

Introduction to the volcanic- and sediment-hosted base-metal ore systems synthesis volume, with a summary of findings

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Peter, J.M. and Gadd, M.G., 2022. Introduction to the volcanic- and sediment-hosted base-metal ore systems synthesis volume, with a summary of findings; in Targeted Geoscience Initiative 5: volcanic- and sediment-hosted massive-sulfide deposit genesis and exploration methods, (ed.) J.M. Peter and M.G. Gadd; Geological Survey of Canada, Bulletin 617, p. 3–13. <https://doi.org/10.4095/328015>

Abstract: This volume presents results of research conducted during phase 5 of the Volcanic- and Sedimentary-hosted Base Metals Ore Systems project of the Geological Survey of Canada's Targeted Geoscience Initiative (TGI) program. The papers in this volume include syntheses and primary scientific reports. We present here a synopsis of the findings during this TGI project. Research activities have addressed several mineral deposit types hosted in sedimentary rocks: polymetallic hyper-enriched black shale, sedimentary exhalative Pb-Zn, carbonate-hosted Pb-Zn (Mississippi Valley-type; MVT), and fracture-controlled replacement Zn-Pb. Other carbonate-hosted deposits studied include a magnesite deposit at Mount Brussilof and a rare-earth element–F–Ba deposit at Rock Canyon Creek, both of which lack base metals but are spatially associated with the MVT deposits in the southern Rocky Mountains. Volcanogenic massive-sulfide deposits hosted in volcanic and mixed volcanic-sedimentary host rock settings were also examined. Through field geology, geochemical (lithogeochemistry, stable and radiogenic isotopes, fluid inclusions, and mineral chemistry), and geophysical (rock properties, magnetotelluric, and seismic) tools, the TGI research contributions have advanced genetic and exploration models for volcanic- and sedimentary-hosted base-metal deposits and developed new laboratory, geophysical, and field techniques to support exploration.

Résumé : Le présent volume rend compte des résultats de recherches menées durant la phase 5 du projet sur les systèmes minéralisés à métaux communs dans des roches volcaniques et des roches sédimentaires du programme de l'Initiative géoscientifique ciblée (IGC) de la Commission géologique du Canada. Il comprend des articles de synthèse et des rapports scientifiques de base. Nous résumons ici les résultats des recherches menées dans le cadre de ce projet de l'IGC. Les activités de recherche se sont intéressées à plusieurs types de gîtes minéraux encaissés dans des roches sédimentaires : gîtes de shales noirs surenrichis à minéralisation polymétallique, gîtes exhalatifs de Pb-Zn dans des roches sédimentaires, gîtes de Pb-Zn dans des roches carbonatées (de type Mississippi-Valley [M-V]) et gîtes de Zn-Pb de remplacement contrôlé par des fractures. Parmi les autres gîtes encaissés dans des roches carbonatées étudiés, mentionnons un gîte de magnésite au mont Brussilof et un gîte d'éléments de terres rares-F-Ba au ruisseau Rock Canyon. Ces deux gîtes sont dépourvus de métaux communs, mais sont spatialement associés aux gîtes de type M-V dans la partie sud des montagnes Rocheuses. Nous avons aussi étudié des gîtes de sulfures massifs volcanogènes encaissés dans des environnements de roches volcaniques et de roches mixtes, volcaniques et sédimentaires. Au moyen de la géologie de terrain et d'outils géochimiques (lithogéochimie, isotopes stables et radiogéniques, inclusions fluides, chimie minérale) et géophysiques (propriétés des roches, magnétotellurique, sismique), les contributions de l'IGC à la recherche ont permis de faire progresser les modèles génétiques et d'exploration pour les gîtes de métaux communs encaissés dans des roches volcaniques et des roches sédimentaires et de mettre au point de nouvelles méthodes de laboratoire, de levés géophysiques et de terrain pour appuyer l'exploration minérale.

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INTRODUCTION AND BACKGROUND

Phase 5 of the Geological Survey of Canada's (GSC) Targeted Geoscience Initiative (TGI) program built on the work of previous program phases; the full scope of phase 5 is outlined in Mercier-Langevin et al. (2017). This volume presents results of research conducted during the Volcanic- and Sedimentary-hosted Base Metals Ore Systems project. This is one of six ore systems studied under TGI; the five other systems are gold, nickel-copper-platinum group elements (PGE)-chromium, porphyry-related mineral, uranium, and specialty metals. Four other publications report the final results of the other ore systems included in the TGI program: gold systems volume (Mercier-Langevin et al., 2020); nickel-copper-PGE-chromium systems volume (Bleeker and Hou  , 2020); porphyry-related volume (Plouffe and Schetselaar, 2020); and uranium systems volume (Potter et al., 2020). As an introduction to this volume, we present a synopsis of these findings, and review findings presented in reports of TGI project activities for 2016 (Rogers, 2017), 2017 (Rogers, 2018a, b), and 2018 (Rogers, 2019).

The Volcanic- and Sedimentary-hosted Base Metals Ore System project was organized into two subprojects: seafloor ore deposition through space and time, and base-metal sources and mineralizing processes. Research activities conducted under these two subprojects addressed several mineral deposit types hosted in sedimentary rocks in British Columbia and Yukon: polymetallic hyper-enriched black shale (HEBS) deposits, sedimentary exhalative (SEDEX) Pb-Zn deposits in fine-grained clastic sedimentary rocks, Mississippi Valley-type (MVT) carbonate-hosted Pb-Zn deposits, fracture-controlled replacement (FCR) Zn-Pb deposits, and (although not bearing base metals) carbonate-hosted magnesite (MgCO_3) and rare-earth element (REE)-F-Ba deposits that are spatially associated with the MVT deposits. Volcanogenic massive-sulfide deposits (VMS) hosted in volcanic and mixed volcanic-sedimentary host rock settings in British Columbia, Nunavut, and Manitoba were also studied.

Collectively, the papers in this volume include syntheses and new scientific findings. They address questions about deposit genesis, exploration models, and new methods and methodologies for deposit discovery. Below are synopses of the research findings, categorized according to deposit type and/or methodology. The findings are presented in the chronological order that they were published.

SCIENTIFIC FINDINGS

Deposit types

Hyper-enriched black shale deposits

Hyper-enriched black shale deposits are an important global resource of many metals, including zinc, nickel, copper, molybdenum, selenium, uranium, vanadium, chromium, cobalt, silver, gold, PGE, and REE. Yukon has some of the best-known examples. There are myriad genetic models, including seafloor hydrothermal, meteorite impact, and hydrogenetic (ambient seawater). Peter et al. (2017a) introduced the aims of the HEBS deposit ore system research activity. Gadd and Peter (2018) presented new field observations and relationships, mineralogy, and mineral chemistry for mineralization at two localities (Peel River and Nick) supplemented with legacy lithogeochemical data. Salient conclusions are that mineralization is generally thinly bedded (<10 cm), stratiform, and geographically widespread at a particular time-stratigraphic horizon, with three discrete, closely spaced horizons documented at Peel River. Abundant woody plant fossils were identified within the mineralization, and the stratigraphic succession was recognized as a condensed section. Preliminary laser-ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) analyses showed that vaesite and pyrite are the residence sites for PGE. Gadd et al. (2019b) presented follow-up LA-ICP-MS mapping of sulfide minerals within HEBS mineralization from Peel River, Yukon, indicating that pyrite is the principal host of Pd, Pt, Re, Au, and Mo. Paragenetically late pyrite contains the highest abundances of these metals, whereas the youngest pyrite in crosscutting veins contains none, indicating that metal enrichment occurred during diagenesis.

Peter et al. (2018a) presented textural and mineralogical characterizations of HEBS-like mineralization at the Akie property in the Kechika trough (the southern extension of the Selwyn Basin), British Columbia. The mineralization is mineralogically similar, broadly coeval, and displays the same element enrichments as HEBS far to the north in Yukon. Further work (including detailed mineralogical, mineral-chemical, and paragenetic study; geochronology; and lithogeochemistry) on the Akie HEBS will appear elsewhere as a Geological Survey of Canada Open File and derivative journal paper (Haimbodi et al., work in progress).

Gadd et al. (2019a) presented lithogeochemical evidence for the genesis and environment of deposition of the Moss HEBS showing, Yukon and Gadd, Peter, Fraser et al. (this volume) present lithogeochemical evidence relating to the Monster River HEBS showings, Yukon. These studies conclude that terrigenous clastic sedimentation prevailed prior to HEBS formation, but chemical sedimentation (biogenic silica) dominated during and after. Negative Ce anomalies

indicate a weakly oxygenated (suboxic) water column during the time interval of HEBS deposition. Molybdenum and uranium systematics at both localities were used to show that a ferromanganese particulate shuttle delivered the metals (including Ni, Mo, and Pt) from seawater to mineralization. Sulfur isotope data from HEBS at the Moss locality indicate that these metals were fixed by microbially reduced seawater sulfate. Crawford et al. (2019) used Mo and Tl isotopes to rule out a seafloor hydrothermal origin for the Peel River HEBS; the isotopic compositions, together with lithogeochemical (including REE) redox indicators, show that mineralization formed in euxinic porewater conditions, and that the overlying water column was suboxic.

Henderson et al. (2019) investigated the occurrence of pyrobitumen, a common constituent within HEBS mineralization, at localities in Yukon (Nick and Peel River). They presented lithogeochemical data for HEBS and host shale, LA-ICP-MS data for pyrobitumen, and mineralogical textures. They showed that bulk metal (Mo, Cu, Pb, Zn, Ni, Co, As, V, and Se) contents for HEBS varies generally between approximately 10 and approximately 70 000 ppm, with each metal varying differently within this range. Metal contents of pyrobitumen in HEBS at Nick are higher (<1 to approximately 6000 ppm; generally 200 to 3000 ppm) than at the other localities studied. The authors concluded that Ni, V, and other metals in the HEBS were sourced from liquid hydrocarbon generated during diagenesis by cracking of organic matter. They also reported the presence of texturally late (deformation-related) sphalerite and sylvanite (Cu_3VS_4) within a large (approximately 2 m wide) vein at the Nick deposit.

In an effort to better understand the origin of the organic matter in HEBS, Peter et al. (this volume) conducted Rock-Eval analyses, petrographic examination of organic macerals, and solvent extraction and gas chromatography–mass spectrometry (GC-MS) for molecular fingerprinting. Extreme thermal maturity (temperature of maximum pyrolysis yield [T_{max}] = 322–599°C) destroyed most biomarkers (except for polycyclic aromatic hydrocarbons and adamantanes at one locality: Peel River), and the samples contain little soluble organic matter. The key Rock-Eval parameters — the amount of thermally freed hydrocarbons in the sample (S1), the amount of hydrocarbons generated through thermal cracking of nonvolatile organic matter (S2), the amount of hydrogen relative to the amount of organic carbon present in a sample (H index), and the amount of organic-bound oxygen relative to the amount of organic carbon present in a sample (O index) — are all low. The high degree of thermal maturity is in contrast with the low metamorphic grade.

Gadd et al. (2020) presented Re-Os isotopic data for HEBS mineralization from Peel River and Nick, together with conodont biostratigraphic information, to precisely determine the time interval of HEBS deposition. Gadd et al. (2020) conclude that the mineralization at these two localities formed synchronously (within error of the isotopic data), within a relatively short time interval in the Eifelian

to Givetian (Middle Devonian) during sedimentation. They point out that this time period coincides with one or more global biotic events (pumilio, Taghanic, Kačák) characterized by eustatic sea-level rise and black shale deposition, and posit that these may be requisite to HEBS formation.

Gadd, Peter, and Layton-Matthews (this volume) synthesize and integrate all of the above research into an internally consistent genetic model for HEBS mineralization in the northern Canadian Cordillera. Mineralization is regionally distributed as narrow horizon(s) at the contact of the Road River Group with the overlying Canol Formation and was deposited in a relatively short period of time. Metals originated from seawater (as evidenced by Os, Mo, and Tl isotopic compositions, and metal enrichment patterns that are similar to seawater), and were sequestered at the seafloor by complexation with aqueous sulfide that originated through microbial reduction of seawater sulfate during diagenesis (evidenced by Re-Os isochrons, conodont biostratigraphy, nonflattened woody plant permineralizations, and sulfur isotopes). The widespread distribution of mineralization at a very specific time-stratigraphic horizon provides a first-order exploration criterion.

Sedimentary exhalative deposits

Several aspects of SEDEX deposits were investigated under the TGI program, including genesis and exploration methodology. Peter et al. (2017b) summarized the paradigm shift in the understanding of the genesis of SEDEX deposits addressed during TGI-4 research, which indicated that, based on microscale variability in the sulfur isotope compositions of pyrite textural varieties from two districts in the Selwyn Basin (Howards Pass and MacMillan Pass), water column anoxia or euxinia were not imperative to the SEDEX mineralizing processes in the Selwyn Basin. To explore this further, Peter et al. (2018b) investigated the Tl isotope systematics of vent-distal SEDEX mineralization (Anniv East zone) and the immediate stratigraphic footwall and hanging-wall host rocks of the Howards Pass district. They reported good general agreement between certain bulk geochemical reduction-oxidation (redox) indicators and the Tl isotopic values for unmineralized samples (reflecting suboxic or oxic conditions for the most negative values), indicating the utility of Tl isotopes as a redox indicator. Mineralized samples have the most positive values, reflecting contributions of isotopically heavy Tl from the mineralizing fluids; because of this, Tl isotopes cannot be used as a redox indicator for mineralized samples. Thallium isotopes do, however, have the potential to fingerprint (distinguish between) sulfides precipitated by different processes.

This study was followed up by an investigation of Mo isotopes (from the same samples) as a redox indicator (Peter et al., 2019). This research contribution found good general agreement between the Mo isotope values and established

bulk geochemical redox indicators for unmineralized and mineralized host rocks; these relationships reflect suboxic or oxic conditions for the most negative values, and anoxic and euxinic conditions for the most positive values. Based on these data, Mo isotopes are also an effective redox indicator in such environments; however, unlike Tl isotopes, Mo isotopes do not appear to be useful in fingerprinting SEDEX mineralization, likely because Mo is not present in the mineralizing fluid.

Peter et al. (this volume) present Rock-Eval, petrographic, and solvent extraction and GC-MS (for molecular fingerprinting) data in an effort to better understand the origin of the organic matter in SEDEX deposits; however, similar to the HEBS samples, all samples experienced extreme thermal maturity that destroyed all biomarkers, and contain little soluble organic matter. The S1, S2, H index, and O index parameters are all low. Similar to the HEBS, the high degree of thermal maturity is in contrast with the low metamorphic grade and burial depth.

Although basinal fluids are generally considered to be the source of metals in SEDEX deposits, in some districts there is a spatial association between volcanic rocks and SEDEX deposits; this association may be inconsequential, or may be an actual driver of mineralization (e.g. magmatism partially provided heat and/or metals). Paradis et al. (2017) introduced research focused on elucidating possible linkages between SEDEX mineralization and Selwyn Basin magmatism. This work was done to determine: precise ages for the magmatism; physical volcanology and geochemical signatures of these spatially associated magmatic rocks; tectonic processes that led to intrusive and extrusive emplacement; whether these rocks reflect specific structural and heat corridors; whether volcanism (magmatic activity) reflects the use of long-lived lithospheric structures that also potentially controlled hydrothermal activity; and whether any of these characteristics can predict the presence or absence of SEDEX mineralization.

Abundant mafic volcanic rocks were emplaced intermittently during the lower Cambrian, upper Cambrian to lower Silurian, and Upper Devonian, although the abundance, distribution, and nature of felsic volcanism is unknown. The relationships of these characteristics to base-metal deposits remain poorly described and require additional research. Paradis et al. (2017) focused on several districts (Keno-Mayo, Anvil, and MacMillan Pass) and documented that the volcanic rocks are products of various styles and types of volcanism that were associated with base-metal mineralization at different times in the geological history of the Selwyn Basin.

Leybourne et al. (2018) continued the research initiated by Paradis et al. (2017), and reported that most volcanic rocks in the Anvil and MacMillan Pass districts are alkalic and mafic, although Paleozoic volcanic rocks and Triassic dykes in the Keno Hill district are subalkalic. Volcanic rocks in all the studied districts are enriched to highly enriched

in Ba, Cs, Nb, and Th and show a positive relationship between Ba and Tl. Leybourne et al. (2018) surmised that these geochemical relationships may record contributions of metals and metalloids (e.g. Ba, Tl) to ore-forming magmatic-hydrothermal fluids derived from the magmas.

Carbonate-hosted (MVT, FCR) Pb-Zn deposits

Paradis and Simandl (2017) examined a variety of carbonate-hosted mineral deposits in southeastern British Columbia, including MVT (Shag, Monarch, Kicking Horse, and Munroe), REE-fluorite (Rock Canyon Creek), and magnesite (Mount Brussilof) deposits. The objective was to investigate possible genetic links among the types of carbonate-hosted deposits, with the premise that deep-seated faults structurally link the deposits and control their distribution. Paradis and Simandl (2018) summarized specific carbonate-hosted Pb-Zn (Grotto-Maverick, Silver Giant, Lead Mountain, Lancaster, and Pedley) deposits and the Mount Brussilof magnesite deposit in southeastern British Columbia. The deposits are hosted in rocks ranging in age from Cambrian to Upper Devonian, and the research aimed to determine potential genetic links. All these Pb-Zn deposits are hosted in platform carbonate rocks. The mineralization styles include veins, open-space filling of cavities, fractures, and breccias, as well as stratabound replacement of host dolostone. Sphalerite, galena, pyrite, and barite are the main ore minerals.

Paradis and Simandl (2019) presented textural and C and O isotope data for hydrothermal carbonate minerals (replacive dolomitization; mineralization (sparry, saddle, ferroan dolomite)) from selected MVT (Oldman, Boivin, Shag, and Hawk Creek), and REE-F-Ba (Rock Canyon Creek) deposits in the southern Canadian Rocky Mountains, southeastern British Columbia. In plots of C versus O isotope composition, distinct fields are identified for sparry and saddle dolomites associated with MVT mineralization and their respective host carbonate rocks. The host limestone and dolostone are depleted in ^{18}O relative to the range of values for Cambrian and Devonian marine carbonate rock. This relationship suggests that the dolomite was precipitated from (or interacted with) hydrothermal fluids, as documented for other MVT deposits.

Paradis, Jackson et al. (this volume) present textural and LA-ICP-MS trace-element data for pyrite in selected MVT (Reeves MacDonald, Jersey-Emerald, Jackpot, and Duncan) and FCR Zn-Pb ($\pm\text{Ag}$, $\pm\text{Au}$; Abbott-Wagner) deposits in southeastern British Columbia. They report three types of pyrite in these deposits: Py1 (subhedral, earliest; sedimentary; only in MVT deposits), Py2 (anhedral to subhedral fractured grains and clusters; hydrothermal; in MVT and FCR deposits), and Py3 (euhedral crystals that typically display 120° triple junctions; metamorphic; in MVT and FCR deposits). The metal enrichment suites are Py1: V, Cu, Ge, Ag, Tl, and Pb; Py2: Co, Ni, Mo, Tl, and Pb; and Py3: Co

and Ni. Pyrite 2 (Py2) in the MVT deposits is neither texturally nor compositionally zoned, whereas Py2 in the FCR deposit displays compositional banding. The authors posit that pyrite trace-element compositions in carbonate-hosted Pb-Zn deposits may serve as an indicator of mineralization type.

Simandl et al. (this volume) present LA-ICP-MS and electron probe microanalyses of carbonate minerals in MVT deposits of the Canadian Rocky Mountains (Munroe, Shag, Kicking Horse, Monarch, Coral, and Robb Lake) and Kootenay Arc (Pend Oreille, Reeves MacDonald, Jersey-Emerald, HB, and Duncan), and the Abbott-Wagner FCR deposit. Rare-earth element patterns (Post-Archean Australian shale (PAAS)-normalized) for these carbonates (including recrystallized dolomite and sparry dolomite) are varied: some are nearly flat with a slight positive or negative overall slope; others show light REE depletion (similar to modern seawater but lacking pronounced negative Ce anomalies) or are upward convex (enriched in middle REE). Most patterns, however, do not display the light REE depletion and strongly negative Ce anomalies typical of oxygenated seawater. All calcite and dolomite samples from the Kootenay Arc, with the exception of dolomite samples from the Pend Oreille mine, display strong positive Eu anomalies, suggesting that they precipitated from or interacted with different fluids than the carbonate minerals that formed the Rocky Mountains MVT deposits. At Pend Oreille, dolomites have flat PAAS-normalized REE patterns. The authors attribute the myriad carbonate mineral REE signatures to reflect crystallization and re-equilibration conditions of carbonate minerals with ambient fluids during diagenesis, deep burial, and/or metamorphic recrystallization.

Kontak et al. (this volume) present an integrated petrographic (optical microscopy and cathodoluminescence), mineral-chemical (scanning electron microscopy with energy dispersive spectroscopy; SEM-EDS), fluid-inclusion, and stable (S, O) isotopic study of carbonate and sulfide minerals (sphalerite, pyrite) from selected MVT deposits in the Rocky Mountain fold and thrust belt, Kootenay Arc, and Western Canada Sedimentary Basin. Collectively, the samples studied display extensive carbonate dissolution and replacement, as evidenced by multiple generations of dolomite cements ranging from an early, low-temperature, fine-grained type to coarser, higher temperature varieties that were deposited together with Zn-Pb sulfides; the latest stage calcite occludes any remaining porosity. The dolomite is generally stoichiometric, but mineralization-related varieties are the most Fe rich and can also contain small sphalerite inclusions.

Kontak et al. (this volume) report that fluid inclusions in sphalerite have a wide range of homogenization temperatures (80–215°C), and salinities from 1 to 28 weight per cent equivalent NaCl. The paucity of inclusion data precluded any definitive conclusions regarding a fluid mixing model for the sulfide mineralization. Oxygen isotope compositions of dolomites and calcites ($\delta^{18}\text{O} = 13\text{--}33\text{‰}$) determined by in situ secondary ion mass spectrometry

(SIMS) reflect formation from different fluids (seawater, basinal brine, and meteoric) over a large temperature range via coupled dissolution-precipitation at variable fluid to rock ratios. Sulfur isotope compositions of sphalerite and pyrite ($\delta^{34}\text{S} = 8\text{--}33\text{‰}$), also analyzed by SIMS, indicate derivation of reduced sulfur from thermochemical sulfate reduction (TSR) or mixed TSR and bacterial sulfate reduction (BSR) within a homogeneous reservoir of reduced sulfur.

Paradis, Simandl et al. (this volume) present a synthesis of all the above studies of the MVT, FCR, REE-fluorite-barite, and magnesite deposits. These deposits occur in Paleozoic platform carbonate rocks at different stratigraphic levels, with most hosted in middle Cambrian, upper Cambrian, and Upper Devonian permeable and reactive rock types where the original carbonate has been replaced by fine-grained dolomite (pre-mineralization), followed by stages of coarser dolomite replacement and cavity-fracture filling (e.g. saccharoidal, sparry, and saddle dolomites) accompanied by sulfide (sphalerite, galena, and pyrite) precipitation. First-order controls on deposit emplacement are structurally controlled facies transitions between the shallow-water carbonate platforms and deep-water basinal rocks of the Paleozoic continental margin. These transitions were activated during periods of episodic rifting along the Paleozoic margin during the middle to late Cambrian and late Devonian to middle Carboniferous.

Paradis, Simandl et al. (this volume) present $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio data for MVT and magnesite deposits (0.71076–0.71484) that are similar to, or higher than, host carbonate minerals (0.70964–0.71044). Hydrothermal dolomite from REE-F-Ba deposits (0.70588–0.70873), however, has similar or lower $^{87}\text{Sr}/^{86}\text{Sr}$ isotopes than host carbonate minerals (0.70866–0.70903). The dolomites for each of the deposit types collectively overlap in their $\delta^{18}\text{O}_{\text{VPDB}}$ (–20.0 to –9.8‰) and $\delta^{13}\text{C}_{\text{VPDB}}$ values (–8.6 to +1.1‰), and they are typically lower than their respective host carbonate minerals ($\delta^{18}\text{O}_{\text{VPDB}} = -15.2$ to -7.1‰ ; $\delta^{13}\text{C}_{\text{VPDB}} = -2.9$ to $+1.2\text{‰}$; VPDB = Vienna Pee Dee Belemnite). These stable isotopic compositions, together with the trapping temperatures for fluid inclusions in sphalerite associated with this dolomite in the MVT deposits (102–187°C, and up to 200°C; Kontak et al., this volume) support interaction of relatively high-temperature fluids with siliciclastic host rocks, and precipitation of sulfide minerals. The $\delta^{34}\text{S}_{\text{VCDT}}$ values (VCDT = Vienna-Canyon Diablo Troilite) of sulfide minerals range from –2.7 to +36.7‰ (with most values from +9.9 to +36.7‰); together with the fluid inclusions temperatures, this indicates that TSR was the dominant provider of sulfur, with local BSR.

Paradis, Simandl et al. (this volume) present lead isotope data for select MVT and magnesite deposits. These data fall into several groupings on a lead isotope evolution diagram: 1) MVT deposits clustering between the orogen and upper crust curves; 2) MVT deposits clustering in a zone ranging from the upper crust curve to well above it; and 3) MVT and magnesite deposits with very radiogenic compositions

well above the upper crust curve. The possible relationship of these clusters to deposit age remains to be investigated. Nevertheless, the elongated, positively sloped nature of each of these clusters indicates mixing between more and less radiogenic leads sourced from different reservoirs.

Volcanogenic massive-sulfide deposits

Although the genetic and exploration models for VMS deposits are among the best understood of all mineral deposit types (e.g. Galley et al., 2007), there remain some unresolved questions. Among these is whether magma directly contributed metals and/or other components (in addition to the by-far predominant contributions leached from the modified seawater circulating through the host rocks). Peter et al. (2017c) introduced research activities aimed at answering this question by directly measuring the metal contents (by LA-ICP-MS) of individual fluid inclusions in the feeder zone to the Windy Craggy Cu-Co-Au deposit in northwestern British Columbia. This deposit is one of the largest VMS deposits in the world (>300 000 000 t grading 2.12 weight per cent Cu, 0.083 weight per cent Co, 0.16 g/t Au, and 3.30 g/t Ag (non NI-43-101 compliant); Downing et al., 1991), and the fluid inclusions display an enigmatically high salinity (ranging up to 17 weight per cent NaCl equivalent, with most between 6 and 16; Peter and Scott, 1993); the deposit size and fluid salinity have been hypothesized to result from magmatic input to the mineralizing system.

Schmidt et al. (2018) reported on the method development of LA-ICP-MS analysis of single fluid inclusions, with application to the Windy Craggy Cu-Co VMS deposit, and presented new fluid-inclusion microthermometric and preliminary LA-ICP-MS results. Their microthermometric data are strongly similar to previous data presented in Peter and Scott (1993). Laser-ablation ICP-MS analyses of fluid inclusions for which there are microthermometric data indicate the presence of Na, K, Ca, Cu, Sr, Sn, Sb, Ba, and Pb as well as trace elements of potential magmatic origin, including Au, W, Sn, In, and Bi.

Schmidt et al. (2019) provided additional constraints with a study that focused on further refining the LA-ICP-MS method, together with high-quality bulk geochemical analyses of least-altered and highly altered volcanic and sedimentary host rocks and stringer and massive mineralization. The Ca/Na values in fluid inclusions are greater than that of seawater and similar to values from mafic-dominated seafloor hydrothermal circulation systems. The fluid inclusions have variable metal and metalloid concentrations, with positive correlations between Cu, Mn, Zn, Sb, Sn, and Bi. The fluid-inclusion data show Fe versus Mn and Cu versus Zn trends that are similar to (and overlap) those in the host rocks; however, Sb, Sn, and Bi, elements that are commonly ascribed to magmatic input, show higher concentrations compared to the host rocks. The authors posited that high

concentrations of certain metals strongly point to direct magmatic contributions to the Windy Craggy mineralizing fluids, and do not simply reflect the leaching of metals from the footwall sedimentary and igneous rocks.

Leybourne et al. (this volume) investigate the residence sites of these and other metals in pyrite and chalcopyrite in mineralized rocks from the Windy Craggy deposit to gain further understanding of metal partitioning. The LA-ICP-MS maps of pyrite reveal that the highest abundances of Au, Ga, Sn, V, W, As, Bi, Hg, In, Sb, Se, Te, Tl, Ag, Cd, Co, Mo, and Zn occur within the ‘gold zone’ of the Windy Craggy deposit, a region located at the northwest edge of the south sulfide body, and in the feeder zone to the south sulfide body, one of the three sulfide lenses that compose the deposit. The authors also compare the sulfide LA-ICP-MS data with legacy assay data ($n \approx 3500$) and high-quality, whole-rock data for mineralization and host rocks. They report that Co, Bi, Mo, Te, Au, As, and Sb generally have the highest abundances in sulfide minerals in the massive sulfide, the gold zone, and some stockwork samples, whereas these elements are either below detection or present in very low (<1 ppm) abundances in bulk mafic volcanic and argillite host rocks. The authors conclude that these trends in sulfide chemistry are consistent with their previous fluid-inclusion LA-ICP-MS data (Schmidt et al., 2019) and suggest there was a direct magmatic contribution of some metals to the Windy Craggy deposit, perhaps via magmatic degassing. Alternatively, these metals, which are enriched in the host basalt (relative to mid-ocean ridge basalt), may have been transferred to the mineralizing hydrothermal system by leaching and deposition in the mineralized zone.

New methods and applications to mineral exploration

Testing of several methodological approaches was conducted, resulting in new method development, including rock- and mineral-chemical vectoring, surficial sediment indicator-mineral vectoring, multiparameter 3-D modelling, and refined geophysical imaging of VMS mineralization.

Rock mineral-chemical vectoring

Leighton et al. (2019a) investigated pyrite geochemistry as an exploration vectoring tool toward SEDEX mineralization in the MacMillan Pass district, which hosts the Tom and Jason deposits. Pyrite was sampled in rocks that were time-stratigraphically equivalent to mineralization from three drillholes situated 2 to 4 km to the west of the Tom deposit. Leighton et al. (2019a) identified four pyrite generations, each with distinct morphological characteristics, mineralogical associations, and (para)genetic origins (Py1: framboids, syndimentary; Py2: nodules and layers, diagenetic; Py3: euhedral, inclusion-rich overgrowths, hydrothermal; Py4: idiomorphic, inclusion-free overgrowths, metamorphic).

Laser-ablation ICP-MS analyses of each pyrite generation indicate that Py3 most likely coincided in time with hydrothermal SEDEX mineralization. Unmineralized rocks that are stratigraphically equivalent to SEDEX mineralization are enriched in Zn, Mn, As, and Co, and these elements are generally more abundant in Py3 than in the other generations of pyrite. This metal enrichment suite was detected 2 to 4 km away from known SEDEX mineralization and may serve as a vector toward concealed mineralization elsewhere along the belt. Leighton et al. (2019b) subsequently refined their previous findings and concluded that only Zn was robust at the kilometre scale, and effectively indicated the presence of mineralization up to a lateral (along strike) distance of 2.7 km away from the deposit.

Indicator-mineral vectoring

Heavy-mineral concentrates (HMC) of indicator minerals recovered from till is used to trace concealed bedrock mineralization up ice. This technique is now common practice in glaciated terrains (e.g. McClenaghan, 2005). Indicator-mineral methods typically involve visual inspection of the greater than 250 μm fraction of the HMC, and little is made of the fine (<250 μm) fraction. Loughheed et al. (this volume) report on the use of the fine (<250 μm) fraction of till HMC, facilitated by automated mineralogical methods (mineral liberation analysis; MLA) that have become relatively widespread during the last decade. Automated mineralogy allows for the straightforward collection of mineralogical data from a large number (10 000–100 000) of heavy-mineral grains in a single sample.

Archived GSC till samples from the highly metamorphosed Izok Lake Zn-Cu-Pb-Ag VMS deposit, Nunavut, were analyzed (Loughheed et al., 2020, this volume). Fine-fraction (<250 μm) HMCs recovered from till samples collected down ice of the deposit contain sulfide ore indicator minerals (chalcopyrite, galena, pyrite, sphalerite, and pyrrhotite) and associated hydrothermal alteration minerals (gahnite, corundum, epidote, and iron oxide) typical of metamorphosed VMS deposits. These indicator minerals were detected in till farther down ice in the less than 250 μm fraction than in the coarser (>250 μm) size fraction recovered from the same samples. The fine fraction, therefore, delineates a larger (longer) dispersal train than the coarse fraction, resulting in enhanced deposit detectability. In addition, some indicator minerals were identified in the less than 250 μm HMC fraction that were not recognized in the coarser fraction. Automated mineralogy also identified indicator minerals present as inclusions within other indicator-mineral grains (sulfides, particularly galena) and allowed for quantification of mineral associations from known metamorphic assemblages (e.g. the presence of gahnite/corundum in the feeder zone to the metamorphosed VMS). The workflow developed by this project can be scaled to broader regional surveys to increase the likelihood of detecting indicator-mineral footprint(s) and provide more detailed mineralogical information from till samples.

Deposit geophysical modelling and imaging

Schetselaar et al. (2017) introduced activities aimed at combining physical rock properties and lithogeochemistry (e.g. alteration index and chlorite-carbonate-pyrite index) with 3-D modelling and imaging of hydrothermal fluid paleo-upflow zones and associated hydrothermal alteration at the amphibolite-facies metamorphosed Lalor VMS Au-Ag-Cu-Zn deposit near Snow Lake, Manitoba. This activity progressed research under the TGI program phase 4, which focused on the hydrothermal alteration zones in the deposit footwall rather than the direct detection of mineralization. The guiding precept is that original hydrothermal alteration minerals were converted into different minerals during subsequent high-grade metamorphism, and that the alteration assemblage has lower densities and higher P-wave seismic velocities (obtained from wireline logs) than the precursor minerals.

Under the auspices of TGI-5, Schetselaar et al. (2018) continued this work at the Lalor mine, which aimed at visualizing the mineralization and paleofluid pathways by integrating modelling of physical rock properties, lithogeochemistry, and 3-D seismic data. Multivariate regression of P-wave velocity and density on lithogeochemical proxies for protolith composition, mineralization, and hydrothermal alteration suggests that footwall hydrothermal alteration enhanced the acoustic impedance contrast between mafic to felsic volcanic units; however, volcanic rock compositions (mafic, intermediate, and felsic) remain the predominant controlling factor on the seismic response. Schetselaar et al. (2018) also presented seismic forward-modelling experiments that showed enhanced seismic reflectivity in the intensely altered footwall when alteration proxies were included in the 3-D seismic rock property models. Finally, initial, unconstrained 3-D magnetotelluric (MT) inversions show a conductive zone between 600 to 800 m depth corresponding to the Lalor deposit, as well as a highly conductive zone between 500 to 1500 m depth, approximately 0.5 to 1.2 km to the southwest of the deposit.

Schetselaar et al. (this volume) is a synopsis of Schetselaar et al. (2019) and both of these studies build on the abovementioned works by integrating not only seismic rock properties and lithogeochemical data, but also SEM-EDS mineral-chemical compositional data, to provide further insights into the effects of hydrothermal alteration on the seismic reflectivity responses in the footwall of the Lalor mine. Hydrothermal alteration effects produce lesser variations in acoustic impedance contrast than does rock type (felsic versus mafic volcanic rocks), which remains the primary control on acoustic impedance variations. As previously shown, there is an increase in P-wave velocity with increasing intensity of hydrothermal alteration. Mixture modelling of the seismic rock properties and mineral abundances shows that the increase in seismic velocity is due to an increase in abundance of cordierite, which is one of the diagnostic aluminosilicates for hydrothermally altered

volcanic rocks metamorphosed in the upper almandine amphibolite facies. Finally, Schetselaar et al. (this volume) considered synthetic seismic data for a simple VMS model consisting of mafic-felsic host rock contacts, a sulfide ore lens, and a discordant feeder zone, all metamorphosed to amphibolite facies. This model shows enhanced seismic reflections at feeder zone–host rock contacts, compared to the same model at lower grade metamorphism (greenschist facies); therefore, there is a greater likelihood of seismically detecting vent-proximal hydrothermal alteration zones in stratigraphic footwall rocks in high-grade metamorphic terrains than in settings with a lower metamorphic grade.

Unconstrained MT inversions commonly produce insufficient inherent resolution to image structurally thinned mineralization. To improve the resolution in such environments, Ansari et al. (2019) presented methodology to more accurately forward model and invert MT data using the Lalor mine as a case study. This work included the development of model construction routines for realistic subsurface structures, forward modelling, and MT inversion strategies. Using a combination of tools, a routine was developed that produced a sealed model using tessellated geological surfaces to represent lithostratigraphic contacts between rock units. This model is suitable for generating volumetric tetrahedral meshes required for mesh-based modelling and inversion of geophysical data. Ansari et al. (2019) also developed a finite-element–based forward-modelling technique that discretizes the MT problem on unstructured tetrahedral meshes. These meshes can be used to produce realistic complex-shaped features. The calculated MT responses for the Lalor mine model generated a space minimum-structure inversion based on the iterative Gaussian-Newtonian approach. This approach used sensitivity matrix-vector products calculated implicitly by finite-element–based forward and pseudo-forward solutions.

Ansari et al. (this volume) is a synopsis of Ansari et al. (2020). Both of these studies build on the above-mentioned work, resulting in the synthesis of 3-D MT responses for geologically realistic models using a finite-element–based forward-modelling tool with unstructured meshes and application to the Lalor mine. This new tool is based on mapping interpolated or simulated resistivity values from wireline logs onto unstructured tetrahedral meshes to reflect the complexity of the host rock geological structure with the aid of 3-D models obtained from drill logs. A sealed, unstructured tetrahedral mesh was generated by compartmentalizing the host rock envelope of the deposit into major lithostratigraphic units, including massive-sulfide ore zones. Each of the nodes in these compartments was attributed with its mean resistivity value, providing a regional 3-D resistivity background model of the deposit. A more detailed model was generated in a subvolume with dense drillhole constraints around the deposit by categorical kriging of the dominant lithofacies, followed by sequential Gaussian simulation of the resistivity wireline log data in each lithofacies class. The resulting stochastic model provides a more realistic representation of

the heterogeneous spatial distribution of the electric resistivity values around the massive, stringer, and disseminated sulfide ore zones. Both models were combined into one seamless tetrahedral mesh of the resistivity field. To capture the complex resistivity distribution in the geophysical forward model, a finite-element code was developed that solves the electromagnetic diffusion equation that was discretized using unstructured meshes. Comparative analyses of the forward models with surface MT data are in reasonable agreement and explain the regional variations associated with geological structure and detect the local anomalies associated with the MT response of the ore zones.

CONCLUDING REMARKS

Noteworthy accomplishments of the TGI-5 volcanic- and sedimentary-hosted base-metal sulfide deposit research activities are

- development of a robust, internally consistent genetic model for HEBS in the northern Canadian Cordillera;
- characterization of HEBS mineralization in the southern extremities of the Selwyn Basin, confirming the widespread nature of this style of mineralization;
- demonstration that metal isotopes in SEDEX deposits are an effective fingerprint of mineralization (Tl) and redox indicators (Tl and Mo);
- establishment of pyrite trace-element; carbonate-REE; fluid-inclusion; and C, O, Sr, and Pb isotope characteristics for carbonate-hosted MVT, magnesite, and REE-F-Ba deposits in the southeastern British Columbia in host rocks ranging in age from middle to late Cambrian and late Devonian to middle Carboniferous;
- evidence, based on LA-ICP-MS analyses of single primary fluid inclusions from the feeder zone of the Windy Craggy VMS deposit, British Columbia, together with LA-ICP-MS analyses of sulfide minerals, that some elements commonly ascribed to magmatic input (e.g. Au, Bi, Co, Mo, Sb, Sn, and Te) were/are present in the mineralizing fluids and/or sulfide minerals, suggesting that there was a direct magmatic contribution of some metals to the deposit, in addition to a leached source for some metals;
- evidence that LA-ICP-MS analyses Zn in pyrite in time-stratigraphically equivalent rocks to SEDEX deposits of the MacMillan Pass district, Selwyn Basin, Yukon, can be used to vector toward mineralization at the kilometre scale;
- development of new methodology using automated mineralogical methods to analyze the (typically unused) fine (<250 µm) HMC fraction of till, using the metamorphosed Izok Lake VMS deposit, Nunavut, as a test site;

- visualization of the mineralization and paleofluid pathways in the footwall at the Lalor VMS mine, Manitoba, using integrated analysis of multidisciplinary data sets (3-D modelling of rock types, lithogeochemical, mineralogical, rock properties, seismic, and magnetotelluric); and
- development of more realistic images of narrow and structurally dismembered sulfide mineralization at the Lalor VMS mine, Manitoba, using 3-D forward modelling and inversion of magnetotelluric data using unstructured meshes, together with rock type, and resistivity values from wireline logs.

The research contributions presented in this volume underpin future efforts to gain deeper insight into the processes responsible for, and the detection of, concealed volcanic- and sediment-hosted base-metal sulfide deposits. Through progressive research, it is clear that many critical and strategic metals are hosted in these types of deposits as trace to minor byproducts (e.g. In, Ga, Sb, Bi, Co, and Te in VMS and Ge in MVT); however, our current understanding of the controls on the origin and enrichment of these elements is inadequate. Future research efforts must focus on understanding the geological, geochemical, and geophysical criteria that control the enrichment (or depletion) of critical and strategic metals. By doing so, exploration methods and methodologies may be developed for the most effective detection of volcanic- and sediment-hosted base-metal sulfide deposits that contain these elements.

New technology will be central to future discoveries of critical and strategic metal-bearing volcanic- and sediment-hosted base-metal deposits. Certain types of deposits (e.g. VMS) can be detected by remotely sensing their spatially associated hydrothermal alteration zones. Exploration by remote sensing may be bolstered by recent technological innovations, particularly with hyperspectral (e.g. shortwave infrared, longwave infrared) sensors mounted on various platforms (fixed-wing aircraft, drones, satellites, and micro-satellites). Metaltectics that are poorly vegetated (e.g. vast regions of northern Canada) are most amenable to remote sensing and warrant further exploration efforts. Because traditional mineral exploration generally requires ‘boots on the ground’, an added benefit of mineral exploration by remote sensing is minimizing disruption and damage to fragile northern ecosystems. These new methods remain untested in Canada’s North, making it an ideal laboratory to test and develop new remote sensing technologies.

Finally, one of the most impactful and enduring contributions of this research program is the training of a new cadre of highly qualified personnel in the form of numerous undergraduate and graduate students. These individuals are vital to the continued and future success of the Canadian minerals industry. Student contributions to the volcanic- and sediment-hosted base-metals ore system are the following

publications: Schmidt et al. (2018, 2019), Crawford et al. (2019), Henderson et al. (2019), Leighton et al. (2019a, b), and Loughheed et al. (2020, this volume).

ACKNOWLEDGMENTS

This research would not have been possible without the strong contributions of our partners and affiliates in other provincial and territorial government institutions, universities, and industry. We thank those who contributed, including management, geologists, professors, students, and support staff. We thank Neil Rogers and Eric Potter for reviews of this contribution. Collective thanks are due to the following who acted as reviewers for the other papers in this volume: Melissa Anderson, Stuart Averill, Guoxiang Chi, Mercè Corbella, Poul Emsbo, Daniel Gregory, John Jamieson, Sean Johnson, Pavel Kabanov, Daniel Kontak, Bernd Milkereit, Suzanne Paradis, Joe Petrus, Jean-Luc Pilote, Alain Plouffe, Eric Potter, Neil Rogers, David Snyder, Stephan Thiel, and Don White. Editorial handling of manuscripts was done by Jan Peter and Michael Gadd. Technical editing and layout were performed admirably by Nicole Barlow and Moretta Shuert of Purple Rock Inc., Victoria, British Columbia, and GSC Scientific Publishing Services.

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