Geochemical analyses of SEDEX deposits in eastern British Columbia

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Front cover:
Hand sample of folded massive sulphide layers (sphalerite, galena, and pyhrrotite) from the past-producing Sullivan mine, Kimberley, British Columbia.

Back cover:
Thin section reflected light photomicrograph of folded beds of sphalerite (shades of brown) and silicate and carbonate minerals (grey/white) with an axial planar foliation that accentuates syndepositional deformation features. Sample is from the Cirque sedimentary exhalative (SEDEX) project, northeastern British Columbia.

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Abstract
Sedimentary exhalative (SEDEX) deposits with primary commodities Pb, Zn, and Ag commonly contain recoverable concentrations of companion metals (e.g., Bi, Cd, Ga, Ge, In, Sb, Sn, Te). These companion metals, which could be recovered as by-products, are on the critical mineral lists of many political jurisdictions. Although SEDEX deposits near the western margin of Ancestral North America have long been recognized, the amount and distribution of companion metals in these deposits remains unclear. This contribution provides bulk-rock geochemical data for 40 mineralized samples retrieved from the British Columbia Geological Survey rock archive from SEDEX and related deposits and mineral occurrences in Belt-Purcell basin, south Kootenay arc, Monashee-Shuswap region, Germansen Landing area, and the Kechika trough. Samples from all regions are strongly enriched (>100x the average concentration of upper continental crust) in Cd, Sb, and Te. Massive sulphide samples from past-producing deposits in Belt-Purcell basin, including the Sullivan mine, are strongly enriched in In (up to 113 ppm) and moderately enriched (10-100x average upper continental crust) in Sn and Bi. Samples from the Cottonbelt occurrence in the Monashee-Shuswap region are weakly to moderately enriched in In (up to 6 ppm). Stratiform laminated sulphide-barite samples from the Cirque project in the Kechika trough are weakly (<10x average upper continental crust) to moderately enriched in Ge and sporadically moderately enriched in In (up to 3 ppm). Samples from the Reeves MacDonald deposit in south Kootenay arc and mineral occurrences in the Germansen Landing area are moderately enriched in Ge (up to 35 ppm).

Keywords:SEDEX, critical metals, critical minerals, companion metals, Sullivan, Kootenay King, Cirque, Akie, Reeves MacDonald, Cottonbelt, Ruddock Creek

1. Introduction

Primary commodities Pb, Zn, and Ag are commonly mined from sedimentary exhalative (SEDEX) deposits found in deep-water siliciclastic successions and from deposits related to shallow-water carbonate shelf successions including Irish, Broken Hill, and Mississippi Valley types. These deposits may also contain many minor 'companion metals' (Mudd et al., 2014, 2017; Nassar et al., 2015) that are on the critical minerals lists of different political jurisdictions (e.g., Hickin et al., 2024), including the 2024 iteration of the Canadian list (NRCan, 2024). These critical companion metals (e.g., Bi, Cd, Ga, Ge, In, Sb, Sn, Te) could conceivably be recovered as by-products of primary commodity mining (e.g., IGF, 2023).

Studies of critical companion metals in SEDEX and related deposits in the province have been limited (e.g., Owens, 2000; Slack et al., 2020) and thus their distribution remain largely unknown. Autochthonous and parautochthonous domains of Ancestral North America in the eastern part of the province include several areas with SEDEX-related mineralization including: 1) the Belt-Purcell basin; 2) the Kootenay arc; 3) the Monashee-Shuswap region; 4) Germansen Landing and 5) the Kechika trough (Fig. 1). Supporting results presented in Graham et al. (2025), the geochemical data provided in Appendix 1 (BCGS_GF2025-13.zip) include analyses of mineralized rock samples from past-producing SEDEX deposits and occurrences in each of these areas (Table 1).

2. Methods

2.1. Sample selection and metadata

A total of 40 samples were retrieved from the British Columbia Geological Survey rock archive (see Rukhlov et al., 2023). The samples were selected from an index of the rock archive that includes available metadata (e.g., sample number, geologist, year, location). Many entries are designated by MINFILE and lack precise location data; these samples appear to have been collected as exemplary ore specimens.

2.2. Sample preparation

Hand specimens and drill core samples were prepared at the BCGS. Samples were cut and excess material was returned to

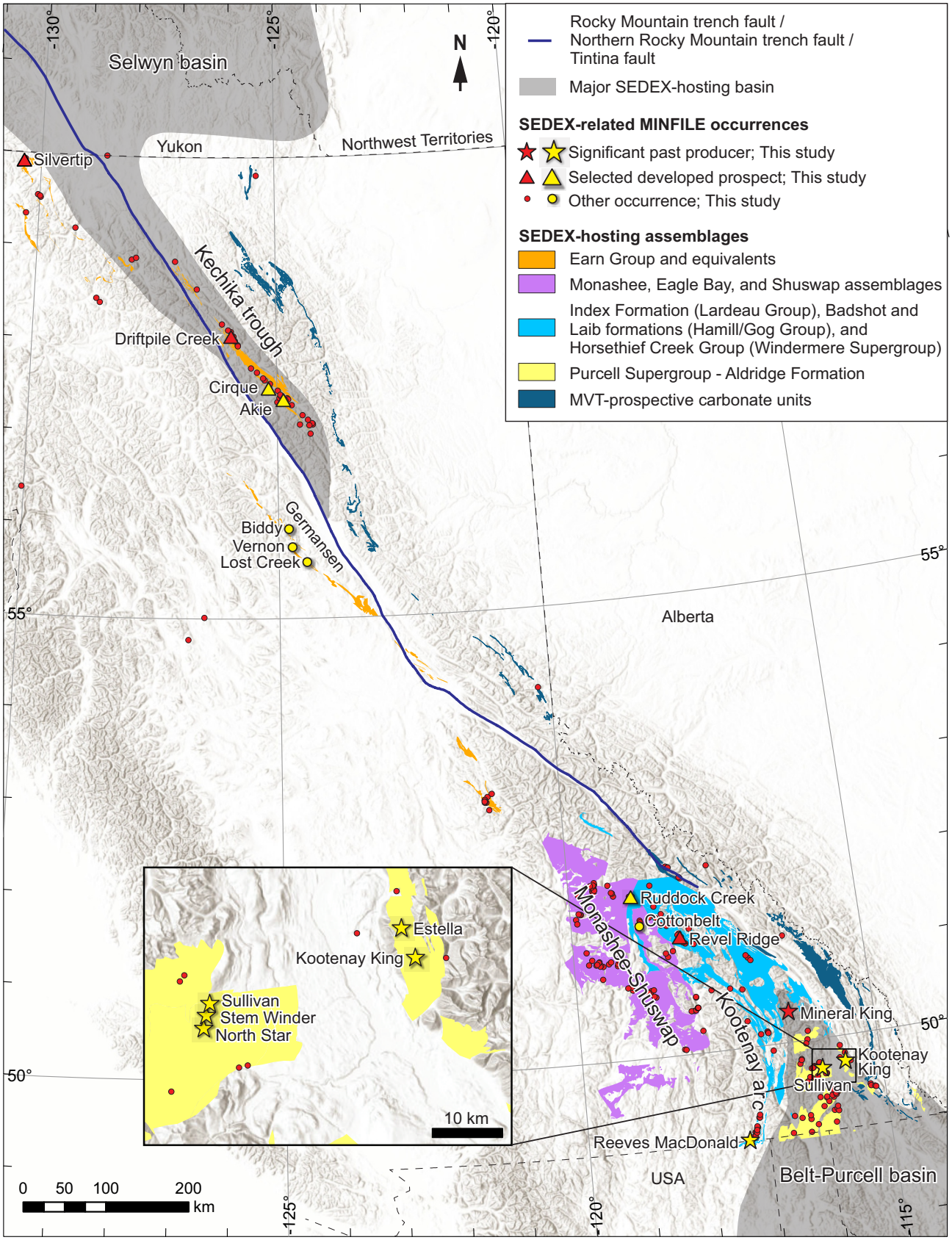

Fig. 1. SEDEX and related mineral occurrences and host rocks in the eastern Cordillera (British Columbia Geological Survey, 2025). Geology from BC Digital Geology version 2021-12-19 (Cui et al., 2017). Belt-Purcell basin from Lydon (2007); Selwyn basin in Yukon and equivalent Kechika trough in British Columbia are from Goodfellow (2007).

Table 1. Mineral deposits and occurrences sampled in this study.

	Deposit	Age	Mineralization style	Host unit	Metamorphism	Vent or intrusion related?	Source
Kechika trough	Cirque Akie	Middle - Upper Devonian	Stratiform pyrite-barite-sphalerite-galena	Earn Group - Gunsteel Formation	Sub-greenschist	No vent evident.	MacIntyre, 1998
Germansen area	Biddy Vernon	Middle - Upper Devonian	Carbonate-hosted sphalerite-galena-pyrite in pods and breccias	Otter Lakes Group	Sub-greenschist	No vent evident.	Ferri and Melville, 1994
	Lost Creek	Late Triassic	Quartz vein with sphalerite-galena-chalcopyrite-tetrahedrite	Takla Group	Chlorite grade	Quartz-galena vein	Ferri and Melville, 1994; BCGS, 2025
Kootenay arc	Reeves MacDonald	Early Cambrian	Kootenay-arc type dolomite-hosted and non-sulphide Pb-Zn	Laib Formation - Reeves limestone member	Local contact metamorphism	No vent evident. Proximal Cretaceous intrusions.	Paradis et al., 2015
Monashee-Shuswap region	Cottonbelt	Neoproterozoic - Early Cambrian	Concordant layer of sphalerite-galena-magnetite-scapolite	Monashee over Sequence - calc-silicate gneiss	Sillimanite-granulite	No vent evident. Stratigraphically below Mt. Grace carbonatite.	Höy, 1987; Höy and Gowin, 1988; Abdale et al., 2024
	Ruddock Creek	Neoproterozoic	Highly deformed concordant massive sulphide layer	Windermere Supergroup -Mica Creek succession	Upper amphibolite	No vent evident. Deformation and metamorphism obscure primary context.	Theny et al., 2015; Theny, 2016
Purcell basin	Sullivan	Mesoproterozoic	Stratiform pyrrhotite-predominant massive sulphide	Purcell Supergroup - Lower Aldridge Formation siltstone and wacke near Lower-Middle Aldridge transition	Greenschist - amphibolite	Vent zone as tourmaline breccia pipe below and surrounding ore.	Lydon, 2000 and references therein
	Stem Winder		Massive sulphide lens and breccia				
	North Star		Stratiform galena-predominant massive sulphide				
	Kellogg		Pyrrhotite lens			Vein	Höy, 1993
	Kootenay King		Laminated massive pyrite-galena-sphalerite	Purcell Supergroup - Middle Aldridge Formation dolomitic siltstone		No vent. Monzonite adjacent to base of ore.	
	Estella		Polymetallic veins Ag-Pb-Zn-Cd-Cu-Au-Co			Proximal to monzonite stock and associated with contact of Moyie diorite.	

the BCGS archive. The samples were crushed using a steel jaw crusher and sieved to isolate the 0.5 to 2 mm fraction. Coarse crush that did not pass through a 10 mesh (2 mm) was retained and archived; the fine fraction that passed through 35 mesh (<500 µm) was discarded. A chromium-steel ring and puck mill dedicated to mineralized samples was used to pulverize each sample for 20 seconds; pulps were then screened to 100% through 200 mesh (<74 µm) using a stainless-steel sieve. The mill was cleaned between each sample by pulverizing ~40 g of silica sand and wiping all parts with ethanol. Coarse silica blanks were pulverized sequentially in the sample stream. Approximately 20 g of <74 µm pulp was sent to ALS Canada Ltd., North Vancouver, for geochemical analysis. Remaining pulp was archived.

2.3. Analytical methods

At ALS Canada Ltd, subsamples of the pulps were analyzed by a package that varies digestion and analysis methods between analytes (method CCP-PKG05; ALS, 2024). Samples that returned greater than the detection range for specific analytes were re-analyzed with ore-grade methods while maintaining consistency in the digestion method (Appendix 1, Attributes). For analytes that yielded greater than detection ranges, results from the ore-grade methods supersede previous results.

Major-element oxides were measured by method ME-ICP06 (ALS, 2024). A 0.1 g subsample was mixed with a Li borate flux and fused in a furnace at 1025°C. The melt was cooled and dissolved in nitric, hydrochloric, and hydrofluoric acid and the resultant solution was analyzed by inductively coupled plasma (ICP) atomic emission spectroscopy (AES). Results were corrected for inter-element spectral interference before reporting and total (%) and loss on ignition (LOI%) values were included. Trace (lithophile) elements (e.g., Ba, Ga, Ge, Sn, U, V, W) were measured by method ME-MS81 (ALS, 2024), which uses the same Li borate fusion and acid digestion as ME-ICP06, but analysis was completed with ICP-mass spectrometry (MS). The fusion is considered the best method for complete dissolution of trace elements from silicates, although some zircon, metal oxides, rare-earth phosphates, and sulphides may not be fully recovered (ALS, 2024). Two standards yielded greater than the detection range for W, but were not re-analyzed because routine samples were not highly elevated in W. Ten samples yielded above the detection range (>1%) for Ba and were re-analyzed with method ME-XRF15c, an X-ray fluorescence (XRF) analysis following Li borate fusion with the addition of strong oxidizing agents to decompose sulphide concentrates in samples with high sulphide contents. Three samples yielded >50% Ba; for these samples Ba values

were calculated from the original BaO analysis (ME-ICP06).

Carbon and S were analyzed by LECO Infrared Spectroscopy (ME-IR08) in which a sample is combusted in a high-frequency LECO induction furnace in a stream of oxygen that converts S into SO_2 and C into CO_2. The resultant gas was passed directly into a cell with infrared (IR) energy, which absorbed the SO_2 and CO_2 at different wavelengths. Absorption was quantitatively detected and used to calculate total S and total C.

Volatile trace elements (e.g., As, Bi, Hg, In, Sb, Te) were analyzed (0.5 g subsample) by ICP-MS using collision cell technology for lowest detection limits following 45-minute digestion by aqua regia. The resulting solution was cooled, diluted to 12.5 mL with de-ionised water and mixed (ALS method ME-MS42). These elements were analyzed using relatively low-temperature aqua regia digestion to avoid volatilization as is common with higher temperature 4-acid digestion or fusion methods. Several of these analytes yielded greater than the detection ranges in batch SEDEX-1 (As, Bi, Hg, In, Sb), and were further analyzed with ME-ICP41a, an intermediate level aqua regia (ICP-AES) method with higher upper and lower detection limits.

Base metals (Ag, Cu, Ni, Zn, Cd, Li, Pb, Co, Mo, Sc) were analyzed with method ME-MS61, which uses ICP-MS following digestion of a 0.25 g subsample in a 4-acid (perchloric, nitric, hydrofluoric, hydrochloric) solution. Samples that yielded greater than the detection ranges (100 g/t Ag, 1000 ppm Cd, or 1% of Pb, Zn, Cu) were re-analyzed for single analytes with method ME-OG62, a 4-acid digestion on 0.4 g subsample followed by ICP-AES analysis. Several samples returned concentrations of Pb (n=12) and Zn (n=5) above the detection range of ME-OG62 (20% Pb, 30% Zn), and were re-analyzed with ME-OG62h, a higher-grade equivalent method. One sample yielded >40% Pb and was re-analyzed by titration.

3. Quality assurance

A total of 17 quality control samples (silica blanks, pulp duplicates, and standards) were inserted into the sample stream at the BCGS preparatory laboratory (Appendix 1, Data).

3.1. Preparation blanks

To monitor sample preparation contamination, five coarse silica sand blanks (Sigma-Aldrich-certified as ≥99.995 weight% SiO_2) were pulverized in the same manner as routine samples (Appendix 1, Blanks-contamination). Analytical results from silica blanks indicate Pb concentrations ≤ 570 ppm and Zn concentrations ≤ 188 ppm, a consequence of pulverizing massive sulphide samples and routine dry-cleaning methods (silica and ethanol wipe). The blank with the greatest Pb contamination (570 ppm) also yielded 1.29 g/t Ag, 10 ppm Cu, and 2.32 ppm Sb. Whereas this level of cross-contamination would be problematic in many datasets, because the samples here are ore grade (i.e., %-range concentrations of Pb, Zn), the level of contamination in base metals does not affect the results. Trace metals show lower, but still present values (e.g., one blank that was pulverized immediately after an In-bearing sample yielded 0.019 ppm In).

3.2. Pulp duplicates

To assess precision of the results, six pulp duplicates were split from their parent sample after pulverization (Appendix 1, Duplicates-precision). The pulp duplicates represent the homogeneity of the pulp after pulverization as well as analytical reproducibility (precision). Analytical precision is assessed by performance of the pulp duplicates relative to their parent samples. Relative analytical precision is estimated by the average coefficient of variation, CV_{AVR} (%) for 6 data pairs (parent-duplicate) and 2 pairs of duplicated standards (e.g., Van der Vlugt et al., 2022).

$$CV_{AVR}\ (\%) = 100\sqrt{\frac{2}{N}\sum_{i=1}^{N}\left(\frac{(a_i-b_i)^2}{(a_i+b_i)^2}\right)} \qquad \text{Eqn. 1}$$

where a_i and b_i are the analytical results for the i^{th} pair of duplicate samples, and N is the number of the data pairs (Abzalov, 2008). In cases where analytes were below or above the detection range for the given method, these analyses were omitted from the calculation of CV_{AVR}.

We consider that CV_{AVR} values of <20% indicate generally acceptable precision. Most analytes had values of < 20%, but some (Zn, Cs, Lu, Nd, Sr, Tm, Ni) had values of 20-30%, and others (Pb, Bi, Ba, Na_2O, Ba, Sn, Ta, Te) had >30% CV_{AVR}. This poor replication of duplicates may be a result of heterogeneity of the pulp, poor analytical precision, or a combination of the two.

3.3. Certified reference materials

Six certified reference materials (i.e., standards/CRM pulps) were included in the sample stream. The results from these reference materials can be used to assess analytical accuracy, which is the analytical result relative to their certified values and standard deviation (or 95% confidence interval). Standards included Canadian Certified Reference Materials Project CANMET CZN-1 (n=2), CANMET MP-1a (n=1), CANMET SU-1a (n=1) and United States Geological Survey GXR-3 (n=2). For replicate analyses of standards, accurate or unbiased analytical results for each analyte satisfy the following condition:

$$\frac{|m-\mu|}{2\sqrt{{\sigma_L}^2+\frac{{S_w}^2}{n}}} \le 1 \qquad \text{Eqn. 2}$$

where m is the average of replicate analyses (or the result if n=1), μ is the certified reference mean (i.e., expected value/ EV), σ_L is the interlaboratory certified standard deviation, n is the number of analyses (i.e., n=1 or 2), and $S_w = CV_{AVR} * m$ (representing analytical precision).

Analytical results are of acceptable accuracy for Zn, Pb, Ag, Cu, Cd, Bi, In, Sn, and Ba. At least one standard had marginally acceptable accuracy for As, Sb, and Hf, and both CRMs with interlaboratory-certified Se means yielded inaccurate Se values. The relatively poor precision (i.e., large CV_{AVR} values), represented by S_w in Equation 2, has the effect of increasing the tolerance for accuracy; this should be considered when using the resultant data.

4. Results

Relative to upper continental crust (Rudnick and Gao, 2014) samples from all regions (Fig. 2) are strongly enriched (>100x the average concentration of upper continental crust) in Cd, Sb, and Te. Massive sulphide samples from past-producing deposits in Belt-Purcell basin, including the Sullivan mine, are strongly enriched in In (up to 113 ppm) and moderately enriched (10-100x average upper continental crust) in Sn and Bi (Fig. 3). Samples from the Cottonbelt occurrence in the Monashee-Shuswap region are weakly to moderately enriched in In (up to 6 ppm) and also have relatively low Hg and high Mn (Fig. 4). Stratiform laminated sulphide-barite samples from the Cirque project in the Kechika trough are weakly (<10x average upper continental crust) to moderately enriched in Ge and sporadically moderately enriched in In (up to 3 ppm) (Fig. 5). Samples from the Reeves MacDonald deposit in south Kootenay arc and mineral occurrences in the Germansen Landing area are moderately enriched in Ge (up to 35 ppm; Figs. 2, 4, 5).

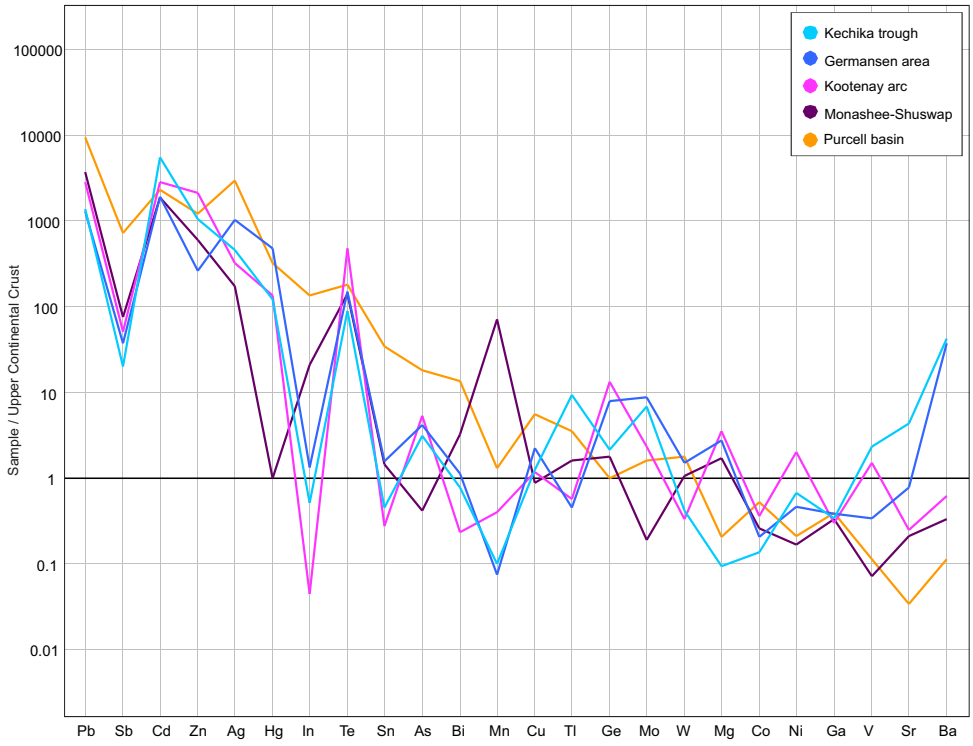

Fig 2. Median elemental enrichments for samples from Purcell basin (n=21), Monashee-Shuswap region (n=5), Kootenay arc (n=2), Germansen Landing area (n=4), and Kechika trough (n=8) (ioGAS™). Metal enrichment is relative to average upper crust of Rudnick and Gao (2014).

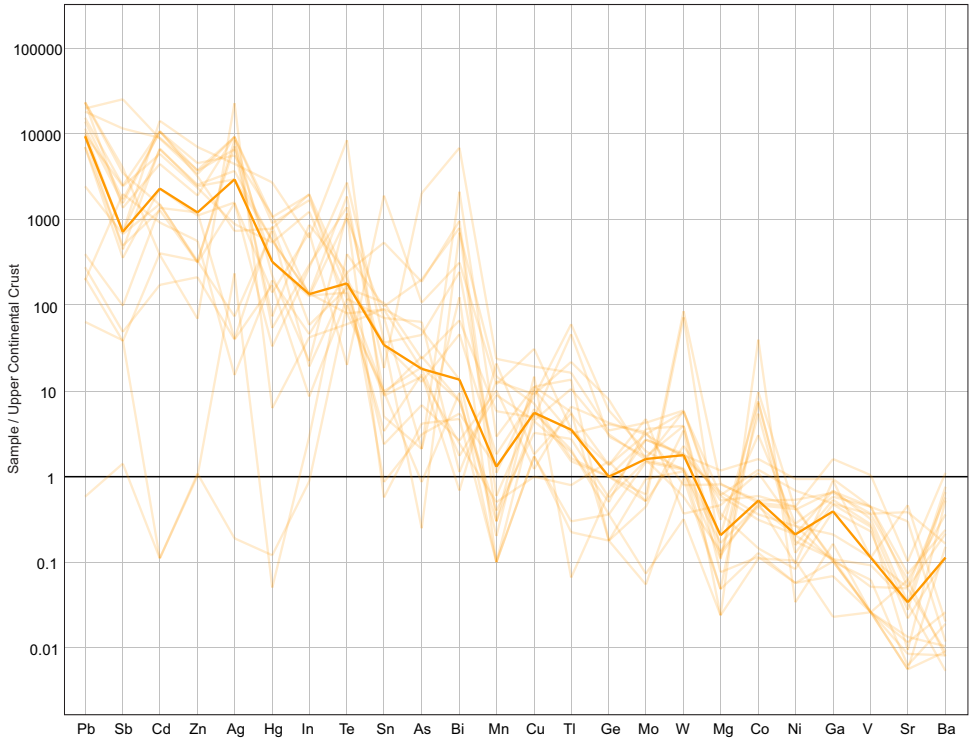

Fig 3. Elemental enrichment relative to average upper crust (Rudnick and Gao, 2014) of samples from Purcell basin (n=21). Faded lines are individual sample concentrations; bold line represents median values.

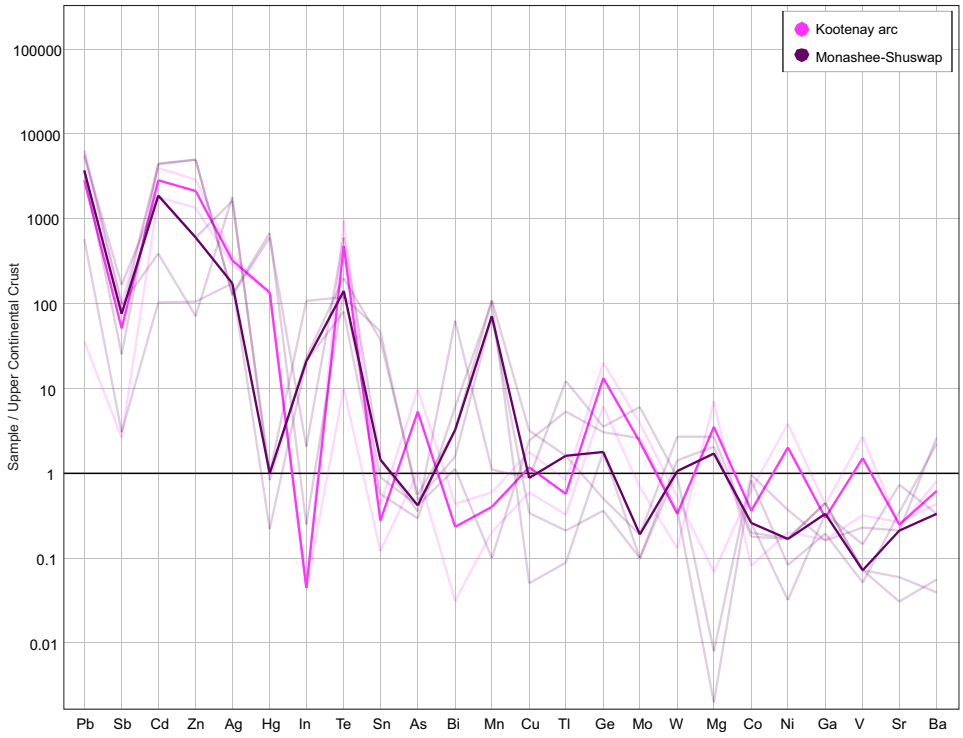

Fig 4. Elemental enrichment relative to average upper crust (Rudnick and Gao, 2014) of samples from Monashee-Shuswap region (n=5) and Kootenay arc (n=2). Faded lines are individual sample concentrations; bold line represents median values.

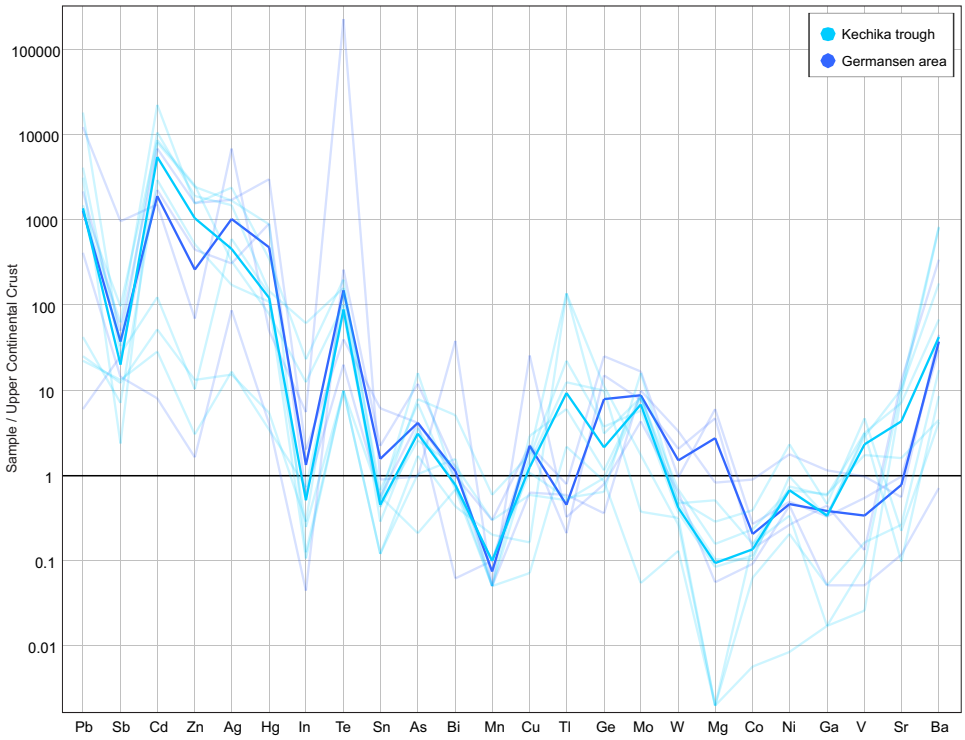

Fig 5. Elemental enrichment relative to average upper crust (Rudnick and Gao, 2014) of samples from Kechika trough (n=8) and Germansen Landing area (n=4). Faded lines are individual sample concentrations; bold line represents median values.

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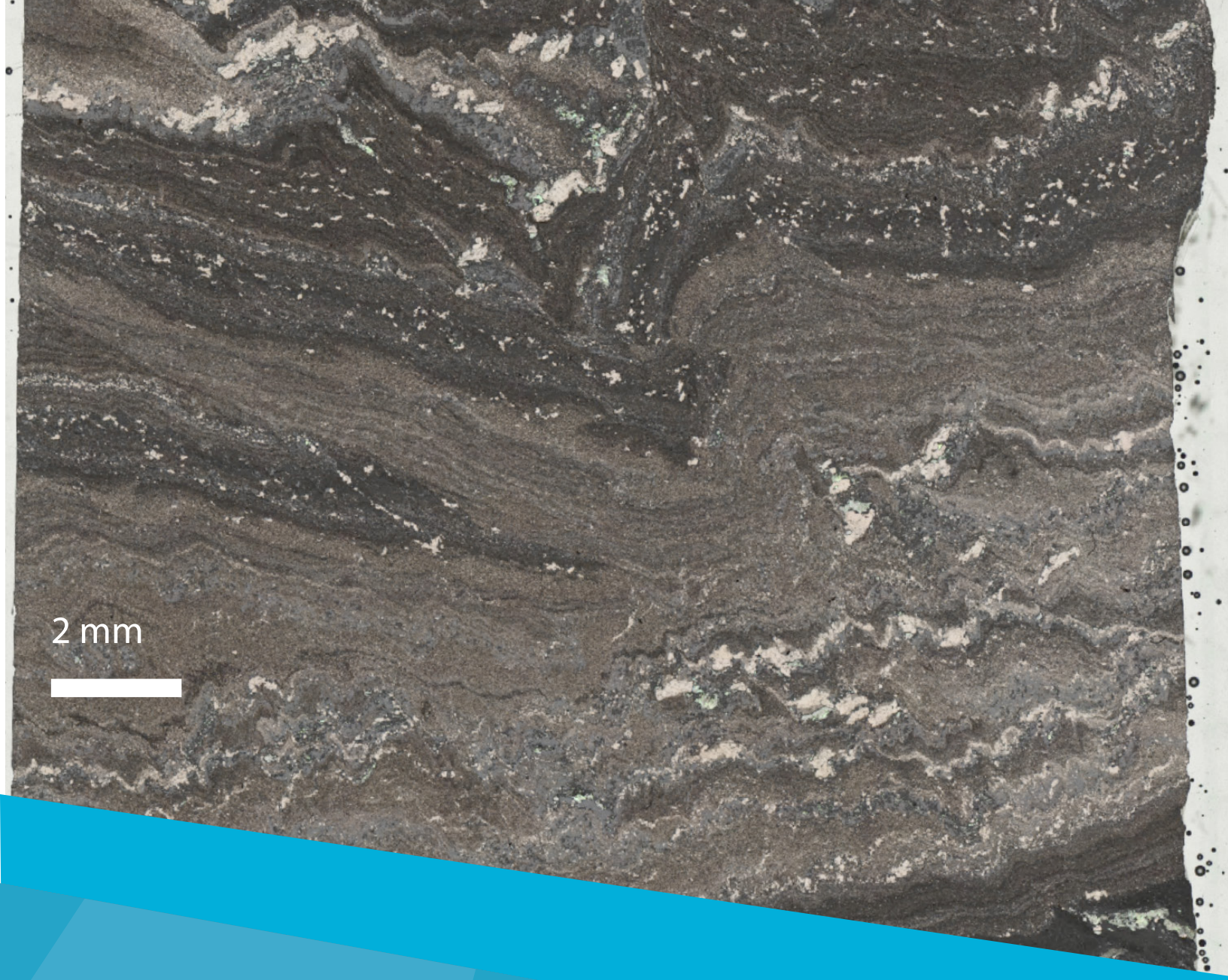

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Ministry of Mining and Critical Minerals

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