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Targeted Geoscience Initiative 4: Contributions to the Understanding of Volcanogenic Massive Sulphide Deposit Genesis and Exploration Methods Development

The Targeted Geoscience Initiative 4 contributions to the understanding of volcanogenic massive sulphide deposit genesis and exploration methods development: introduction and preface

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Contribution to the Geological Survey of Canada's Targeted Geoscience Initiative 4 (TGI-4) Program (2010–2015)

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ABSTRACT

Research on topical aspects of the genesis of, and exploration for, volcanogenic massive sulphide (VMS) deposits was formulated and carried out under the auspices of the Volcanogenic Massive Sulphide Ore System of the Targeted Geoscience Initiative 4 Program. Research activities were focussed on addressing two main themes: 1) development of innovative, new, and unconventional detection and vectoring methodologies for VMS exploration; these studies were conducted at the Izok Lake deposit, Nunavut, and regionally throughout the Bathurst Mining Camp, northern New Brunswick, as well as at numerous VMS deposits and prospects regionally throughout the Slave Province, Nunavut and Northwest Territories; and 2) understand the controls on precious metal (gold, silver) endowment or enrichment in VMS deposits. These studies were conducted at several deposits: Lalor Mine, Manitoba; Lemarchant deposit, Newfoundland; Ming Mine, Newfoundland; and the Lemoine deposit, Quebec.

Detection and development of vectoring methods focussed on the application of optical reflectance spectrometry (airborne, ground, laboratory), oxygen isotope geochemistry, laser ablation inductively coupled plasma mass spectrometric analysis of volatile elements, multiple sulphur isotope geochemistry, till geochemistry and indicator minerals, and integration of rock properties and geophysics. Each of these research activities produced results that influence exploration strategies for VMS deposits in Canada and elsewhere.

Studies focussed on determining the controls on precious metal endowment or enrichment in VMS deposits employed geology, volcanology/volcanic architectural analysis, lithogeochemistry, chemostratigraphy, geodynamic setting analysis, geochronology, hydrothermal alteration systematics, petrography, mineralogy and mineral chemistry (mineralization, alteration, host rock), oxygen isotope geochemistry, sulphur isotope geochemistry, lead isotope geochemistry, and metallogenic considerations. Collectively these studies demonstrate that in all cases, gold enrichment was primary (not late/secondary; i.e., seafloor and aerial weathering, overprinted unrelated mineralizing systems) and was the result of one or more of the following processes: 1) magmatic input, as evidenced by the presence of complex mineral assemblages that include sulphosalts and native elements, anomalous trace element signatures (e.g. epithermal suite: Au-As-Sb-Ag-Hg; felsic magma-associated: Bi-W-Te-In-Sn); and 2) boiling in a shallow-water setting. Only minimal remobilization of gold occurred in deposits in response to greenschist- and amphibolite-facies metamorphism.

INTRODUCTION

The recently completed Targeted Geoscience Initiative 4 (TGI-4) Program (April 1, 2010 – March 31, 2015) was focussed on expanding geoscientific knowledge and developing new cutting-edge tools to increase industry's success in exploring for deep mineral deposits. The TGI-4 program was carried out in collaboration with territorial and provincial government geological survey organizations, industry, and academia. Seven ore deposit types (so-called "ore systems") were studied: lode gold, Ni-Cu-(PGE); volcanogenic massive sulphide, SEDEX, intrusion-related; uranium, and rare metals, together with exploration methods development.

Canada's base metal reserves and production largely reside within and come from volcanogenic massive sulphide (VMS) deposits. Various sources, including Natural Resources Canada's Minerals and Metals Sector data, indicate that 27% of Cu, 49% of Zn, 20% of Pb, 40% of Ag, and 3% of Au production in 2012 came from VMS deposits. Despite redoubled exploration efforts, reserves are steadily declining, mainly

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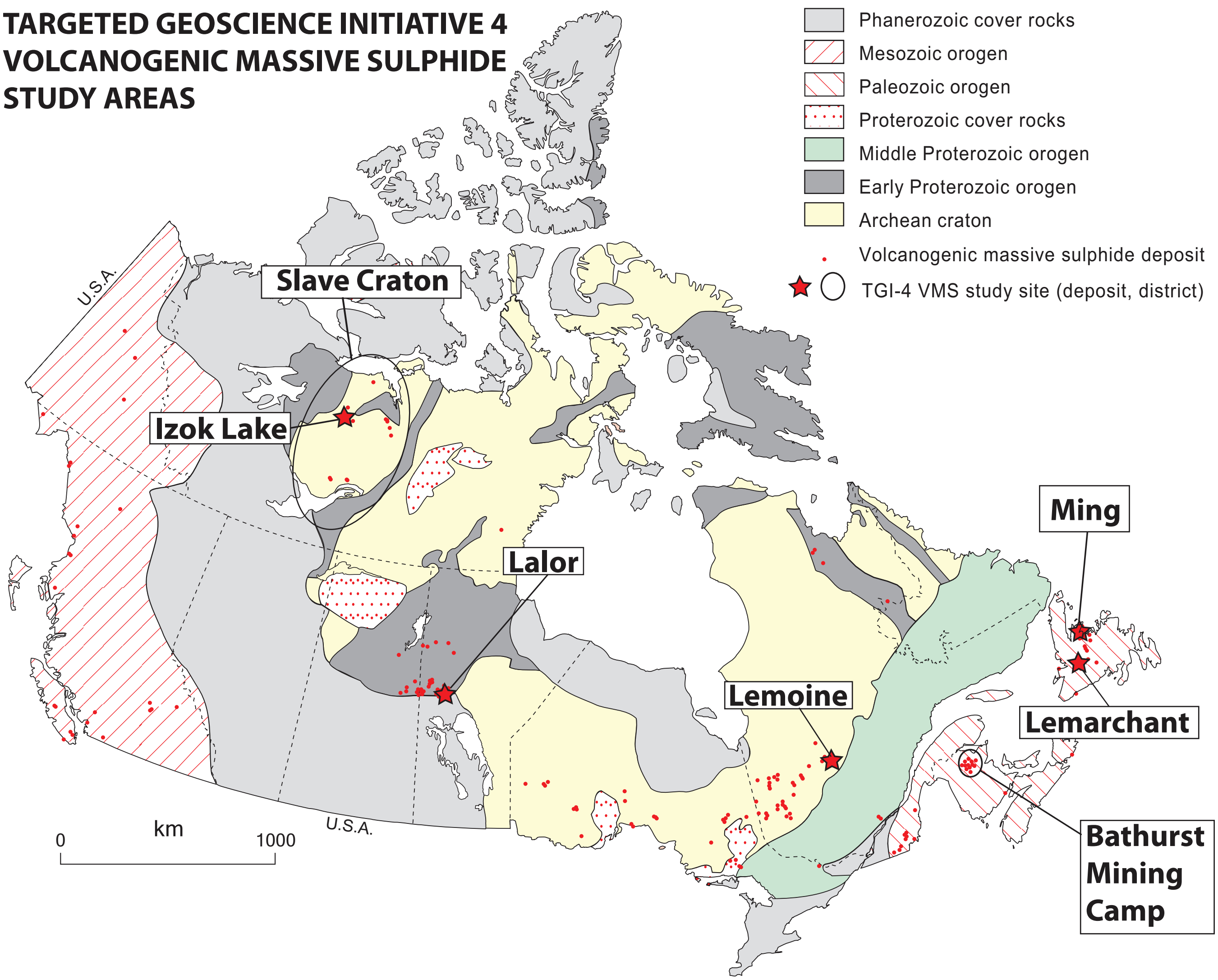

Figure 1. Map of Canada showing the locations of the volcanogenic massive sulphide deposits and mining/mineral deposit districts in which TGI-4 research was conducted.

because traditional exploration methods have discovered most of the deposits that are either exposed or shallowly buried.

In a concerted effort to reverse this trend, research activities at several sites (Fig. 1) were initiated to enhance exploration effectiveness centered on addressing two main premises:

1. New, unconventional, and innovative technologies that are not currently employed in VMS exploration combined with new tools and methodologies could be used to identify fertile VMS systems and vector (give directional and distance information) toward concealed, so-called “deeply buried” deposits. The TGI-4 program investigated technologies and methods that included a) a study of the efficacy of airborne and ground hyperspectral optical spectroscopy in the recognition of VMS-associated hydrothermal alteration at the Izok Lake deposit test site; b) a study of bulk rock oxygen isotope mapping at the Izok Lake deposit test site and its effectiveness in providing additional/ancillary lithogeochemical data to vector toward mineralization in areas with high metamorphic grades; c) a reconnaissance study to determine the applicability of multiple sulphur isotope analysis of VMS deposits across the Slave Province for fingerprinting fertile terrains or precious metal-rich terrains; d) a study of laser ablation inductively coupled plasma mass spectrometry of volatile trace elements (e.g. As, Cd, Hg, In, Sb, Tl) in pyrite, chlorite, and white mica from select polymetallic VMS deposits and host rocks in the Bathurst Mining Camp (BMC) to determine it’s potential as a tool to vector toward mineralization; e) a synoptic review of surficial exploration methods for VMS deposits (including boulder tracing, till geochemical, and indicator mineral surveying); f) a study integrating deposit-specific rock property data with geophysi-

cal data using the BMC as a test site for the creation of more accurate predictive models and methodologies.

2. Precious metal-enriched (gold, silver) VMS deposits are a much more attractive exploration target than base metal-only deposits because gold and silver credits can significantly increase the value of the ore. Although VMS deposits are perhaps the best understood of all metallic mineral deposits (largely because of the discovery and study of modern seafloor massive sulphide analogues), the salient controls on the enrichment of Au and Ag remain poorly and incompletely understood. For this reason, particular focus was placed on the study of several VMS deposits across Canada with precious-metal enrichment (Lalor Mine, Snow Lake Camp, Manitoba; Lemarchant deposit, Tally Pond volcanic belt, Newfoundland; Ming Mine, Rambler and Ming Mining Camp, Newfoundland; and the Lemoine deposit, Abitibi greenstone belt, Quebec. Some site-specific research studies of the TGI-4 Lode Gold project gathered key knowledge about linkages between gold-rich VMS and synvolcanic gold deposits (Dubé et al., 2015, and references therein). Below, we provide a brief overview of the research themes outlined above, their rationales, methodologies, and salient conclusions.

VOLCANOGENIC MASSIVE SULPHIDE DEPOSIT DETECTION AND VECTORING RESEARCH ACTIVITIES

Hyperspectral Optical Reflectance Spectrometry in the Exploration for Volcanogenic Massive Sulphide Deposits

This research activity investigated the application of ground and airborne optical remote sensing methods for the detection of hydrothermal alteration zones associated with VMS deposits using the Archean Izok Lake polymetallic (Zn-Cu-Pb-Ag) deposit, Nunavut as a test site. The current resource is 15 Mt grading 13% Zn, 2.3% Cu, 1.4% Pb, and 73 g/t Ag (MMG Inc., 2013 Annual Report). The deposit is located in a subarctic environment where lichens are abundant on the rock outcrops. The rhyolitic host rocks to the deposit have been hydrothermally altered and contain white mica. White mica has an Al-OH absorption feature in the short-wave infrared (SWIR) wavelength region that shifts due to chemical compositional changes. In and around the Izok Lake deposit there are systematic trends in the wavelength of the Al-OH absorption feature that corresponds to distance from the massive sulphide lenses. Furthermore, these trends can be detected in whole-rock data of outcrop samples that have been collected throughout the area. Research results demonstrate the feasibility of using hyperspectral remotely sensed data to delineate metamorphosed VMS-associated hydrothermal alteration zones and determine alteration intensity in high-latitude regions. The study constitutes the first successful demonstration of the application of airborne hyperspectral mapping of metamorphosed hydrothermal alteration (white mica distribution and chemical variation) as a vectoring tool in northern Canada where rock-encrusting lichen is pervasive. The findings have been presented in this volume (Laakso et al., 2015a), a journal paper (Laakso et al., 2015b), a submitted manuscript, and in a recently completed Ph.D. thesis (Laakso, 2015). An ancillary project was also completed that demonstrated the successful application of airborne hyperspectral imaging in the detection of hydrothermal alteration associated with orogenic gold mineralization in the Hope Bay Belt (a subset of data over a known deposit was used), and this was reported in Yarra et al. (2014) and a B.Sc. Honours thesis (Yarra, 2013).

Oxygen Isotope Mapping in the Exploration for Volcanogenic Massive Sulphide Deposits

Mapping of the oxygen isotope compositions of bulk rocks has long been known to be useful in deciphering the hydrothermal fluid-flow patterns and the fluid-rock interactions in hydrothermal mineral deposit environments (e.g. Taylor, 1979). In VMS environments, oxygen isotope mapping studies have effectively delineated high-temperature altered rocks in the footwall (^{18}O depleted) from low-temperature altered rocks in the hanging wall (^{18}O enriched), and can be used to distinguish hydrothermal systems that formed a single deposit from those that formed multiple, stacked deposits (e.g. Cathles, 1993; Taylor and Holk, 1998; Holk et al., 2008). However, previous such studies (of VMS systems) commonly investigated rocks that have been metamorphosed to greenschist facies or lower, and there are even fewer case studies of rocks that have undergone amphibolite-facies grade or higher metamorphism. Furthermore, few (if any) studies have integrated optical reflectance data. To address this knowledge-gap, such research was conducted at the Izok Lake deposit in concert with the study of Laakso et al. (2015a) detailed above.

At the same time as outcrop samples were collected for determining spectral data in the vicinity of the deposit, samples were also collected of felsic rocks (host to mineralization) for determination of oxygen isotope compositions. In most instances, the samples for oxygen isotope studies were the same (subset of) as those used for the spectral measurement, or they were collected from the same outcrop. A few additional samples were collected for which no spectral measurements were collected. The data show a distinct oxygen isotope zonation that is centred over the massive sulphide lenses, with high ^{18}O values (>10 per mil, ranging up to 14.7‰) around the mineralization (in hanging-wall rocks); further away to the south-southwest, ^{18}O values are lower (<10, down to below 6‰) in the footwall. This zonation is the product of water/rock interaction during the formation of the deposit, and the centring of this zonation over the massive sulphide lenses indicates that this paleohydrothermal system is relatively "up right" (i.e. top-down or plan view). The isotopic zonation broadly corresponds to a zone of bulk rock Na_2O depletion, and, to some extent, with a mapped distribution of the Ishikawa alteration index and short-wave infrared spectral mapping of white mica and biotite+chlorite-related absorption features; however, the pattern of oxygen isotope zonation provides a more focussed "target" and forms a hanging-wall "vector" to the buried sulphide lenses. The isotopic signatures have been retained despite subsequent amphibolite-facies metamorphism. This study contrasts with most of the other oxygen isotopic studies of VMS environments that describe ^{18}O-depleted upflow zones in the stratigraphic footwall (e.g. Mercier-Langevin et al., 2014a). Results of the study are documented in Taylor et al. (2015a), and a subset of the oxygen isotope data (together with X-ray diffractometry data) forms the basis of a B.Sc. Honours thesis (Davis, 2014).

Multi-Sulphur Isotope Fingerprinting of Volcanogenic Massive Sulphide Deposits

Sulphur isotopic analysis has long been used to study metallic mineral deposits, including VMS deposits (e.g. Ohmoto and Rye, 1979). These studies employed the isotopes of ^{34}S and ^{32}S. More recently, mass independent fractionation amongst the sulphur isotopes has been identified (Farquhar et al., 2000), and there is a growing awareness that this could be useful in deciphering the role of mantle (juvenile) and atmospherically cycled sulphur in VMS and other deposit types of Paleoproterozoic or older age (e.g. Bekker et al., 2009; Farquhar et al., 2010; Jamieson et al., 2013).

The typical mass-dependent fractionation (MDF) trend between ^{33}S and ^{34}S is linear ($\delta^{33}S = 0.515\ \delta^{34}S$: Farquhar et al., 2000). However, prior to 2.45 Ga, the distribution of sulphur isotopes was controlled by the production of anomalous amounts of ^{33}S through photolysis reactions in the atmosphere (e.g. Farquhar et al., 2001). This was facilitated by the low atmospheric oxygen concentrations that allowed the mass-independent fractionation (MIF) of the isotopes of sulphur. This fractionation resulted in deviations (both positive and negative) in $\Delta^{33}S$ ($\delta^{33}S_{\text{MEASURED}} - \delta^{33}S_{\text{MDF-PREDICTED}}$) from this linear trend (e.g. Farquhar and Wing, 2003) that can be used as a tracer of surface-processed sulphur. The sulphur produced by MIF is transported to the Earth's surface as sulphur (S°; $\Delta^{33}S > 0‰$) and sulphate (H_2SO_4; $\Delta^{33}S < 0‰$), and incorporated in sulphides via bacterial sulphate reduction (BSR) or thermal (TSR) sulphate reduction.

A study was initiated to assess the usefulness of multiple sulphur isotopic (^{32}S, ^{33}S, ^{34}S, and ^{36}S) analysis of VMS sulphides in Archean (pre-2.45 Ga) rocks in serving as a fingerprint of petrotectonic setting and/or mineralizing processes. A previous lead isotope study of samples from 30 Archean VMS deposits and occurrences throughout the Slave Province conducted by Thorpe et al. (1992) provided the ideal sample suite (and Pb isotope data for comparison). These galena, sphalerite, and pyrite separates reveal a variable contribution from Archean atmosphere-derived sulphur, as evidenced by variable $\Delta^{33}S$ values. The data indicate that bimodal-mafic type (bimodal rift setting) deposits have a restricted range of $\Delta^{33}S$ (-0.3 to 0.1‰), whereas bimodal-felsic type (arc-like settings) deposits exhibit a broad range of $\Delta^{33}S$ (-0.8 to 0.6‰). Mantle-derived (juvenile) sulphur is essentially the sole source of sulphur in bimodal-mafic type deposits; these deposits are also characterized by relatively low silver contents. Bimodal-felsic type deposits, typified by high silver contents, contain variable amounts of atmosphere-derived sulphur that was more readily available in arc-like settings. Thus, this study, presented in Taylor et al. (2015b), indicates that multiple sulphur isotopic analyses may be useful in discrimination between, and selection of, terranes for VMS exploration, particularly those that are precious metal-rich.

Volatile Element Vectoring for Volcanogenic Massive Sulphide Deposit Exploration

Mercury, a volatile element (i.e. possesses a high vapour pressure), in bulk rocks has long been used as a pathfinder element in VMS exploration (see Lentz, 2005, and references therein). Thallium, another volatile element, has also been shown (also in bulk rocks) to be useful as an exploration vector in VMS exploration (Large et al., 2001). The advent of inductively coupled plasma mass spectrometry (ICP-MS) provides for the facile quantitative analysis of these and other volatile elements at the ppm to ppb levels in geological materials. The coupling of ICP-MS with laser ablation (LA-ICP-MS) provides in situ, high-spatial-resolution sampling and allows discrete mineral phases to be analyzed (e.g. Danyushevsky et al., 2011).

The application of LA-ICP-MS volatile element (including As, Cd, Hg, In, Sb, Tl) analysis of pyrite, chlorite, and white mica from selected polymetallic Zn-Pb-Cu-Ag VMS deposits of the Bathurst Mining Camp (BMC), northern New Brunswick as a vectoring tool in VMS exploration has been investigated. These minerals were selected because they are ubiquitously present within the mineralization and/or the hydrothermally altered host rocks to VMS mineralization and can accommodate a wide range of volatile trace elements. The data for the BMC indicate that pyrite, chlorite, and white mica contain significant abundances of volatile trace elements. In particular, pyrite grains typically contain As, Sb, Tl, Au, Hg, In, and Cd; white mica typically contains As, Sb, Tl, In, Hg, Cd, and Bi, and in comparison to white mica, chlorite is preferentially enriched in Cd and Bi. Volatile element contents of chlorite and white mica indicate that these elements are crystal lattice-bound.

Stratigraphic profiles of the examined deposits reveal distinct volatile trace element features. Pyrite in the footwall alteration zones typically displays systematically increasing volatile trace element contents with decreasing distance stratigraphically upward to the ore horizon. However, in the hanging-wall alteration zones, there are no consistent pyrite chemical compositional trends. Pyrite in the hanging wall of some deposits shows high As in the upper portions and, to a lesser extent, higher abundances of other volatile trace elements. The volatile trace element contents of chlorite and white mica in hanging wall- and footwall-altered rocks increase with decreasing distance toward mineralization. The study outlining these relationships is presented in Soltani Dehnavi et al. (2014, 2015), with the Ph.D. thesis research continuing after the end of the TGI-4 program. Results have shown that systematic trends in distribution of volatile trace element contents of pyrite, chlorite, and white mica can be used to vector toward VMS mineralization in the BMC. This methodology may be applicable in other areas where polymetallic deposits occur, and may complement other geochemical and geophysical exploration methods.

Boulder Tracing, Till Geochemistry, and Indicator Minerals in the Exploration for Volcanogenic Massive Sulphide Deposits

Given that most of Canada has been glaciated and is extensively covered by glacial drift, exploration methods employing surficial materials remain vitally important to VMS exploration. As such, a critical review and appraisal of best practises for drift prospecting for VMS, together with a review of selected case studies from different regions across Canada was completed under TGI-4. Focus was placed on boulder tracing, till geochemistry, and indicator minerals. Till sampling, appropriate size fractions of till to analyze, sample processing, and analytical techniques were all considered. As expected, Cu, Pb, and Zn are shown to be indicator elements of VMS deposits, and pathfinder elements include As, Ag, Au, Ba, Bi, Cd, Hg, In, Sb, Se, Sn, and Tl. Abundances of these elements should be determined in the <0.063 mm (silt + clay) fraction of till. Indicator minerals of VMS deposits should be recovered from the >3.2 specific gravity heavy mineral concentrate of till, and effect minerals include galena, sphalerite, chalcopyrite, pyrite, and pyrrhotite, native gold, electrum, cassiterite, cinnabar, and barite, and, in metamorphic terrain, metamorphosed minerals of mineralization, alteration, or exhalites, including sillimanite, andalusite, gahnite, staurolite, and spessartine. There has been much recent research on the application of the chemical composition of magnetite as a VMS exploration tool (Dupuis and Beaudoin, 2011; Makvandi et al., 2013), and this mineral may also be considered in exploration. The findings are presented in McClenaghan and Peter (2013), McClenaghan et al. (2015), and McClenaghan and Peter (in press). This work has identified avenues for future research of drift exploration methods for VMS deposits, including reducing sample size, lowering analytical costs, and identifying new indicator minerals and chemical discrimination criteria.

Integration of Rock Property and Geophysical Data for Volcanogenic Massive Sulphide Exploration

Geophysical modelling algorithms and methodologies are becoming increasingly more sophisticated and capable of providing realistic results. However, in order for these models to provide optimal results, actual rock property parameters must be used. Physical rock property information provides a direct link between the geophysical data and geological interpretations. Research into the better integration of rock property and geophysical data was conducted within TGI-4 with the aim of developing or refining selected methodologies or work-flow. The data-rich Bathurst Mining Camp (BMC), northern New Brunswick (the same site of the volatile element vectoring study described above), was used as the test site for this research. The study used an existing physical rock property (density and magnetic susceptibility measurements) database for host rocks and VMS mineralization that was then expanded by incorporating new measurements taken of in situ samples and drill cores.

Density data were used to reprocess existing ground gravity and airborne gravity gradiometry (AGG) survey data by applying a laterally variable Bouguer and terrain density correction linked to averaged, measured density values and mapped extents of the different tectonostratigraphic groups that make up the BMC. The results of this reprocessing changed the previously determined gravity and gradient anomaly patterns and allowed isolated anomalies to be more discretely resolved, thus reducing the impact of the terrain-related signal in the AGG data. Helicopter-borne frequency domain electromagnetic (EM) data were inverted for magnetic susceptibility and forward modelled into a magnetic anomaly grid for a small test site in the BMC. Magnetic susceptibility values from the physical property database were used to validate the results of the inversion, and this computed near-surface magnetic anomaly grid was used as a reference to effectively filter measured total magnetic intensity data to represent solely near surface magnetic sources (i.e. potential VMS targets). Although petrophysical measurements in the BMC may differ from other locales, the various methodologies developed can be used elsewhere.

The research results are summarized in Tschirhart and Morris (2015), with individual research aspects covered in Tschirhart et al. (2014a,b, in press-a, in press-b), a submitted manuscript, and a recently completed M.Sc. thesis (Tschirhart, 2013).

PRECIOUS METAL-ENRICHMENT PROCESSES IN VOLCANOGENIC MASSIVE SULPHIDE DEPOSITS

Volcanogenic massive sulphide deposits can contain variable amounts of precious metals (Au, Ag), and the credits received from these metals during mining can significantly enhance the economic potential of these deposits such that they are highly desirable exploration targets. The currently understood spectrum of enrichment processes in these deposits ranges from one, or a combination of (e.g. Hannington and Scott, 1989; Huston, 2000; Dubé et al., 2007; Mercier-Langevin et al., 2011): 1) "fertile" Au- and/or Ag-enriched source rocks and fluids that originated in a specific geodynamic setting, or from magmatic input, respectively; 2) optimal ligand complexing and transport of the metals and/or their efficient deposition by processes such as boiling/phase separation and zone refining; 3) superposition of another (type of) mineralization style such as epithermal, intrusion-related, or orogenic; 4) supergene weathering on the seafloor or on land; and/or 5) metamorphic redistribution. In an effort to refine the genetic and exploration models for Au and/or Ag enriched VMS deposits, research was conducted at several precious metal-enriched VMS deposits across Canada (Lalor Mine, Snow Lake Camp, Manitoba; Lemarchant deposit, Tally Pond volcanic belt, Newfoundland; Ming Mine, Rambler, and Ming Mining Camp, Newfoundland; and the Lemoine deposit, Abitibi greenstone belt, Quebec.

Mercier-Langevin et al. (2015) provide a summary of these various enrichment processes and the TGI-4 research that addresses some of these processes. Key observations and circumstantial lines of evidence include the following: volcanogenic massive sulphide deposits in volcanic belts that formed in pericratonic settings or on older crust basement in the early stages of rifting are commonly slightly better endowed in precious metals than those formed in belts or settings with limited to no basement influence (see also the multi-sulphur isotope study of the Slave VMS deposits, which is outlined above, as well as in Taylor et al. (2015b), which presents a similar observation). Gold-rich and auriferous VMS are preferentially associated with calc-alkaline or transitional magmatic successions that display the full continuum of magmatic differentiation fractionation (andesite-dacite-rhyodacite-rhyolite) and with thick felsic volcanic packages. Evidence for a magmatic input includes i) the presence of complex mineral assemblages comprising sulphosalts, sulphides, native elements; and ii) anomalous trace element signatures (e.g. enrichment in the "epithermal suite" of elements Au-As-Sb-Ag-Hg and/or in felsic magma-associated elements Bi-W-Te-In-Sn) (e.g. Gill et al., 2015; Pilote et al., 2015; see below); and iii) a laterally extensive sericitic (phyllic) ±siliceous alteration halo or a zone of intense aluminous (argillic- to advanced argillic-style) alteration (e.g. Dubé et al., 2014). Deposition in response to boiling/phase separation (in a shallow water setting) is evidenced by i) bladed textures of certain minerals (e.g. Gill et al., 2015; see below); and ii) heterogeneous Au and Ag distributions and mineralogical residence sites within or near the sulphide bodies.

Lalor Volcanogenic Massive Sulphide Deposit

Characteristics and Gold-Enrichment Processes of the Lalor Deposit

Lalor is a Paleoproterozoic VMS deposit that contains 25.3 Mt of ore grading 2.9 g/t Au, 25 g/t Ag, 5 wt% Zn, and 0.79 wt% Cu, including 8.8 Mt at 4.6 g/t Au. Lalor is the largest deposit (and also most Au-rich) in the Snow Lake Camp, Manitoba; TGI-4 conducted two research projects here: 1) a Ph.D. study to understand the geological evolution of the deposit and the ore-forming hydrothermal system, including the controls on gold enrichment; and 2) a M.Sc. study of the mineralization styles in the deposit.

Major findings of the first study are 1) Lalor is within a complex volcanic package (Lalor volcanic succession) composed of mafic to felsic, tholeiitic to calc-alkaline, extrusive to intrusive volcanic rocks of the ca. 1.89 Ga Lower Chisel subsequence; 2) the ore is hosted in both mafic and felsic rocks; 3) the Lalor deposit is not situated at the top of the Lower Chisel subsequence as is typical of the other Zn-rich deposits of the Snow Lake district, but is at a slightly lower stratigraphic position; 4) the host rocks were affected by intense and laterally extensive hydrothermal alteration that occurred during ore deposition; 5) the altered rocks and the deposit were subsequently subjected to syndeformational amphibolite-grade metamorphism that resulted in the development of distinct minerals and metamorphic mineral assemblages of varying composition from variably altered precursor lithologies; 6) Five distinct alteration and metasomatic chemical associations (K, K-Mg-Fe, Mg-Fe, Mg-Ca, and Ca) are recognized, based on mineralogical (mineral assemblages) and bulk geochemical compositions; 7) mineralization occurs within stratigraphically and structurally stacked Zn-rich, Au-rich, and Cu-Au-rich ore lenses; 8) the Zn-rich massive sulphide lenses are preferentially associated with the low- to high-temperature K and Mg-Ca alteration zones; 9) the Cu-Au-rich zones, which occur at depth, stratigraphically below the Zn-rich mineralization, are hosted in transposed, presumably originally discordant high-temperature Mg-Fe altered rocks; and 10) Au has been in part locally remobilized into low-strain sites that are not spatially associated with any particular chemical association. These conclusions are summarized from the following cadre of research conducted at Lalor: Caté et al. (2013, 2014a,b,c, 2015) and Mercier-Langevin et al. (2014a). The Ph.D. thesis research (Caté) is continuing beyond the conclusion of the TGI-4 program.

Two major findings for the second study are that there are four ore types at Lalor and that these types are associated with different host rocks.

Four Ore Types of the Lalor Deposit

Type 1 Fe-Zn massive sulphide ore is the most common ore type in 6 (of the 11) ore lenses and consists of massive coarse-grained pyrite and sphalerite with trace galena.

Type 2 Cu-Au mineralization consists of semi-massive and stockwork chalcopyrite and pyrrhotite.

Type 3 Au-Ag-Pb-Cu-rich ore consists of stringer and disseminated sulphides and sulphosalts. Galena is an important indicator of Au mineralization and occurs in this ore type as fine-grained blebs in a matrix of chlorite, dolomite, calcite, anthophyllite, Ca-plagioclase, and calc-silicate minerals (epidote, grossular, diopside, Ca- amphibole ± scapolite). Where abundant, the galena is associated with chalcopyrite, pyrite, and pyrrhotite, and with minor to trace sphalerite, Ag-Sb-Pb sulphosalts, electrum, and native gold.

Type 4 low-sulphide ore contains ≤10 vol% disseminated pyrite, and has variable Au grades. The sulphides and sulphosalts in ore types 3 and 4 are thought to have been remobilized from pre-existing disseminated mineralization during metamorphism.

Host Rocks of Mineralization at the Lalor Deposit

Type 1 mineralization occurs predominantly occurs in quartz-muscovite±kyanite-biotite schist (K-alteration association). Type 2 mineralization occurs in garnetiferous quartz- biotite±staurolite-amphibole-cordierite gneisses (footwall Mg-Fe alteration association). Type 3 mineralization mainly occurs in chlorite-carbonate-actinolite schist (Mg-Ca and Ca alteration associations). Type 4 mineralization occurs in quartz-biotite-anthophyllite gneiss, with minor chlorite, staurolite, and coarse almandine garnet.

Despite extensive recrystallization and local remobilization, type 1 and 2 ore are interpreted to represent typical (metamorphosed) low- and high-temperature VMS deposit ore assemblages, respectively. Significant Au was introduced first by high-temperature (>300°C) fluids responsible for the Type 2 Cu-Au mineralization. The Type 3 Au-Ag-Pb-Cu mineralization is thought to have formed in the subseafloor from late-stage, lower temperature (and possibly boiling) hydrothermal fluids (<300°C). Although all the ore types are extensively recrystallized and partly remobilized, Au enrichment at Lalor is thought to have been primary, and not secondary; this is supported by lead isotopic compositions of ore galena and whole-rock oxygen isotope compositions. Furthermore, the Au-rich assemblages are very similar to those in unmetamorphosed Au-rich VMS deposits.

The above research summary is detailed in Duff et al. (2013, 2015) and is the subject of a M.Sc. thesis that is still in progress (Duff).

Lemoine Au-Rich Volcanogenic Massive Sulphide Host Succession, Waconichi Formation, Abitibi

The Lemoine deposit, which is now mined out, was a small but exceptionally rich auriferous (0.76 Mt grading 4.2 wt % Cu, 9.6 wt % Zn, 4.2 g/t Au, and 83 g/t Ag) VMS deposit in the Chibougamau area of the Archean Abitibi greenstone belt (Mercier-Langevin et al., 2014b). The deposit was the second highest grade VMS deposit in Canada, and occurred in the predominantly tholeiitic Lower Lemoine Member of the Waconichi Formation, which is overlain by transitional basalt and transitional to calc-alkaline rhyolite of the Upper Lemoine Member. Research at Lemoine aimed to reconstruct the volcanic architecture immediately east of the deposit to elucidate whether this might have been a salient control responsible for the high base and precious metal grades. Field mapping, geochemical analyses, and detailed core logging of every accessible drillhole in the study area, east of the former mine, helped to refine the volcanic architecture of the Lower Lemoine Member subunits and identify their mode of emplacement. This work also identified previously unrecognized volcanic vents northeast of the Lemoine deposit, which may have been the site of paleohydrothermal fluid up-flow and may host additional mineralization. Furthermore, results show that many of the felsic-dominated host rocks to the Lemoine are shallow intrusive rocks that define a major thermal corridor over a large synvolcanic intrusion. This research, summarized above, is presented in Boulerice et al. (2015), and is the subject of a M.Sc. thesis that remains in progress (Boulerice).

Lemarchant Volcanogenic Massive Sulphide Deposit and Precious Metal-Enrichment Processes

Lemarchant, a Cambrian precious metal-enriched Zn-Pb-Ba-Ag-Au VMS deposit, is located in the bimodal felsic Tally Pond Group of the Central Mobile Belt, Newfoundland Appalachians. TGI-4 research aims here were to 1) characterize the ore facies and zonation of ore; 2) determine the paragenetic sequence of the ore minerals; 3) determine the siting of precious metals in the host rocks and ore assemblages; 4) determine the source(s) of mineralizing fluids; and 5) determine the causes of base and precious metal-enrichment. Research results show that the deposit was formed in three discrete stages: Stage 1: barite-rich, low-temperature (<250°C) VMS mineralization; Stage 2: 150 to 250°C intermediate- to high-sulphidation epithermal-style mineralization; and Stage 3: polymetallic, high-temperature (>300°C) VMS mineralization. Sulphur isotopes suggest that S is derived from three sources: thermochemically reduced seawater sulphate, leached igneous basement rock, and magmatic SO_2. Lead isotopes indicate that Pb is primarily derived from evolved crustal material, with some input from juvenile volcanic rocks (i.e. arc-rift). Precious metals associated with epithermal-style mineralization are consistent with a magmatic contribution to the hydrothermal fluid. Precious metals were precipitated from intermittently boiled fluids (evidenced by bladed barite), at relatively shallow (<1500 m) water depth. This summary is extracted from Gill et al. (2015), Gill and Piercey (2014), Gill et al. (2013), and a recently completed M.Sc. thesis (Gill, 2015).

Ming Volcanogenic Massive Sulphide Deposit and Gold-Enrichment Processes

Ming is a VMS deposit hosted by the Rambler rhyolite in the Rambler Camp, Baie Verte Peninsula, northwest Newfoundland. Research funded by TGI-4 aimed to reconstruct the architecture and morphology of the deposit and its Au-rich zones, and identify the hydrothermal alteration zoning and key associations. The deposit is hosted in Cambro-Ordovician intermediate to felsic rocks that are underlain by ca. 490 Ma ophiolite slivers of boninitic composition. The deposit consists of five elongated, moderately plunging, semi-massive to massive sulphide lenses that occur in the uppermost part of a calc-alkaline intermediate to felsic volcanic succession. The immediate hanging wall varies from mafic volcanic breccia to magnetite-rich volcanogenic siltstone. There are seven distinct alteration mineral assemblages (from proximal to distal from mineralization): quartz-pyrite, quartz-calcite-garnet, sericite-green mica-sulphide, sericite-quartz-pyrite, chlorite-amphibole-quartz, chlorite-sericite-quartz-sulphide, and chlorite-stringer zone. A chalcopyrite-pyrrhotite-pyrite stringer zone associated with the chlorite-stringer zone assemblage occurs 50–100 m stratigraphically below the Ming North and Ming South lenses, at what was the site of high-temperature fluid discharge from a hydrothermal system. Brueckner et al. (2014) showed that Au-enrichment was syngenetic, based on the complex assemblage of sulphide minerals (e.g. sulphosalts, Au-Ag-Hg-bearing phases), and not due to subsequent remobilization, as had been previously suggested. Research outlined above is summarized from Pilote et al. (2014, 2015), Pilote and Piercey (2013), and Ph.D. thesis (Pilote) research, which is continuing beyond the completion of the TGI-4 program.

IMPLICATIONS FOR EXPLORATION

The legacies of TGI-4-funded VMS research in the exploration for VMS deposits are myriad. There are a number of key findings and advances in the development of exploration and vectoring methods:

1. A test of the efficacy of airborne and ground hyperspectral optical spectroscopy for recognition of VMS-associated hydrothermal alteration at the Izok Lake deposit showed that chlorite and white mica alteration minerals possess spectral variability that relates to the chemical compositional variations in the altered rocks. This information can be used to vector toward mineralization and areas for further exploration in Canada's North, and has direct application to other hydrothermal ore deposits with similar alteration styles (e.g. orogenic lode gold deposits), and can serve as a first-pass "green" (i.e. no boots on the ground) method to define areas for follow-up work.
2. Bulk-rock oxygen isotope mapping at the Izok Lake VMS deposit identified a relatively "upright" paleohydrothermal system with a hanging-wall "cap" centred over the mineralization, as defined by high $\delta^{18}O$ values (up to 14.7‰). These results reaffirm that this method can be used to not only recognize high-temperature hydrothermally altered footwall rocks associated with mineralization, but also to determine the overall morphology and orientation (i.e. architecture) of a paleohydrothermal fluid flow system, as well as to vector toward the

concealed mineralization. Such isotopic "fingerprints" are retained in the rocks that have been metamorphosed, even up to high-grade conditions.

3. Multiple sulphur isotope analysis was undertaken on sulphide minerals from 30 VMS deposits across the Slave Province. The distribution of $\delta^{34}S$ and $\Delta^{33}S$ of sulphides across the Slave Craton does not reflect known variations in the crustal age or the origin of the crust, nor the metal content of the VMS; however, deposits formed in rift settings are characterized by a restricted range of $\Delta^{33}S$ values (from approximately -0.3 to 0.1‰), whereas deposits formed in arc-like settings exhibit a broad range in $\Delta^{33}S$ values (approximately -0.8 to 0.6‰), indicating atmospheric-derived sulphur was more readily available in the latter. The former group of deposits mostly have lower Ag contents than the latter.
4. Volatile trace element (e.g. As, Cd, Hg, In, Sb, Tl) contents of pyrite, chlorite, and white mica in selected polymetallic VMS deposits of the BMC, as determined by laser ablation inductively coupled plasma mass spectrometry, are shown to be a potential tool in vectoring toward mineralization. Pyrite in the footwall alteration zones typically displays systematically increasing volatile trace element contents with decreasing distance stratigraphically upward to the ore horizon. Chlorite and white mica show that volatile element contents in both hanging wall- and footwall-altered rocks increase with decreasing distance toward mineralization.
5. A review of surficial exploration methods for VMS mineralization included boulder tracing, till geochemical, and indicator mineral surveying. Best practices for till sampling and analyses have been identified. Geochemical indicators of mineralization include Cu, Pb, Zn, As, Ag, Au, Ba, Bi, Cd, Hg, In, Sb, Se, Sn, and Tl, all in the <63 µm (silt+clay) fraction. VMS indicator minerals recovered from the <3.2 specific gravity heavy mineral concentrate of till include the main ore minerals (galena, sphalerite, chalcopyrite, pyrite, and pyrrhotite), accessory minerals (native gold, electrum, cassiterite, cinnabar, and barite), and, in metamorphic terrain, metamorphosed minerals of mineralization, alteration, or exhalites, including sillimanite, andalusite, gahnite, staurolite, and spessartine.
6. Rock property (density and magnetic susceptibility) data were integrated with geophysical data (ground gravity, airborne gravity gradiometry, airborne magnetics and EM) in the Bathurst Mining Camp, which has led to the development of several new tools: a new laterally variable density correction procedure to produce more accurate geological maps, and a methodology to separate near-surface from deep-seated magnetic sources in frequency domain EM data; these methodologies have application elsewhere.

The studies that focussed on determining the controls on precious metal endowment or enrichment in VMS deposits resulted in several key implications:

1. In all the deposits that were studied, gold enrichment was primary, and was not due to secondary processes, such as seafloor and/or aerial weathering or overprinting by subsequent (non-VMS) mineralizing systems.
2. In several deposits studied (Lemarchant, Ming, Lemoine), gold enrichment was facilitated by magmatic input, as evidenced by the presence of complex mineral assemblages that include sulphosalts and native elements, with anomalous trace element signatures (e.g. epithermal suite: Au-As-Sb-Ag-Hg; felsic magma-associated: Bi-W-Te-In-Sn). Such mineralogical and metal relationships are strong prognostic indicators for potentially economic gold enrichment.
3. In several deposits studied (Lemarchant, Ming, and perhaps Lalor), boiling in a shallow-water setting is thought to have destabilized the gold complexes and produced gold-enriched mineralization. Exploration should be focussed on identifying shallow-water regimes (e.g. calderas and arc settings) in which seafloor hydrothermal activity may have taken place.
4. In the most highly metamorphosed and strongly deformed deposits studied (Lalor, Ming), there was only minimal remobilization during metamorphism and deformation subsequent to primary gold enrichment. Therefore, exploration for gold-enriched deposits should focus on primary permissive geological environments, and undue emphasis should not be placed on (high) metamorphic grade or on overprinting structural features (e.g. shear zones).

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