitic (hosted externally to the intrusion) even when they form within an intrusion (endogranitic). This principle is particularly relevant in terms of choice of mineralogical analysis as a means to provide vectors to ore, as minerals that remain "open" (liable to constantly re-equilibrate with host and derivative fluids), such as biotite, can be an effective proxy for the whole intrusive system rather than an individual phase that may not be associated with ore genesis. Another implication of this is pluton that develops through multiple pulses of magma can cause recycling and concentration of ore metals through batch processing with ore precipitating at a physico-chemical threshold between or within earlier intrusive phases. This model represents a potential explanation for the increasing grade of ore with depth that is observed in deep levels of some porphyry-style deposits.

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References

Anderson, R.G., Plouffe, A., Ferbey, T., and Dunn, C.E., 2012. The search for surficial expressions of buried Cordilleran porphyry deposits; background and progress in a new Targeted Geoscience Initiative 4 activity in the southern Canadian Cordillera, Geological Survey of Canada, Current Research 2012-7, 15 p.

Ash, C.H., 2001. Geology of the Gibraltar copper-molybdenite deposit, east central BC; *in* Geological fieldwork 2000; BC Ministry of Energy and Mines, Paper 2001-1, p. 119-134.

Ash, C.H., and Riveros, C.P., 2001. Geology of the Gibraltar copper molybdenite deposit, east-central British Columbia (93B/9); *in* Geological Fieldwork 2000, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2001-1, p. 119-133.

Ash, C.H., Panteleyev, A., MacLennan, K.L., Payne, C.W., and Rydman, M.O., 1999a. Geology of the Gibraltar mine area (NTS 93B/8, 9); British Columbia Geological Survey, Open File OF1999-07, 1 sheet.

Ash, C.H., Rydman, M.O., Payne, C.W., and Panteleyev, A., 1999b. Geological setting of the Gibraltar mine, south central British Columbia (93B/8 and 9); *in* Exploration and mining in BC, 1998, part B – Geological descriptions of selected properties, p. A1-A15.

Audétat, A., 2010. Source and Evolution of Molybdenum in the Porphyry Mo(-Nb) Deposit at Cave Peak, Texas; Journal of Petrology, v. 51, p. 1739-1760.

Azadbakht, Z., Lentz D.R., and McFarlane, C.R.M., 2015a. Magmatic biotite and its use to distinguish barren and mineralized granitic systems in New Brunswick, Canada; *in* TGI 4 – Intrusion Related Mineralisation Project: New Vectors to Buried Porphyry-Style Mineralisation, (ed.) N. Rogers; Geological Survey of Canada, Open File 7843, p. 565-566.

Azadbakht, Z., Lentz D.R., and McFarlane, C.R.M., 2015b. Magmatic evolution in Devonian granitic rocks and relation to granophile mineralization in New Brunswick: Application of biotite trace element mapping with EPMA and LA-ICP-MS; *in* TGI 4 – Intrusion Related Mineralisation Project: New Vectors to Buried Porphyry-Style Mineralisation, (ed.) N. Rogers; Geological Survey of Canada, Open File 7843, p. 507-519.

Azadbakht, Z., Lentz D.R., McFarlane, C.R.M., and Rogers, N., 2015c. Biotite chemistry as a monitor of magma fertility and mineralisation potential: Results from the Devonian granitoids of New Brunswick; *in* TGI 4 – Intrusion Related Mineralisation Project: New Vectors to Buried Porphyry-Style Mineralisation, (ed.) N. Rogers; Geological Survey of Canada, Open File 7843, p. 563-564.

Burnham, C.W., 1967. Hydrothermal fluids at the magmatic stage; *in* Geochemistry of Hydrothermal Ore Deposits, (ed.) H.L. Barnes; Holt, Rinehart and Winston Inc., New York, p. 34-76.

Burnham, C.W., 1979. Magma and hydrothermal fluids; *in* Geochemistry of Hydrothermal Ore Deposits, 2nd edition, (ed.) H.L. Barnes; Wiley Interscience, New York, p. 71-136.

Bysouth, G.D., Campbell, K.V., Barker, G.E., and Gagnier, G.K., 1995. Tonalite-trondhjemite fractionation of peraluminous magma and the formation of syntectonic porphyry copper mineralization, Gibraltar mine, central British Columbia; *in* Porphyry deposits of the northwestern Cordillera of North America, (ed.) T.G. Schroeter; Canadian Institute of Mining and Metallurgy, Special Volume 46, p. 201-213.

Candela, P.A., 1989. Calculation of magmatic fluid contributions to porphyry-type ore system: predicting fluid inclusion chemistries; Geochemical Journal, v. 23, p. 295-305.

Candela, P.A., and Bouton, S.L., 1990. The Influence of oxygen fugacity on tungsten and molybdenum partitioning between silicate melts and ilmenite; Economic Geology, v. 85, p. 633-640.

Candela, P.A., and Holland, H.D., 1986. A mass transfer model for copper and molybdenum in magmatic hydrothermal systems: the origin of porphyry-type ore deposits; Economic Geology, v. 81, p. 1-19.

Carten, R.B., Geraghty, E.P., and Walker, B.M., 1988. Cyclic development of igneous features and their relationship to high-temperature hydrothermal features in the Henderson porphyry molybdenum deposit, Colorado; Economic Geology, v. 83, p. 266-296.

Chi, G., Chou, I.M., and Lu, H., 2003. An overview on current fluid-inclusion research and applications; Acta Petrologica Sinica, v. 19, p. 201-212.

Christiansen, E.H., Burt, D.M., Sheridan, M.F., and Wilson, R.T., 1983. The petrogenesis of topaz rhyolites from the western United States; Contributions to Mineralogy and Petrology, v. 83, p. 16-30.

Cline, J.S., and Bodnar, R.J., 1991. Can economic porphyry copper mineralization be generated by a typical calc-alkaline melt?; Journal of Geophysical Research, v. 96, p. 8113-8126.

De Souza, S., Dubé, B., McNicoll, V.J., Dupuis, C., Mercier-Langevin, P., and Creaser, R., 2014. Fracture-controlled hydrothermal alteration at the Canadian Malartic deposit: Toward a multiphase model for Archean intrusion-related low-grade bulk tonnage gold deposits; Abstracts, Volume 37, Geological Association of Canada – Mineralogical Association of Canada Joint Annual Meeting; Fredericton, NB, p. 70.

Drummond, A.D., Tennant, S.J., and Young, R.J., 1973. The interrelationship of regional metamorphism, hydrothermal alteration and mineralization at the Gibraltar mines copper deposit in BC; Canadian Mining and Metallurgical Bulletin, v. 66, no. 730, p. 48-55.

Eadington, P.J., 1974. Microprobe analysis of the non-volatile constituents of fluid inclusions; Neues Jahebuch für Mineralogie, v. 11, p. 518-525.

Erdmer, P., and Cui, Y., 2009. Geological Map of British Columbia; B.C. Ministry of Energy, Mines and Petroleum Resources, Geoscience Map 2009-1, scale 1:1,500,000.

Gao, J.F., Jackson, S.E., Dubé, B. and De Souza, S., 2014. Gold mineralization in the Canadian Malartic deposit, Canada: Insights from textural and quantitative elemental mapping of pyrite; Abstracts, Volume 37, Geological Association of Canada – Mineralogical Association of Canada Joint Annual Meeting; Fredericton, NB, p. 97-98.

Goeddeke, C.R., Chapman, J.B., and Samson, I.M., 2015. Controls on indium mineralisation in tin-tungsten-base metal deposits of the Canadian Appalachians; *in* TGI 4 – Intrusion Related Mineralisation Project: New Vectors to Buried Porphyry-Style Mineralisation, (ed.) N. Rogers; Geological Survey of Canada, Open File 7843, p. 101-110.

Haynes, F.M., and Kesler, S.E., 1987. Chemical Evolution of Brines during Mississippi Valley-Type Mineralization: Evidence from East Tennessee and Pine Point; Economic Geology, v. 82, p. 53-71.

Heinrich, C.A., Ryan, C.G., Mernach, T.P., and Eadington, P.J., 1992. Segregation of ore metals between magmatic brine and vapor: a fluid inclusion study using PIXE microanalysis; Economic Geology, v. 87, p. 1566-1583.

Hibbard, J., van Staal, C.R., Rankin, D., and Williams, H., 2006. Lithotectonic map of the Appalachian orogen, Canada – United States of America; Geological Survey of Canada, Map 2096A, scale 1:1,500,000.

Holliday, J.R., and Cooke, D.R., 2007. Advances in geological models and exploration methods for copper ± gold porphyry deposits; *in* Proceedings of Exploration 07: Fifth Decennial International Conference on Mineral Exploration, (ed.) B. Milkereit; Prospectors and Developers Association of Canada, p. 791-809.

Hu, X., Bi, X., Hu, R., Shang, L., and Fan, W., 2008. Experimental study on tin partition between granitic silicate melt and coexisting aqueous fluid; Geochemical Journal, v. 42, p. 141-150.

Jackson, K.J., and Helgeson, H.C., 1985. Chemical and thermodynamic constraints on the hydrothermal transport and deposition of tin: I. Calculation of the solubility of cassiterite at high pressures and temperatures; Geochimica et Cosmochimica Acta, v. 49, p. 1-22.

Katz, L.R., Kontak, D.J., Dubé B., and Rogers, J.R., 2015. Chemical fingerprinting of the Archean Côté Gold deposit: A large-tonnage, low-grade intrusion-related deposit system, Ontario, Canada; *in* TGI 4 – Intrusion Related Mineralisation Project: New Vectors to Buried Porphyry-Style Mineralisation, (ed.) N. Rogers; Geological Survey of Canada, Open File 7843, p. 445-458.

Kelley, K.D., Eppinger, R.G., Lang, J., Smith, S.M., and Fey, D.L., 2011. Porphyry Cu indicator minerals in till as an exploration tool: example from the giant Pebble porphyry Cu-Au-Mo deposit, Alaska, USA; Geochemistry: Exploration, Environment, Analysis, v. 11, p. 321-334.

Kelley, D.L., Kelley, K.D., Coker, W.B., Caughlin, B., and Doherty, M.E., 2006. Beyond the obvious limits of ore deposits: The use of mineralogical, geochemical, and biological features for the remote detection of mineralization; Economic Geology, v. 101, p. 729-752.

Kellett, D.A., Rogers, N., McNicoll, V.J., Kerr, A., and van Staal, C.R., 2014. New age data refine extent and duration of Paleozoic and Neoproterozoic plutonism at Ganderia–Avalonia boundary, Newfoundland; Canadian Journal of Earth Sciences, v. 51, p. 943-972.

Keppie, J.D., (comp.) 1979. Geological map of the province of Nova Scotia; Nova Scotia Department of Mines and Energy map, scale 1:500,000.

Keppler, H., and Wyllie, P.J., 1991. Partitioning of Cu, Sn, Mo, W, U, and Th between melt and aqueous fluid in the systems haplogranite-H_2O−HCl and haplogranite-H_2O−HF; Contributions to Mineralogy and Petrology, v. 109, p. 139-150.

Kerr, A., 2014. The south Newfoundland granophile mineral district: Features and opportunities for research on blind deposits; Abstracts, Volume 37, Geological Association of Canada – Mineralogical Association of Canada Joint Annual Meeting; Fredericton, NB, p. 137-138.

Kerr, A., and McNicoll, V.J., 2012. New U-Pb geochronological constraints from mineralized granites in southern Newfoundland; *in* Current Research, Newfoundland Department of Natural Resources, Geological Survey, Report 12-1, p. 21-38.

Kerr, A., Dickson, W.L., Hayes, J.P., and Fryer, B.J., 1993. Devonian postorogenic granites on the southeast margin of the Newfoundland Appalachians: A review of geology, geochemistry, petrogenesis and mineral potential; *in* Current Research, Newfoundland Department of Natural Resources, Geological Survey, Report 93-1, p. 239-279.

Kerr, A., Jenner, G.A., and Fryer, B.J., 1995. Sm-Nd isotopic geochemistry of Precambrian to Paleozoic granitoid suites and the deep-crustal structure of the southeast margin of the Newfoundland Appalachians; Canadian Journal of Earth Sciences, v. 32, p. 224-245.

Kirkham, R.V., and Sinclair, W.D., 1988. Comb quartz layers in felsic intrusions and their relationship to the origin of porphyry deposits; *in* Recent Advances in the Geology of Granite-related Mineral Deposits, (ed.) R.P. Taylor and D.F. Strong; The Canadian Institute of Mining and Metallurgy, Special Volume 39, p. 50-71.

Klemm, L.M., Pettke, T, and Heinrich, C.A., 2008. Fluid and source magma evolution of the Questa porphyry Mo deposit, New Mexico, USA; Mineralium Deposita, v. 43, p. 533-552.

Lentz, D.R., 1992. Petrogenesis and geochemical composition of biotites in rare-element granitic; pegmatites in the southwestern Grenville Province, Canada; Mineralogy and Petrology, v. 46, p. 239-256.

Loferski, P.J., and Ayuso, R.A., 1995. Petrography and mineral chemistry of the composite Deboullie pluton, northern Maine, USA: Implications for the genesis of Cu-Mo mineralization; Chemical Geology, v. 123, p. 89-105.

Logan, J.M., Schiarizza, P., Struik, L.C., Barnett, C., Nelson, J.L., Kowalczyk, P., Ferri, F., Mihalynuk, M.G., Thomas, M.D., Gammon, P., Lett, R., Jackaman, W., and Ferbey, T. (comp.), 2010. Bedrock geology of the QUEST map area, central British Columbia; Geoscience BC Report 2010-5, British Columbia Geological Survey, Geoscience Map 2010-1 and Geological Survey of Canada, Open File 6476, scale 1:500,000.

Lynch, E.P., Selby, D., Feely, M., and Wilton, D.H.C., 2009. New constraints on the timing of molybdenite mineralization in the Devonian Ackley Granite suite, southeastern Newfoundland: Preliminary results from Re-Os geochronology; *in* Current Research, Newfoundland Department of Natural Resources, Geological Survey, Report 09-1, p. 225-235.

Lynch, E.P., Selby, D., and Wilton, D.H.C., 2012. The timing and duration of granite-related magmatic-hydrothermal events in southeastern Newfoundland: Results of Re-Os molybdenite geochronology; Abstracts with Programs, Geological Association of Canada – Mineralogical Association of Canada Joint Annual Meeting. St. John's, Newfoundland.

MacDonald, M.A., 2001. Geology of the South Mountain Batholith, southwestern Nova Scotia; Nova Scotia Department of Natural Resources, Open File Report ME 2001-2, 281 p.

Manning, D.A.C., and Pichavant, M., 1988. Volatiles and their bearing on the behaviour of metals in granitic systems; *in* Recent Advances in the Geology of Granite-related Mineral Deposits, (ed.) R.P. Taylor and D.F. Strong; The Canadian Institute of Mining and Metallurgy, Special Volume 39, p. 13-24.

Massey, N.W.D., MacIntyre, D.G., Desjardins, P.J., and Cooney, R.T., 2005. Geology of British Columbia; British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, Geoscience Map 2005-3, scale 1:1,000,000.

McClenaghan, M.B., Parkhill, M.A., Pronk, A.G., Seaman, A.A., McCurdy, M.W., Poulin, R.S., McDonald, A.M., Kontak, D.J., and Leybourne, M.I., 2015. Till, stream sediment, and stream water geochemical signatures of intrusion-hosted Sn-W deposits: examples from the Sisson W-Mo and Mount Pleasant Sn-W-Mo-Bi-In deposits, New Brunswick; *in* TGI 4 – Intrusion Related Mineralisation Project: New Vectors to Buried Porphyry-Style Mineralisation, (ed.) N. Rogers; Geological Survey of Canada, Open File 7843, p. 39-58.

McCutcheon, S.R., Sinclair, W.D., McLeod, M.J., Boyd, T., and Kooiman, G.J.A., 2010. Part 2: Mount Pleasant Sn–W–Mo–Bi–In Deposit; *in* Polymetallic Deposits Of Sisson Brook And Mount Pleasant, New Brunswick, Canada, (ed.) L.R. Fyffe, and K.G. Thorne; New Brunswick Department of Natural Resources; Lands, Minerals and Petroleum Division, Field Guide No. 3, p. 37-68.

McCutcheon, S., Reddick, J., McKeen, J., Scott, S., El-Rassi, D., and Kociumbas, M., 2013. Amended Technical Report of the Mount Pleasant Property, Including Mineral Resource Estimates, Southwestern New Brunswick, for Adex Mining Inc; Watts, Griffis and McOuat, Toronto. 222 p.

McMillan, W.J., 1985. Geology and ore deposits of the Highland Valley camp; Geological Association of Canada, Mineral Deposits Division, Field Guide and Reference Manual Series, Number 1, 121 p.

McMillan, W.J., Anderson, R.G., Chen, R., and Chen, W., 2009. Geology and mineral occurrences (MINFILE), the Guichon Creek Batholith and Highland Valley porphyry copper district, British Columbia, Geological Survey of Canada, Open File 6079, 2 sheets.

McPhie, J., Kamentsky, V., Allen, S., Ehrig, K., Agangi, A., and Bath, A., 2011. The fluorine link between a supergiant ore deposit and a silicic large igneous province; Geology, v. 39, p. 1003-1006.

Muecke, G.K., and Clarke, D.B., 1981. Geochemical Evolution of the South Mountain Batholith, Nova Scotia: Rare-Earth-Element Evidence; Canadian Mineralogist, v. 19, p. 133-145.

Nelson, J., Colpron, M., and Israel, S., 2013. The Cordillera of British Columbia, Yukon and Alaska: tectonics and metallogeny; *in* Tectonics, Metallogeny, and Discovery - the North American Cordillera and similar accretionary settings, (ed.) M. Colpron, T. Bissig, B. Rusk and J.F.H. Thompson; Society of Economic Geologists, Special Publication 17, p. 53-109.

O'Brien, S.J., 1998. Geology of the Connaigre Peninsula and adjacent areas, southern Newfoundland; Geological Survey, Department of Mines and Energy, Open File Map NFLD/2660; 1:100,000 scale.

O'Brien, S.J., O'Driscoll, C.F., Greene, B.A., and Tucker, R.D., 1995. Pre-Carboniferous geology of the Connaigre Peninsula and the adjacent coast of Fortune Bay, southern Newfoundland; *in* Current Research, Newfoundland Department of Natural Resources, Geological Survey Branch, Report 95-1, p. 267-297.

Oliver, J.L., Crozier, J., Kamionko, M., and Fleming, J., 2009. The Gibraltar mine, British Columbia. A billion tonne deep copper molybdenum porphyry system: structural style, patterns of mineralization and rock alteration; *in* Roundup 2009 program with abstracts; Association for Mineral Exploration British Columbia, Vancouver, British Columbia, p. 35-36.

Phillips, W.J., 1973. Mechanical effects of retrograde boiling and its probable importance in the formation of some porphyry ore deposits; Institute of Mining and Metallurgy Transactions, v. B82, p. 90-98.

Plouffe, A., and Ferbey, T., 2015. Till composition near Cu-porphyry deposits in British Columbia: Highlights for mineral exploration; *in* TGI 4 – Intrusion Related Mineralisation Project: New Vectors to Buried Porphyry-Style Mineralisation, (ed.) N. Rogers; Geological Survey of Canada, Open File 7843, p. 15-37.

Plouffe, A., Ferbey, T., Levson, V.M., and Bond, J.D., 2012. Glacial history and drift prospecting in the Canadian Cordillera: recent developments; Geological Survey of Canada, Open File 7261, 51 p.

Rempel, K.U., Williams-Jones, A.E., and Migdisov, A.A., 2008. The solubility of molybdenum dioxide and trioxide in HCl-bearing water vapour at 350°C and pressures up to 160 bars; Geochimica et Cosmochimica Acta, v. 72, p. 3074-3083.

Richards, J.P., 2009. Postsubduction porphyry Cu-Au and epithermal Au deposits: Products of remelting of subduction-modified lithosphere; Geology, v. 37, p. 247-250.

Richards, J.P., 2011. Magmatic to hydrothermal metal fluxes in convergent and collided margins; Ore Geology Reviews, v. 40, p. 1-26.

Rogers, N., Kellett, D.A., McNicoll, V.J., van Staal, C.R., Kerr, A., and Ruberti, G., 2015a. Tectonostratigraphic controls on the Connaigre Peninsula of south-central Newfoundland and their implications for intrusion-related mineral resources; *in* TGI 4 – Intrusion Related Mineralisation Project: New Vectors to Buried Porphyry-Style Mineralisation, (ed.) N. Rogers; Geological Survey of Canada, Open File 7843, p. 59-78.

Rogers, N., McClenaghan, M.B., Plouffe, A., Kellett, D.A., Chapman, J., Azadbakht, Z., Tweedale, F., Ruberti, G., and Anderson, B., 2014. TGI 4 – Intrusion Related Mineralisation Project: New Vectors to Buried Porphyry-Style Mineralisation; *in* Abstracts 2014:

Exploration, Mining and Petroleum New Brunswick, (ed.) E.A. Keith; New Brunswick Department of Energy and Mines, Geoscience Report 2014–5, p. 31.

Rogers, N., McClenaghan, M.B., Thorne, K.G., Fyffe, L.R., Seaman, A.A, Parkhill, M.A., McClenaghan, S.H., Pronk, A.G., Beal, K.L., Lentz, D.R., Wilson, R.A., Rice, J.M., and Lentz, C., 2015b. Granite-related mineralization and alteration in the Acadian Plutonic Belt: implications for Sn-W-Mo-Cu exploration in central New Brunswick – TGI 4 Field Guide; *in* TGI 4 – Intrusion Related Mineralisation Project: New Vectors to Buried Porphyry-Style Mineralisation, (ed.) N. Rogers; Geological Survey of Canada, Open File 7843, p. 113-204.

Schiarizza, P., 2015. Geological setting of the Granite Mountain batholith, south-central British Columbia; *in* Geological Fieldwork 2014, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2015-1, p. 19-39.

Shannon, J.R., Walker, B.M., Carter, R.B., and Geraghty, E.P., 1982. Unidirectional solidification textures and their significance in determining relative ages of intrusions at the Henderson mine, Colorado; Geology, v. 19, p. 293-297.

Shinohara, H., Kazahaya, K., and Lowenstern, J.B., 1995. Volatile transport in a convecting magma column: Implications for porphyry Mo mineralization; Geology, v. 23, p. 1091-1094.

Siahcheshm, K., Calagari, A.A., Abedini, A., and Lentz, D.R., 2012. Halogen signatures of biotites from the Maher-Abad porphyry copper deposit, Iran: characterization of volatiles in syn- to post-magmatic hydrothermal fluids; International Geology Review, v. 54, p. 1353-1368.

Sillitoe, R.H., 2010. Porphyry copper systems; Economic Geology, v. 105, p. 3-41.

Sinclair, W.D., 2007. Porphyry deposits; *in* Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods, (ed.) W.D. Goodfellow; Geological Association of Canada, St. John's, Newfoundland, p. 223–243.

Sinclair, W.D., Kooiman, G.J.A., Martin, D.A., and Kjarsgaard, I.M., 2006. Geology, geochemistry and mineralogy of indium resources at Mount Pleasant, New Brunswick, Canada; Ore Geology Reviews, v. 28, p. 123-145.

Spirito, W., McClenaghan, M.B., Plouffe, A., McMartin, I., Campbell, J.E., Paulen, R.C., Garrett, R.G., and Hall, G.E.M., 2011. Till sampling and analytical protocols for GEM projects: from field to archive; Geological Survey of Canada, Open File 6850, 83 p.

Sutherland Brown, A., 1974. Gibraltar Mine (93B-12, 13); *in* Geology, Exploration and Mining in British Columbia 1973, B.C. Ministry of Energy, Mines and Petroleum Resources, p. 299-318.

Thomas, R., Webster, J.M., Rhede, R., Seifert, W., Rickers, K., Förster, H-J., Heinrich, R., and Davidson, P., 2006. The transition from peraluminous to peralkaline granitic melts: Evidence from melt inclusions and accessory minerals; Lithos, v. 91, p. 137-149.

Tuach, J., Davenport, P.H., Dickson, W.L., and Strong, D.F., 1986. Geochemical trends in the Ackley granite, southeast Newfoundland: Their relevance to magmatic metallogenic processes in high-silica granitic systems; Canadian Journal of Earth Sciences, v. 23, p. 747-765.

Tweedale, F., Hanley, J.J., Kontak, D.J., and Rogers, N., 2014. Petrographic observations and evaporate mound analysis of quartz-hosted fluid inclusions: Applications to assess metal fertility in granites; Abstracts with Programs, Volume 37, Geological Association of Canada – Mineralogical Association of Canada Joint Annual Meeting; Fredericton, NB, p. 275-276.

Tweedale, F., Hanley, J.J., Kontak, D.J., and Rogers, N., 2015. Petrographic observations and evaporate mound analysis of quartz-hosted fluid inclusions hosted by granitoid samples from the South Mountain Batholith, Nova Scotia: An exploration tool for vectoring towards mineralized areas in intrusive rocks; *in* TGI 4 – Intrusion Related Mineralisation Project: New Vectors to Buried Porphyry-Style Mineralisation, (ed.) N. Rogers; Geological Survey of Canada, Open File 7843, p. 79-99.

Ulrich, T., 2004. Molybdenum solubility and transport under hydrothermal-magmatic conditions; *in* Abstracts, 14th Annual Goldschmidt Conference, v. 3, p. 23.

Ulrich, T., and Mavrogenes, J., 2008. An experimental study of the solubility of molybdenum in H_2O and KCl-H_2O solutions from 500°C to 800°C, and 150 to 300 MPa; Geochimica et Cosmochimica Acta, v. 72, p. 2316-2330.

van Staal, C.R., Ruberti, G., Kerr, A., Conliffe, J., Rogers, N., 2015. The Coast of Bays: Paleozoic tectonic evolution of the Gander margin and adjacent Avalonia in southeastern Newfoundland – TGI 4 Field Guide; *in* TGI 4 – Intrusion Related Mineralisation Project: New Vectors to Buried Porphyry-Style Mineralisation, (ed.) N. Rogers; Geological Survey of Canada, Open File 7843, p. 205-245.

van Staal, C.R., Whalen, J.B., Valverde-Vaquero, P., Zagorevski, A., and Rogers, N., 2009. Pre-Carboniferous, episodic accretion-related, orogenesis along the Laurentian margin of the northern Appalachians; *in* Ancient Orogens and Modern Analogues, (ed.) J.B. Murphy, J.D. Keppie and A.J. Hynes; Geological Society, London, Special Publications, v. 327, p. 271-316.

van Staal, C.R., Zagorevski, A., McNicoll, V.J., and Rogers, N., 2014. Time-Transgressive Salinic and Acadian Orogenesis, Magmatism and Old Red Sandstone Sedimentation in Newfoundland; Geoscience Canada, v. 41, p. 138-164.

Vry, V.H., Wilkinson, J.J., Seguel, J., And Millán, J., 2010. Multi-stage intrusion, brecciation, and veining at El Teniente, Chile: Evolution of a nested porphyry system; Economic Geology, v. 105, p. 119-153.

Wang, R.C., Xie, L., Chen, J., Yu, A., Wang, L., Lu, J., and Zhu, J., 2013. Tin-carrier minerals in metaluminous granites of the western Nanling Range (southern China): Constraints on processes of tin mineralization in oxidized granites; Journal of Asian Earth Sciences, v. 74, p. 361-372.

Whalen, J.B., 1993. Geology, petrography and geochemistry of Appalachian granites in New Brunswick and Gaspesie, Quebec; Geological Survey of Canada, Bulletin 436, 124 p.

Whitney, J.A., 1975. Vapour generation in a quartz monzonite magma: a synthetic model with application to porphyry copper deposits; Economic Geology, v. 70, p. 346-358.

Whitney, J.A., 1984. Volatiles in magmatic systems; in Fluid-mineral Equilibria in Hydrothermal Systems; Reviews in Economic Geology, v. 1, p. 155-175.