TGI-4 Sediment-hosted Zn-Pb Deposits: Research Highlights

S. Paradis
Geological Survey of Canada, 9860 West Saanich Road, Sidney, BC, V8L 4B2
Suzanne.paradis@NRcan-RNcan.gc.ca

Introduction

The genetic model for SEDimentary EXhalative (SEDEX) deposits, on which most modern exploration strategies for this deposit type, was formulated more than 30 years ago. New data collected during the Targeted Geoscience Initiative 4 (TGI-4) program, a five-year (2010-2015) collaborative federal geoscience program, indicates that significant changes to several concepts behind the genetic model need to be made. This should lead to more realistic and efficient exploration strategies and exploration techniques. In doing so, we achieves the goal of the TGI-4 program, which was to provide the mining and exploration industry with new geoscience knowledge and innovative techniques to target buried deposits more effectively.

The term "SEDEX" has a genetic connotation, implying that the sulphide deposit formed on the sea floor from exhaled ore fluids. For lack of better terminology, the term is used in this open file despite the evidence generated by the project (e.g. Magnall et al., 2015; Gadd et al., 2015) that subsurface deposition and replacement is a major process in the formation of SEDEX deposits, at least those of the MacMillan Pass and Howard's Pass districts.

Objectives

The main objectives of the "TGI-4 SEDEX" project" were to:

- characterize the physico-geochemical processes of the hydrothermal system related to sediment-hosted Zn-Pb deposits,
- identify new mineralogical, geochemical, and isotopic tools to vector to ore deposits,
- understand the processes that control surficial geochemical dispersion of metals around sediment-hosted Zn-Pb deposits, and
- develop new methods for regional-scale 3D geological extrapolation in sedimentary basins.

Research Activities

Most field work for research activities was carried out on three major sedimentary basins of western Canada, listed below (Figure 1 and Table 1).

- Mesoproterozoic Purcell Basin in southeastern British Columbia, which hosts the world-class Sullivan Pb-Zn-Ag deposit and other smaller deposits such as North Star and Kootenay King.
- Phanerozoic Selwyn Basin, containing the Howard's Pass and MacMillan Pass districts in Yukon, and the Prairie Creek district and Misty Creek Embayment in the Northwest Territories.

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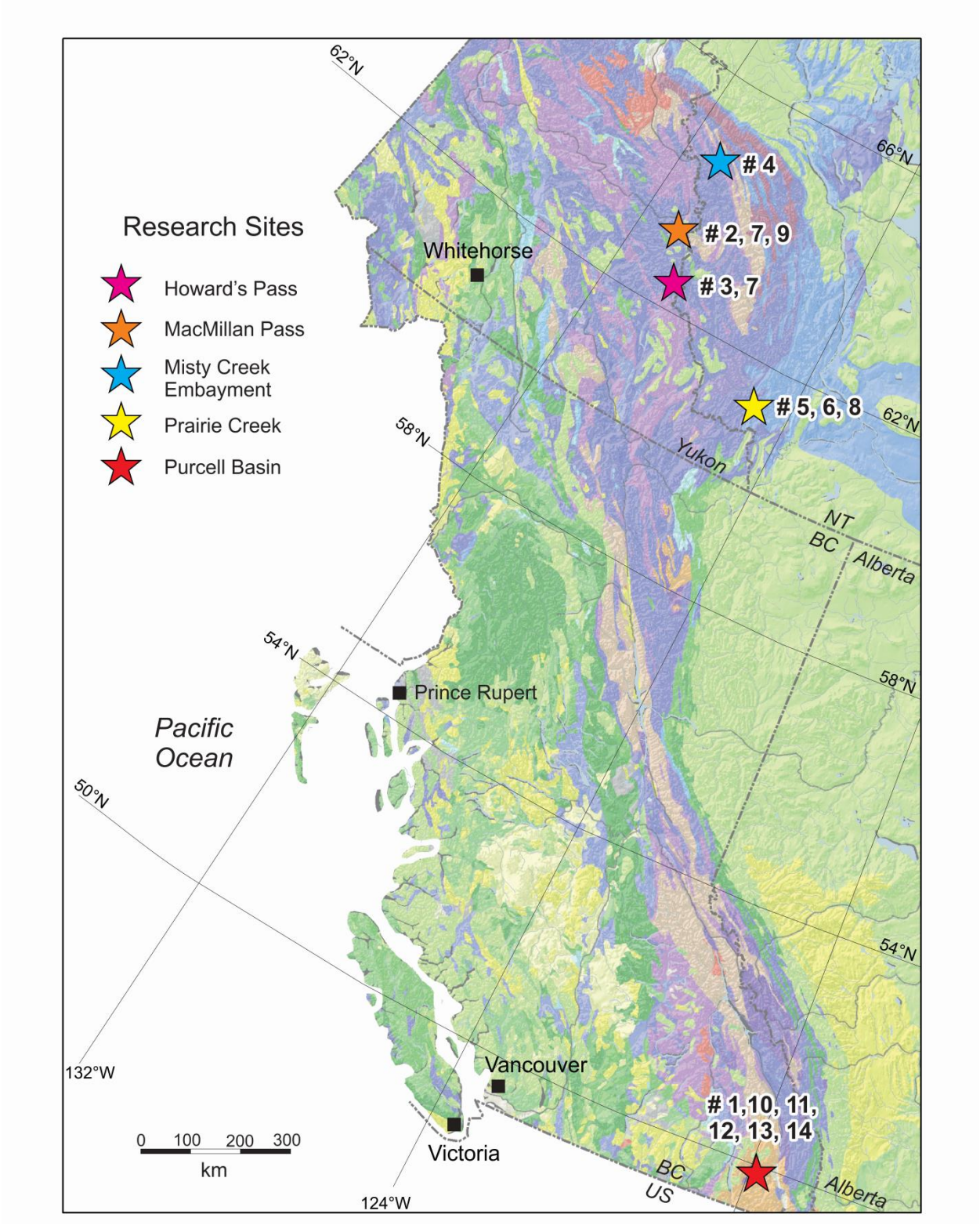

Figure 1. Location of research activities (corresponding to paper # in the open file) within the Purcell Basin and the Howard's Pass, MacMillan Pass, Misty Creek Embayment, and Prairie Creek districts of the Selwyn Basin. Refer to Table 1 for the list of papers (activities).

Table 1. List of papers presented in the open file. The papers are organized according to the four themes that follow the objectives of the "TGI-4 SEDEX" project. Location of research activities is shown in Fig. 1.

Physico-geochemical characteristics of the hydrothermal system of sediment-hosted Zn-Pb deposits

Paper # 1: Lydon, J.W. The leachability of metals from sedimentary rocks.

Paper # 2: Magnall, J.M., Stern, R.A., Gleeson, S.A, and Paradis, S. Widespread euxinic conditions are not a prerequisite for sediment-hosted base metal (Pb-Zn-Ba) mineralization at Macmillan Pass, Yukon.

Paper # 3: Gadd M.G., Layton-Matthews, D., Peter, J.M., and Paradis, S. In situ trace element and sulphur isotope analyses of pyrite constrain timing of mineralization and sources of sulphur in the Howard's Pass SEDEX Zn-Pb District, Yukon.

Mineralogical, geochemical, and isotopic tools to vector to sediment-hosted Zn-Pb deposits

Paper #4: Turner, E.C. Base-metal enrichment in Stage-5 (mid-Cambrian) black shale of the Hess River Formation, Misty Creek Embayment, Selwyn Basin.

Paper #5: Taylor, B.E., Paradis, S., Falck, H., and Wing, B. In situ sulphur isotope study of the Prairie. Creek deposit, Southern Mackenzie Mountains, Northwest Territories: Deciphering the conundrum of three deposit styles in one.

Paper #6: Paradis, S. Sulphides and nonsulphides of the Prairie Creek district; update on the isotope geochemistry.

Paper #7: Peter J.M., Layton-Matthews, D., Gadd, M.G., Gill, S., Baker, S., Plett, S., and Paradis, S. Application of visible-near infrared and short wave infrared spectroscopy to sediment-hosted Zn-Pb deposit exploration in the Selwyn Basin, Yukon.

Processes controlling the surficial geochemical dispersion of metals around sediment-hosted Zn-Pb deposits

Paper #8: Stavinga, D.B, Jamieson, H., Paradis, S., and Falck, H. Geochemical and mineralogical controls on metal(loid) mobility in the Oxide Zone at Prairie Creek, Northwest Territories.

Paper #9: Bryson, S.E., Fortin, D., McCurdy, M.W., and Nyheim-Rivet, A. Geochemical signatures of the South MacMillan River in the MacMillan Pass, Yukon, including drainages from the Tom and Jason Pb-Zn deposits.

Regional-scale 3D geological modelling of the Purcell Basin, southern British Columbia

Paper #10: de Kemp, E.A., Schetselaar, E.M., Hillier, M.J., Lydon, J.W., Ransom, P.W., Montsion, R. and Joseph, J. 3D geological modelling of the Sullivan time horizon, Purcell Anticlinorium and Sullivan Mine, East Kootenay region, southeastern British Columbia.

Paper #11: Schetselaar, E.M., de Kemp, E.A., Ransom, P.W., Buenviaje, R., Nguyen, K., Montsion R. and Joseph, J. Drillhole database compilation from legacy archives in support of 3D geological modelling and mineral exploration in the Purcell Anticlinorium, British Columbia.

Paper #12: Montsion, R., de Kemp, E.A., Lydon, J.W., Ransom, P.W., and Joseph, J. 3D stratigraphic, structural and metal zonation modelling of the Sullivan Mine, Kimberley, British Columbia.

Paper # 13: Hillier, M.J., de Kemp, E.A., and Schetselaar, E.M. Implicit 3D modelling of geological surfaces with the generalized radial basis functions (GRBF) algorithm.

Paper #14: Thomas, M.D. Magnetic modelling insights into the third dimension of the Purcell Anticlinorium.

- Western Canada Sedimentary Basin of Saskatchewan, Alberta and British Columbia, which hosts metalliferous brines.

Other research activities were not area specific, and included a spectrum of activities ranging from innovative laboratory techniques to devising new mathematical algorithms for 3-D geological modelling.

Physico-geochemical processes of the hydrothermal system related to sediment-hosted Zn-Pb deposits

Most models explaining the origin of SEDEX deposits envisage that metals were derived from the basinal sediments hosting the deposits (Lydon et al., 2000; Goodfellow and Lydon, 2007; Emsbo, 2009; Wilkinson, 2014). As part of this project, Lydon (2015) tested the leachability of metals and other elements on outcrop and core samples of marine sedimentary rocks at different stages of burial metamorphism. The samples were collected along a transect across western Canada, stretching from Mesozoic rocks of the Western Canada Sedimentary Basin in Saskatchewan, via Paleozoic and Mesoproterozoic rocks of eastern British Columbia, to modern ocean sediments west of Vancouver Island. His findings indicate that nearly all the Zn, Pb, and Cu in fine-grained sedimentary rocks are contained within the structure of the rock-forming minerals, and not loosely adsorbed on to the surfaces of clays, iron or manganese oxides, or organic matter, as has been widely assumed in the scientific literature on the generation of ore fluids. Considering the low reactive capacity of pore fluids at the natural low water/rock ratios of sedimentary rocks, his results indicate that ore fluids containing >1 ppm metal can only be produced during leaching windows provided by metamorphic mineralogical transformations that are driven by increasing temperature and pressure during burial.

Historically, global euxinic conditions have been considered a pre-requisite for the formation of the SEDEX deposits of the Howard's Pass and Macmillan Pass districts in the Selwyn Basin (Goodfellow and Jonasson, 1984; Goodfellow, 1987, 2004, 2007). This view considered the metal trap to be reduced sulphur in the marine water column produced by near-quantitative bacterial reduction of seawater sulphate. Research of Magnall et al. (2015) indicates that at MacMillan Pass, precipitation of base metal sulphides was mostly below the sediment water interface rather than from a stratified euxinic water column. The mineral paragenesis of the MacMillan Pass deposits shows that barite and two generations of pyrite formed during early diagenesis, pre-dating the hydrothermal sulphides (pyrite, sphalerite and galena), which replace the diagenetic barite-pyrite assemblage. This suggests that one potential sulphur source would be the recycling of barite-sulphur by the hydrothermal fluid. At Howard's Pass, the research of Gadd et al. (2015) is based on detailed field and petrographic observations and LA-ICP-MS (laser ablation-inductively coupled plasma-mass spectrometry) and SIMS (secondary ion mass spectrometry) geochemical analyses. Their data shows that mineral paragenesis is complex and involves several generations of pyrite (synsedimentary to early diagenetic, diagenetic and metamorphic). The variation of minor and trace elements of pyrite mimics the textural characteristics of the grains. The

base metal sulphides post-date the formation of the synsedimentary-early diagenetic pyrite and therefore interpreted to be of diagenetic origin, similar to the MacMillan Pass deposits (Magnall et al., 2015). In situ sulphur isotope microanalyses done on galena, and several generations of pyrite revealed distinct negative and positive values that reflect the contribution of bacterially reduced (negative) and thermochemically reduced (positive) seawater sulphate. Importantly, the earliest pyrite generation yields negative sulphur isotope values, whereas the later diagenetic pyrite and galena yields positive ones in mineralized strata. The model for the Howard's Pass deposits invoked by Gadd et al. (2015) calls for dense, bottom-hugging metalliferous brines that were exhaled in pulses from a submarine vent distal to the present location of the deposit. The hydrothermal pulses were related to the reactivation of growth faults. The brines migrated to, and eventually settled into, a bathymetric low (i.e. the Howard's Pass sub-basin), and percolated downwards through, unconsolidated sulphidic carbonaceous muds and precipitated metals.

Mineralogical, geochemical, and isotopic tools to vector to ore deposits

Deep-water turbiditic limestone of the Cambrian Hess River Formation in the Misty Creek Embayment (MCE) of the Selwyn Basin contains a >20 m-thick black shale interval with elevated base metal and barium content which constitute geochemical evidence of hydrothermal venting (Turner, 2015). Carbon isotope stratigraphy of the formation indicates that the black shale interval was deposited in mid-Cambrian. This depositional age may be identical to that of strata hosting SEDEX mineralization in the Anvil District, Yukon Territory (YT). The MCE is remote and has received very little exploration attention, but its litho- and chemostratigraphic characteristics suggest potential for SEDEX mineralization.

The Prairie Creek district, located in another embayment of the Selwyn Basin, hosts three styles of sediment-hosted Zn-Pb-Ag mineralization: classic (open-space filling) Mississippi Valley-type (MVT), stratabound replacement sulphides, and quartz-carbonate-sulphide veins (Taylor et al., 2015; Paradis, 2015). Preliminary in situ sulphur isotope analyses reveal similarity in $\delta^{34}S$ between the stratabound [18.4 to 26.8‰ (avg. 22‰)] and vein [19.6 to 21.7‰ (avg. 20.3‰)] sulphides, suggesting a connection between the two (Taylor et al., 2015). However, the MVT sulphides have lower $\delta^{34}S$ values [12.9 to 17.1‰ (avg. 15.2‰)], and are therefore not connected (in terms of sulphur source) to the stratabound replacement sulphides. The principal stratabound sulphide lens (SD1) records a variation in calculated isotopic temperatures, from ~250°C near the centre of the lens and close to the vein system, and cooler values of ~150°C towards the margins of the sulphide lens. This suggests that thermal gradients can be potentially used to vector towards centers of mineralizing systems, which would increase the efficiency of deposit scale mineral exploration.

Another way to vector towards base metal mineralization was demonstrated by Peter et al. (2015) using the visible-near infrared and short wave infrared spectroscopy (VNIR-SWIR) on sediments of the Howard's Pass and MacMillan Pass districts. In the Howard's Pass District, the Active member of the Duo Lake Formation, hosting the Zn-Pb mineralization, is spectrally weak to unresponsive, except in and adjacent to

significant mineralization. The spectra of sediments spatially associated with the base metal sulphide mineralization include siderite, montmorillonite, and phengite, and are also characterized by high mean spectral reflectances. A similar pattern occurs in the MacMillan Pass District, where siderite, muscovite, phengite and montmorillonite are spectrally identified within the feeder zone of the Tom Pb-Zn-Ba deposit. At the base of the stratiform mineralization overlying the feeder zone, there is a 5m-wide interval of siderite-montmorillonite that has high reflectance values, but the immediate hangingwall and footwall rocks to mineralization do not have a spectral expression.

Processes controlling the surficial geochemical dispersion of metals around sediment-hosted Zn-Pb deposits

The third part of this open file documents the surficial geochemical dispersion of Zn, Pb, and Ag (±Cu, ±As, ±Sb, ±Cd, ±Se, ±Hg) around sediment-hosted Zn-Pb deposits of the Prairie Creek (Stavinga et al., 2015) and Macmillan Pass (Bryson et al., 2015) districts. Mobility of these elements in near surface environments is important from an economic and environmental point of view. At Prairie Creek, the oxidized upper portion of the quartz-carbonate-sulphide veins forms high grade zones rich in smithsonite ($ZnCO_3$), cerussite ($PbCO_3$), and other secondary metal carbonates, arsenates, and sulphides (Paradis, 2015; Stavinga et al., 2015). These secondary minerals represent a significant resource and also a potential component of future mine waste material. In the short term, the near-neutral pH conditions of the mine waste dumps, trace metal(loid)s will be retained in solids. In the long term, oxidation and dissolution of the secondary metal carbonates, arsenates, and sulphides will affect the eH and pH in the mine waste setting, which could significantly increase metal release in the environment.

At Macmillan Pass, the geochemical signatures of stream waters of a system draining the Tom and Jason Zn-Pb deposits and the surrounding barren shales of the Devonian Earn Group vary widely in dissolved metal concentrations and pH values (2.9 to 8.2) (Bryson et al., 2015). Streams draining the Tom and Jason deposits are acidic (pH = 3.0) and neutral, respectively. The Tom deposit drainage contains 14,575 ppb dissolved Zn, and 33.6 ppb dissolved Pb. The fine sediment fraction of the drainage system contains 549.4 ppm Zn and 483.1 ppm Pb, which means that the presence of the mineral deposits would be easily recognized during an exploration geochemical program. Neutral streams (pH = 7.7) draining the Jason deposit have overall lower metal concentrations, but do show elevated zinc (470 ppm) and lead (53 ppm) in the fine sediment fraction downstream from the deposit.

Regional-scale 3D geological modelling of the Purcell Basin

Regional-scale 3D modelling enhances our geological understanding of the subsurface to explore for mineral deposits occurring at depth. The challenge is to extrapolate information available in densely drilled mine sites to regional 3D models where subsurface data is sparse. A series of papers (de Kemp et al., 2015; Hillier et al., 2015; Montsion et al., 2015; Schetselaar et al., 2015) present innovative methods used for regional-scale 3D geological modelling of the Purcell Anticlinorium in BC, which host the world-class Sullivan Pb-Zn-Ag deposit. To achieve a regional-scale 3D model, integration of geological map, drillhole and geophysical data (Thomas, 2015) was

leveraged in a 3D environment to support interpretation of the entire ore system, thereby increasing the potential for deep discovery.

Implications for Exploration

Mineral exploration is guided by deposit models, and therefore providing the industry with accurate and up-to-date genetic models is essential for the industry to formulate the most efficient exploration programs targeting these deposits across Canada. Key factors identified during the course of the project and described in this open file which have potential application to improve the success rate of the search for new deposits include:

Genetic implications - Physico-geochemical processes of the hydrothermal system:

- Maximum leaching of metals, notably Zn and Pb by chloride brines in SEDEX/MVT systems is restricted to the 90-130ºC smectite-illite thermal transition window of burial diagenesis (Lydon, 2015).
- SEDEX/MVT ore systems can develop only in sedimentary basins with a prior history of evaporitic conditions that existed within the basin or adjacent carbonate platform (Lydon, 2015).
- Regional euxinic condition in the Selwyn Basin is not a prerequisite for the formation of SEDEX deposits (Magnall et al., 2015).
- Howard's Pass and MacMillan Pass sulphide deposits are diagenetic, and not syngenetic as previously suggested, and the bulk of sulphides (± barite) formed subseafloor (Gadd et al., 2015; Magnall et al., 2015). Therefore exploration for SEDEX deposits in Howard's Pass and MacMillan Pass districts should not be limited to specific stratigraphic units.

Mineralogical, geochemical, and isotopic tools to vector to ore:

- Detailed petrographic and geochemical examinations of sulphide minerals can yield valuable information about the hydrothermal processes involved in sediment-hosted Zn-Pb formation (Gadd et al., 2015; Magnall et al., 2015). For example, several generations of pyrite can be recognized; and sulphur isotopes and minor and trace elements mimic the zonation within pyrite grains. Ore-stage diagenetic pyrite that are texturally sooty (i.e. inclusion-rich) and composed of fine-grained aggregates, and bedded (laminated) and nodular pyrite sequestered several trace elements (e.g. Tl, As, Sb and possibly Mn) that can be indicative of hydrothermal input. Recrystallized metamorphic pyrite is usually poor in these trace elements.
- Carbon isotope stratigraphy can be a powerful tool to decipher the tectonic, stratigraphic, and metallogenic history of sedimentary basins, especially in correlating monotonous deep-water successions with sparse biostratigraphic control, or recognizing subtle differences between formations, and diachronous changes in sedimentation regimes. Using this tool within the deep-water lower Paleozoic strata of the Misty Creek Embayment in the northern Mackenzie Mountains (NT) allows establishment of a stratigraphic framework for the basin's evolution, including sediment accumulation rates and the recognition of periods

of sediment starvation and black shale deposition intervals (Turner, 2015). A black shale interval identified is possibly of the same age as the host rocks of the SEDEX Anvil District.

- In situ sulphur isotope analyses on the micrometer-scale can be used to document isotopic variation of minerals within their textural context. At Prairie Creek, Taylor et al. (2015) observed that isotopic disequilibrium is common within the three ore styles of the district: Mississippi Valley-type (MVT), stratabound replacement sulphides (SRS), and quartz-carbonate-sulphide veins. The preliminary in situ sulphur isotope analyses indicate both connections and disconnections between the three styles of mineralization (e.g. SRS and vein sulphides are related but SRS and MVT sulphides are not related in terms of sulphur sources). The in situ sulphur isotope analyses also suggest temperatures of formation (~170-250ºC for SRS) and recognize isotopic gradients within the main SRS lens that could indicate paleo-hydrothermal flow.
- Zinc or lead oxides, silicates and carbonates are direct indicators for nonsulphide base metal deposits and indirect indicator minerals of MVT, SEDEX, Irish-type, and vein-type Zn-Pb deposits (Paradis, 2015).
- Portable analytical tools, such as the VNIR-SWIR (short wavelength infrared spectrometer) can be of some use in the exploration for sediment-hosted Zn-Pb deposits in the Howard's Pass and MacMillan Pass districts of the Selwyn Basin (Peter et al., 2015). Siderite, muscovite, phengite, and montmorillonite are spatially associated with sulphide (± barite) mineralization and can be spectrally recognized, though the response may be quite muted.

Surficial geochemical dispersion of metals:

- Detailed microanalytical techniques [e.g. ICP-OES, SEM, EMP, LA-ICP-MS, XRD, synchrotron based trace element mapping, synchrotron-based grain-scale micro-X-ray Diffraction (μXRD), micro-X-ray Fluorescence (μXRF), and SEM-based MLA] can reveal the presence of valuable (e.g. Ag) or deleterious (e.g. Hg) elements in carbonate-hosted sulphide and nonsulphide minerals (Stavinga et al., 2015).
- Sediment and water samples from the South MacMillan River and streams from the Tom and Jason Pb-Zn-Ba deposits in the MacMillan Pass District, Yukon, are anomalous in ore-forming and ore-associated elements (Bryson et al., 2015). The Tom deposit stream waters are acidic and high in dissolved Pb and Zn, and the fine fraction of the stream silt sediments are high in Pb, signatures that can be readily detected by routine geochemical techniques. On the other hand, neutral pH streams draining the Jason deposit have low to moderate dissolved Pb and Zn; and high Pb concentrations in fine sediments. The water pH values should be taken into consideration in studies of metal dispersion, this would assure that careful analysis of drainage systems with low to moderate Pb and Zn values are investigated.

Regional-scale 3D geological modelling:

- Methods developed for 3D regional- and local-scale geological modelling of the Purcell Basin (de Kemp et al., 2015; Schetselaar et al., 2015; Hillier et al., 2015)

and Sullivan Mine (Montsion et al., 2015) allow an objective assessment of basin architecture for distal indications of SEDEX deposits (e.g. synsedimentary faults, sub-basins, cryptic geophysical response, geochemical dispersal patterns, etc.).

- Magnetic anomalies are modelled to provide new and deep perspectives on individual structures (e.g. northwestern flank of the Moyie anticline, Moyie Fault, Moyie sills, St. Mary Fault, Iron Range Fault) within the Purcell Basin (Thomas, 2015). They also provided insights into the 3D modelling of the basin.

Future Work

The papers in this open file represent preliminary results, and will be superseded by more detailed documents in the form of refereed journal publications and student theses. Even at this early stage, it is apparent that significant research milestones were reached as to the knowledge of sediment-hosted Zn-Pb deposits, and the identification of new vectoring tools to point to mineralized domains within sedimentary basins. Although early results are impressive, many knowledge gaps remain in our understanding of these deposits. Thus, there is a need for new "SEDEX" geoscience studies in Canada as existing and future exploration, mining, and land-use challenges arise.

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