A preliminary assessment of critical companion metals in SEDEX deposits of eastern British Columbia: Examples from the historic Sullivan mine and the Cirque project

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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. Preliminary bulk-rock geochemistry of samples from the historical Sullivan mine, hosted in Mesoproterozoic rocks of Belt-Purcell basin in southeastern British Columbia, shows that massive-sulphide ore is strongly enriched (>100 - >1000x the average concentration of upper continental crust) in Sb, Cd, Hg, In, and Te, and moderately enriched (10 - 100x) in As, Bi, and Sn. Four samples of Sullivan ore yielded >1000x the average concentration of the upper crust (56 ppb) of In, with the highest at 112.5 ppm In. Stratiform and laminated Upper Devonian sulphide-barite samples from the Cirque project in the Kechika trough of northeastern British Columbia are moderately to strongly enriched in Cd, Hg, and Te but only weakly or variably enriched in In (≤3.45 ppm), Sb, and Sn. Renewed mineral potential modelling by the BCGS indicates that the Kechika trough has the highest SEDEX prospectivity ranking in the northeastern part of the province and that two smaller areas to the west may also be prospective.

Keywords: SEDEX, Sullivan, Cirque, critical metals, companion metals, mineral potential

1. Introduction

Primary commodities Pb, Zn, and Ag are commonly mined from sedimentary exhalative (SEDEX) deposits found in deep-water siliciclastic successions and Mississippi Valley-type (MVT) deposits found in shallow-water carbonate shelf successions. However, both deposit types 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).

To assess the critical metal endowment of British Columbia, deposits with significant critical companion metals need to be identified, the distribution of metals in these deposits needs to be resolved, and potentially prospective but under-explored areas need to be recognized. Paradis (2015), Paradis et al. (2022, 2023), and Lawley et al. (2022) addressed critical companion metals in MVT and other carbonate-hosted deposits in the province. However, studies of critical companion metals in SEDEX deposits have been limited (e.g., Owens, 2000; Slack et al., 2020) and thus their distributions remain largely unknown.

In the Cordilleran orogen, autochthonous and parautochthonous rocks of Ancestral North America include several stratigraphic units with SEDEX mineralization (Figs. 1, 2). These units include the Aldridge Formation of the Belt-Purcell basin (Mesoproterozoic) at the past-producing Sullivan mine and the aerially extensive Earn Group (Upper Devonian), which hosts the Cirque project in the Kechika trough (Figs. 1, 2). This is the first report from a multi-year project to examine sediment-hosted critical minerals in British Columbia. Herein we provide preliminary results of bulk-rock geochemical analyses to assess the critical companion metal content of Sullivan ore and Cirque mineralization. We also present results from renewed mineral potential mapping of northeast British Columbia highlighting prospectivity for SEDEX deposits.

2. Context

SEDEX deposits are stratabound and typically stratiform accumulations of Pb-Zn-Ag-bearing sulphides that were deposited during hydrothermal venting at the seafloor-sediment interface, commonly in continental rift basins (Goodfellow and Lydon, 2007; Huston et al., 2023); 'vent-proximal' and 'vent-distal' endmembers are recognized (e.g., Sangster, 2018). Metalliferous formational brines generated at depth are exhaled through vents and syn-depositional growth faults to

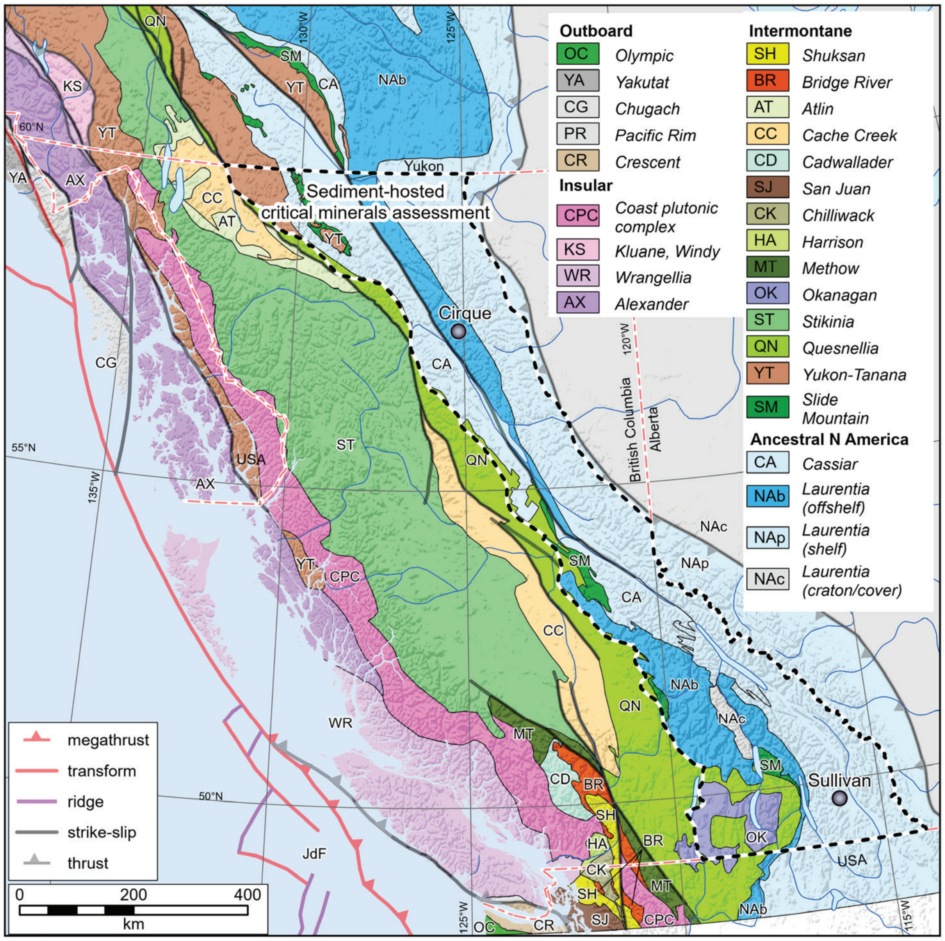

Fig. 1. Area of autochthonous and parautochthonous rocks in eastern British Columbia being assessed for sediment-hosted critical minerals; location of historical Sullivan mine and Cirque developed project. Terranes after Colpron (2020).

the seafloor, where they interact with seawater (Badham, 1981; MacIntyre, 1998; Goodfellow, 2007). Continued venting into anoxic or euxinic basins, changes in temperature, pH, total sulphur, and redox conditions induce metal deposition in favourable units at or near the sediment-water interface (Turner et al., 2000; Cooke et al., 2000). Prolonged hydrothermal activity can produce giant deposits (e.g., Sullivan >149 Mt; Table 1) that are important global sources of Pb-Zn-Ag and other metals (e.g., Ga, Ge, In; Leach et al., 2005; Ye et al., 2011; Shanks et al., 2017; Hickin et al., 2024).

The main SEDEX-hosting areas of British Columbia (Fig. 2) are: 1) the Belt-Purcell basin, an intracratonic sag basin in western Laurentia that formed in the Mesoproterozoic (e.g., Winston, 1990; Lydon, 2007 and references therein); 2) the Kootenay arc, a curvilinear geomorphic high comprising Neoproterozoic-Paleozoic sedimentary and lesser volcanic rocks; 3) the Monashee-Shuswap region, where the Monashee, Eagle Bay, and Shuswap metamorphic complexes host scattered occurrences (Höy, 1988; Theny et al., 2015); and 4) the Kechika trough, a long-lived narrow fault-bounded sedimentary basin that evolved from the Neoproterozoic to the early Paleozoic (Ferri et al., 1999; Nelson et al., 2002, 2013). The Belt-Purcell basin and Kootenay arc host past-producing SEDEX and related deposits (Table 1), whereas the Kechika trough and Monashee-Shuswap region host several prospects with existing resource estimates (Table 2). Herein we present preliminary geochemical results from the Sullivan mine (Belt-Purcell basin) and the Cirque property (Kechika trough).

2.1. Belt-Purcell basin and Sullivan mine

Sedimentary rocks of the Belt Supergroup (USA) and Purcell Supergroup (Canada) extend across ~200,000 km^2 in British Columbia, Alberta, Washington, Montana, and Idaho (e.g., MacLean and Sears, 2016 and references therein), and host several mineral deposits (Figs. 2, 3; e.g., Lydon, 2000, 2007; Lydon et al., 2000 and references therein). The northwest-trending basin formed as an intracontinental sag near the western margin of Laurentia in the Mesoproterozoic. In the lower part of the Purcell Supergroup, the Aldridge Formation, a 12 km-thick section of fine-grained siliciclastic rocks and intercalated mafic sills (Moyie sills) hosts the past-producing Sullivan deposit (>149 Mt), the largest known SEDEX deposit in Canada (Fig. 3). Sullivan ore (Figs. 4a, b) consists of stratiform massive sulphides containing Pb-Zn-Ag, with Au-

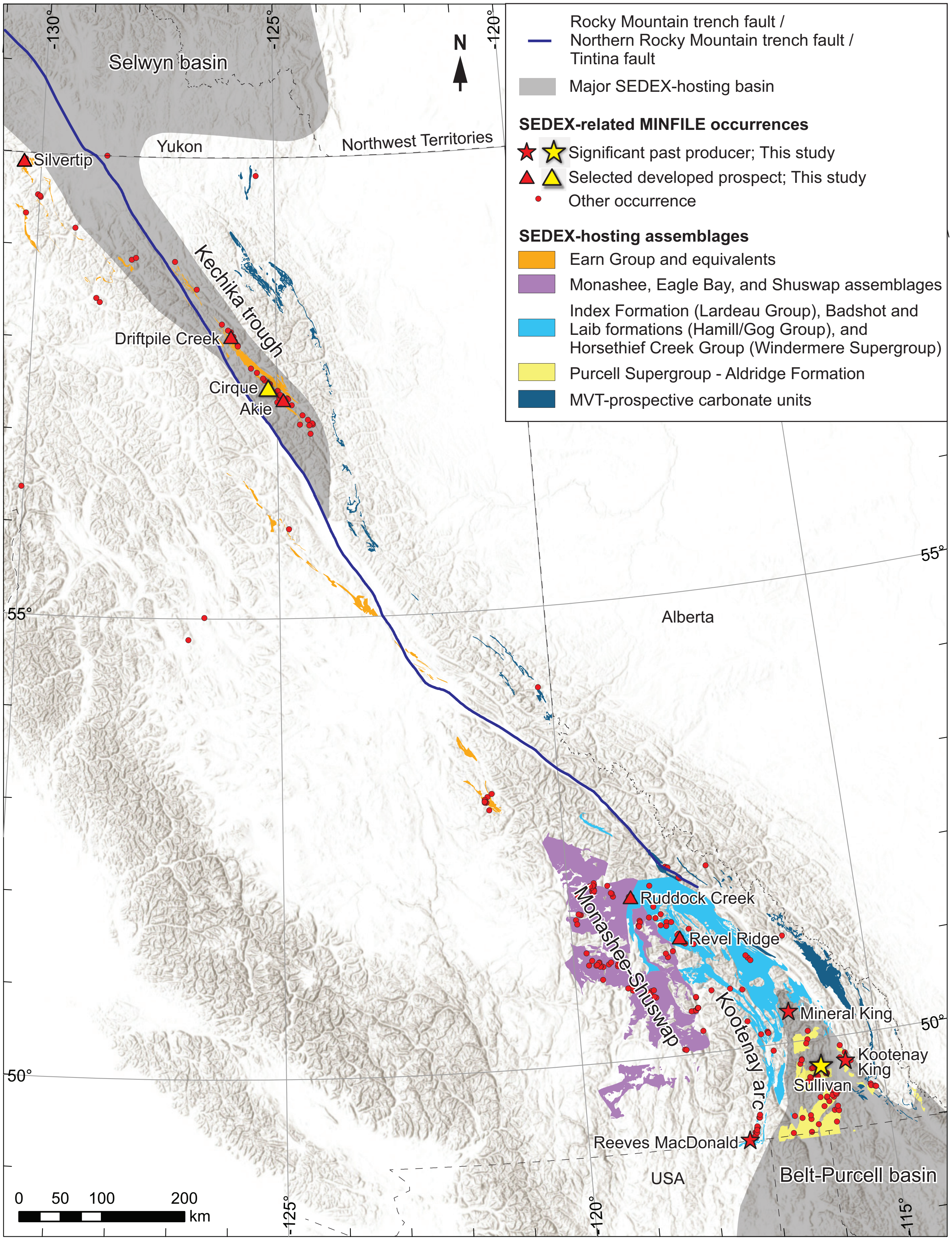

Fig. 2. SEDEX and related mineral occurrences and host rocks in the eastern Cordillera. Belt-Purcell basin from Lydon (2007); Selwyn basin (Yukon) and equivalent Kechika trough (British Columbia) from Goodfellow (2007).

Table 1. Significant SEDEX and related past-producing deposits in British Columbia sourced from MINFILE.

	Deposit/ MINFILE No.	Volume (Mt)	Au (kg)	Ag (t)	Pb (kt)	Zn (kt)	Cu (t)	Cd (t)	Ba (kt)	Bi (t)	Sn (kt)	Sb (t)	Other critical companion metals
Belt-Purcell basin	Sullivan 082FNE052	149.17	174.9	9264.2	8412.1	7944.4	5106.7	3094.9	--	21.9	9.7	413.7	In but unknown amount
	Ave. Grade (g/t)		0.00117	62.1	56391.2	53256	34	20.7	--	0.1	65.0	2.8	--
	Mineral King 082KSE001	2.10	--	57.7	37.4	90.4	662.0	314.6	57.2	--	--	--	unknown
	Ave. Grade (g/t)		--	27.4	17802	42975	314	149.6	27220	--	--	--	--
	Kootenay King 082GNW009	0.01	0.7	0.1	0.7	0.9	enriched	1.0	--	--	--	--	unknown
	Ave. Grade (g/t)		0.05392	6.7	53610	66469	--	74.3	--	--	--	--	--
	North Star Mine 082FNE053	0.06	--	41.7	21.8	0.01	enriched	--	--	--	--	--	unknown
	Ave. Grade (g/t)		--	679.5	355047	102	--	--	--	--	--	--	--
	Stemwinder 082FNE116	0.03	1.3	2.0	0.9	4.0	--	--	--	--	--	--	unknown
	Ave. Grade (g/t)		0.05098	76.3	36898	155773	--	--	--	--	--	--	--
Cassiar terrane	Silvertip* 104O 038	0.39	--	46.2	11.2	13.8	--	--	--	--	--	--	--
	Ave. Grade (g/t)		--	119.6	29045	35870	--	--	--	--	--	--	--
Kootenay arc	Reeves MacDonald 082FSW026	5.85	--	19.8	57.7	203.6	27.6	1215.7	--	--	--	--	Ga, Ge
	Ave. Grade (g/t)			3.4	9870	34836	4.7	208.0	--	--	--	--	--

Source: British Columbia Geological Survey (2024).
*Polymetallic manto with sub-economic upper SEDEX horizon (Coeur Mining Inc., 2023).

Table 2. Mineral resource estimates of selected SEDEX and related developed projects in British Columbia.

	Deposit/ MINFILE No.	Volume (Mt)	Au (kg)	Ag (t)	Pb (kt)	Zn (kt)	Companion metals	Source
Monashee-Shuswap	Ruddock Creek 082M 084	12.9	--	--	163.2	828.7	unknown	Simpson and Miller-Tait (2012)
Cassiar terrane	Silvertip* 104O 038	8.6	--	2293.9	439.3	906.5	Sn-Sb-As-Cu-Cd	Bolu et al. (2019) Coeur Mining Inc. (2023)
Kootenay arc	Revel Ridge** 082M 003	14.7	63059.1	721.1	252.2	497.3	S-As	Murray et al. (2023)
Kechika trough	Cirque*** 094F 008	53.5	--	2289.6	1053.0	4078.5	Cd-Ba-Hg-Te	Loughrey (2017), this study
	Akie 094F 031	30.2	--	410.6	457.6	2417.7	Cd-Ba-Sn-In-Ga-Tl in black shale below SEDEX horizon	Makarenko et al. (2018) Gadd et al. (2022)
	Driftpile Creek*** 094K 066	2.4	--	--	75.6	290.4	unknown	Nelson et al. (1995)

Mineral resource estimates include all classes (Proven and Probable, Measured and Indicated, Inferred)

*Polymetallic manto with sub-economic upper SEDEX horizon

**Includes orogenic Au zone (RRMZ - Revel Ridge main zone) and "Kootenay-arc type" carbonate replacement (RRYJ-Revel Ridge Yellowjacket) zones

*** Historic, preliminary, and non-NI 43-101 compliant mineral resource estimates

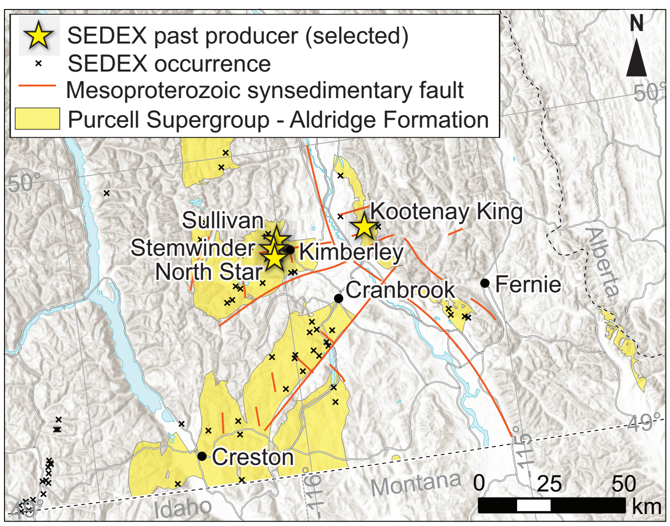

Fig. 3. Extent of the Aldridge Formation and associated SEDEX mineralization in the Purcell basin. Geology from BC Digital Geology version 2021-12-19 (Cui et al., 2017). Mesoproterozoic faults from Höy et al. (2000).

Bi-Cd-Cu-Fe-In-S-Sb-Sn (Table 1) lying atop and adjacent to a subvertical fragmental pipe. The deposit is spatially and possibly genetically related to intrusion of the Moyie sills (ca. 1.47 Ga; Anderson and Davis, 1995), which were emplaced into wet unconsolidated sediments (Höy et al., 2000; Lydon, 2004). The deposit was deformed and metamorphosed (~450°C; DePaoli and Pattison, 2000) during the Proterozoic and folded and faulted in the Cenozoic (e.g., Lydon et al., 2000). Three main ore domains were recognized with variable relative metal concentrations (Lydon et al., 2000). Sullivan ore locally contained Sn (Slack et al., 2020), and In was produced as a by-product, although concentrations remain unreported (e.g., Sargent, 1956).

2.2. Kechika trough and Cirque project

The Kechika trough is a NNW-trending basin in the northern Rocky Mountain fold and thrust belt (Fig. 2; Nelson and Colpron, 2007). Supracrustal rocks in the Kechika trough, and its northern extension the Selwyn basin (Yukon), were deposited during the protracted breakup of Rodinia during the Neoproterozoic through to the Late Devonian (Ferri et al., 1999; Campbell et al., 2019). Pelitic rocks exhibit low-grade (white mica-chlorite-quartz-calcite-dolomite) sub-greenschist metamorphic facies (Ferri et al., 1999).

During the Late Paleozoic, subsidence and sedimentation resulted from back-arc extension during subduction and accretion of peri-Laurentian terranes (Nelson et al., 2002; Goodfellow, 2007; Nelson et al., 2013). Upper Devonian SEDEX occurrences include Cirque, Driftpile Creek, and Akie (Fig. 2; Table 2; MacIntyre, 1992; Paradis et al., 1998; Ferri et al., 1999).

Although barite ±Pb-Zn horizons occur at different stratigraphic levels, Zn±Pb±Ag mineralization is hosted exclusively by the Gunsteel Formation in the lower part of the Earn Group (Ferri et al., 1999). Cirque is the largest developed project in the Kechika trough, with 2-60 m thick pyrite-sphalerite-galena-barite mineralization parallel to

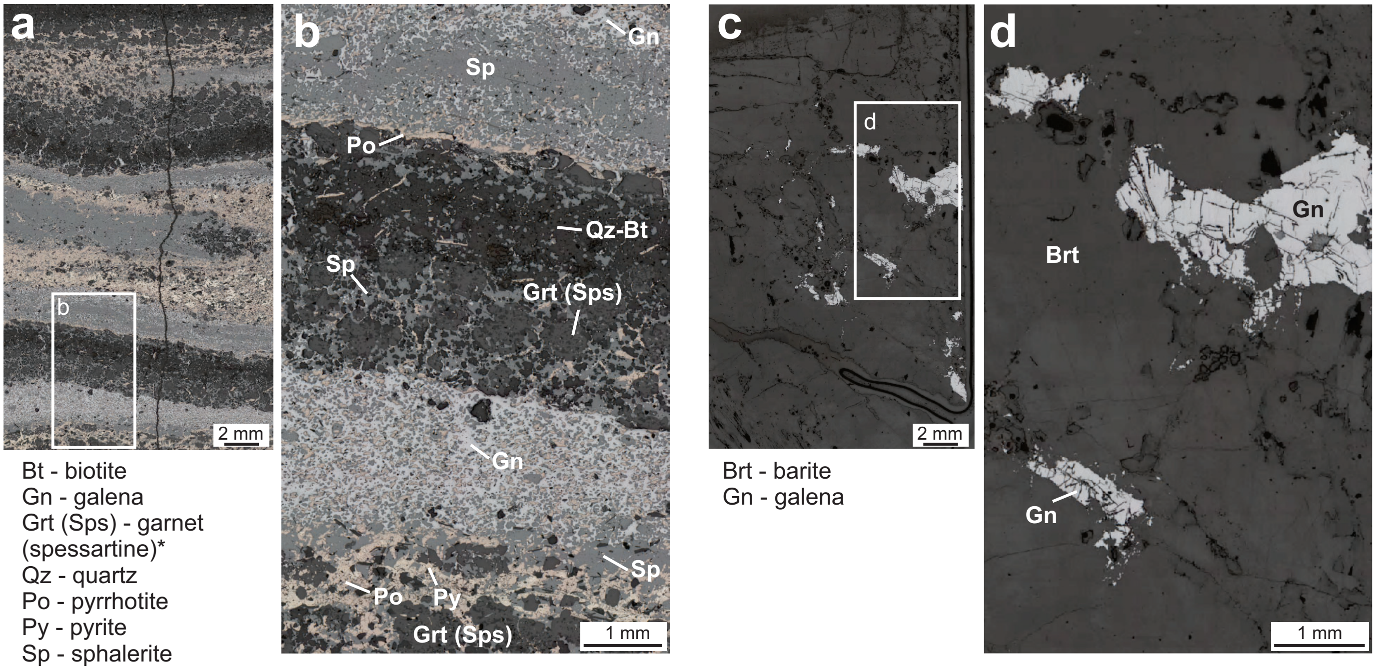

Fig. 4. Photomicrographs of SEDEX mineralization (reflected light). **a-b)** Banded ore and gangue from the past-producing Sullivan mine. *The spessartine composition of garnet is from De Paoli and Pattison (2000). **c-d)** Massive barite and galena from an outcrop hand sample from the Cirque project. Mineral abbreviations from Whitney and Evans (2010).

beds of carbonaceous shale and siliceous argillite (Table 2; Loughrey, 2017). Barite and sulphides (Figs. 4c-d) are commonly coincident although lenses of sub-mm barite nodules may not host sulphides, and folded laminae of pyrite occur without barite locally (Loughrey, 2017). Gallium and Ge have been recognized in Devonian SEDEX deposits in the Selwyn basin (Landry et al., 2024) and drillholes at the Akie project have intersected a narrow layer of hyper-enriched black shale below the SEDEX-mineralized horizon (Table 2; Makarenko et al., 2018; Gadd et al., 2022). Below we report previously unrecognized companion metal values from the Cirque deposit.

3. Methods

3.1. Geochemistry

We analyzed previously collected samples stored in the British Columbia Geological Survey (BCGS) rock archive (Rukhlov et al., 2023). Samples were split, crushed, and pulverized at the BCGS and sent to ALS Canada Ltd. in North Vancouver for geochemical analysis using a complete characterization package, which varies digestion and spectral analysis methods between analytes. Lithium-borate fusion and 3-acid digestion were followed by ICP-AES analysis for major-element oxides and by ICP-MS for trace elements (CCP-PKG05; ALS, 2024). Volatile trace elements were analyzed by ICP-MS following digestion by aqua regia; base metals following 4-acid digestion. Carbon and S were analyzed by LECO Infrared Spectroscopy. Samples that returned greater than the upper limit of detection for specific analytes were re-analyzed with ore-grade methods, maintaining consistency in the digestion method. Full analytical details and results are in Graham and Ootes (2025). Samples from Sullivan (n=10) represent a range of mineralization styles, including massive and banded sulphides, but precise locations from within the deposit are unavailable. Samples from Cirque (n=7) are from archived exploration drill core intersections and outcrop hand samples.

3.2. Mineral potential mapping

As part of a province-wide program of renewed mineral potential modelling, Wearmouth et al. (2024b) completed a map for SEDEX and MVT mineral systems for a large area of northeastern British Columbia (Fig. 5). As described in Wearmouth et al. (2024a) the current mineral potential modelling workflow uses multiple datasets, knowledge of mineral systems, and the weights of evidence technique to assess the mineral potential of an area. The weights of evidence method, in combination with the mineral systems concept, tests the statistical spatial analysis of numerous mappable proxies (Table 3) serving to represent the important ore-forming processes (source, transport, and trap).

4. Results

4.1. Critical companion metals in the Sullivan and Cirque SEDEX deposits

We evaluate our geochemical results, the details of which are in Graham and Ootes (2025), using average upper crust-normalized trace metal values (Fig. 6; Rudnick and Gao, 2014). Sullivan ore samples (n=10) are strongly enriched (median >100x) in Pb, Sb, Cd, Zn, Ag, Hg, and In, and moderately

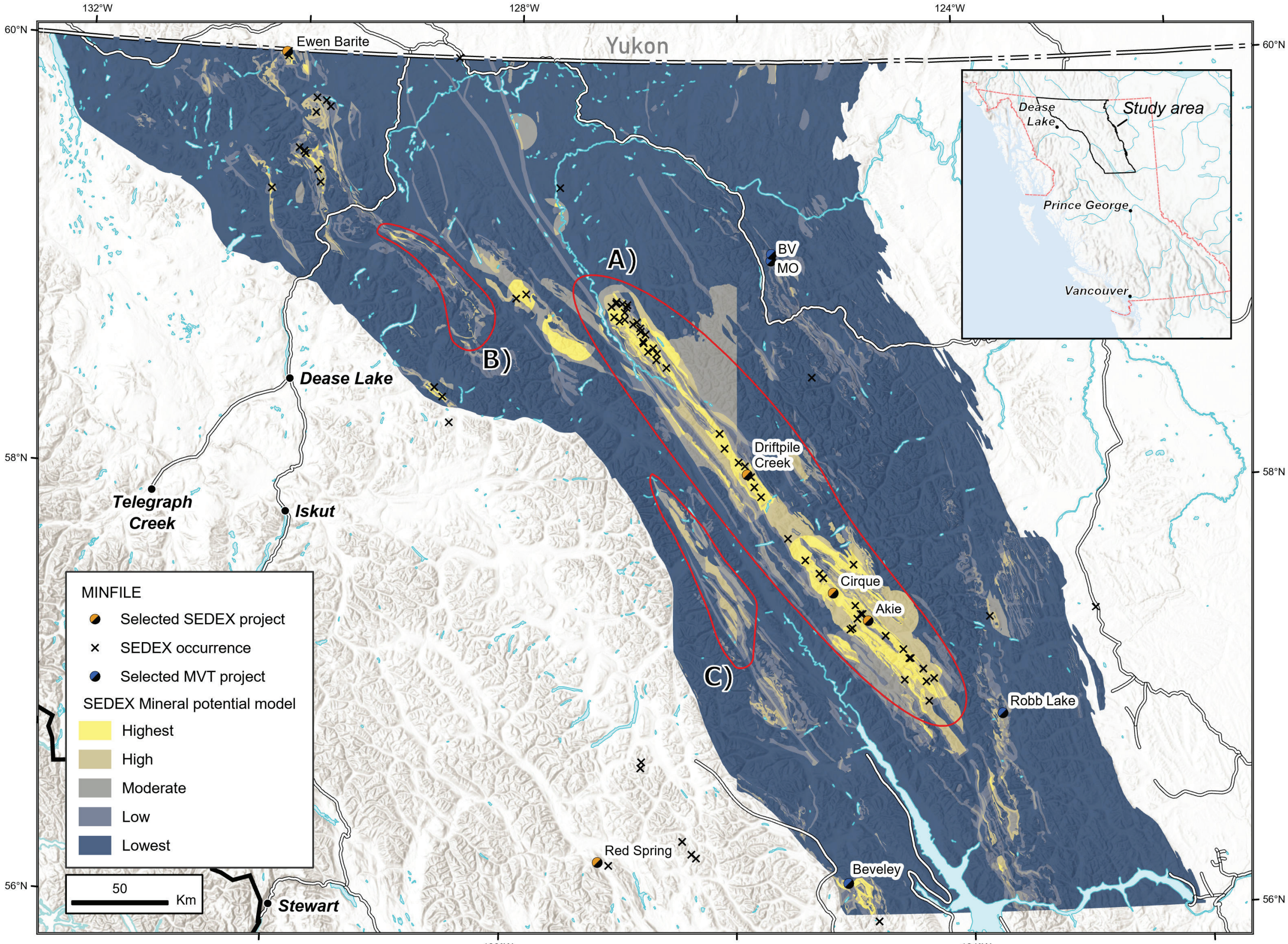

Fig. 5. Mineral potential map of northeastern British Columbia displaying relative prospectivity values (in five equal percentile divisions) for SEDEX mineralization. Outline in red: A, Kechika trough area; B, Dease River to Turnagain river area; C, Finlay River area. After Wearmouth et al., 2024b.

enriched (median 10-100x) in Sn, As, and Bi (Fig. 6). Four samples of Sullivan ore yielded >1000x the upper crust average concentration (56 ppb) of In, with the highest at 112.5 ppm In. Cirque mineralized samples (n=7) are strongly enriched in Cd, Pb, Zn, Ag, and Hg, moderately enriched in Ba and Sb, and weakly enriched in Mo and As. They are generally weakly depleted to weakly enriched in In (Fig. 6).

Principal Component Analysis (PCA) of the enriched elements shows differences and similarities in metal signatures between the two deposits (Figs. 7a-c). The small sample size and lack of systematic spatial distribution preclude robust statistical analysis, and the results are provided here only to illustrate key elemental associations. Positive values of PC1, which accounts for 50.0% of variance between samples, indicate correlated enrichment of In-Sb-Sn and many other companion metals. Sullivan samples generally have +PC1 values while Cirque samples have -PC1 values (Figs. 7a, b). Negative values of PC2 (19.0% of variance) indicate correlated enrichment of Ag-Pb-Zn-Hg-Cd-Ba and positive values are associated with elevated Te-Bi-Sn-Sb-In-As (Figs. 7a, c). Samples occur within a relatively narrow range of PC3 (10% of variance), without notable differences between deposits. There is a strong positive correlation between In-Sb-Sn ±Cd at Sullivan (Figs. 7a-c). The level of In enrichment in Sullivan ore is comparable to other notably In-enriched SEDEX deposits (e.g., the most In-rich ore at Rammelsberg (Germany), contains 180-300 ppm In; Paradis, 2015). Strong correlations of companion metals (e.g., Cd, Hg) with Zn imply that they occur within sphalerite, whereas divergence of In-Sb-Sn from Zn (Figs. 7a, b) indicates possible presence in minerals other than sphalerite (e.g., galena, tin-sulphosalts, cassiterite, stannite).

At both Sullivan and Cirque, Ag and Pb are correlated (Figs. 7a-c), suggesting the Ag is predominantly in galena. Cirque samples exhibit positive correlations between Ag-Cd (-PC2 values; Figs. 7a, c); this association is not evident at Sullivan, where Cd is correlated with In-Sb-Sn (Fig. 7b). Variations in metal signatures in the Cirque samples (e.g., two samples with positive PC2 values; Fig. 7a, c) suggest deposit-scale variations that are not adequately represented by the small sample size.

Table 3. Selected proxies to generate predictive maps used in mineral potential modelling of SEDEX and MVT mineral systems in northeastern British Columbia.

Mineral system component	Mineral system process/ criteria	Mappable proxy	Dataset	Data source
Source/Trap	Source: basinal fluids, metals Trap: anoxic basins	Ancestral North America deep-water basin strata	Digital geology maps	Cui et al. (2017)
Source/Trap	Source: basinal fluids, metals, and brines Trap: fluid reducing environment	Presence of fine-grained siliciclastic rocks, limestone		
Transport	Fluid concentration	Proximity to all faults (<1100 m)		
Transport/Trap	Fluid seals or baffles	High density fault areas		
Trap/Deposition	Change in fluid pH, redox, temperature, or total sulphur	Presence of Earn and Road River groups and the Stone, Dunedin, and Besa River formations		
Trap	Sedimentary basins	Regional low magnetic responses	Aeromagnetic surveys	NRCan (2020)
Deposition	Mineral occurrences	Medium to high density of SEDEX and sedimentary Ba mineral occurrences and rock chips anomalous in Pb and/or Ba	Mineral occurrences	British Columbia Geological Survey (2024)

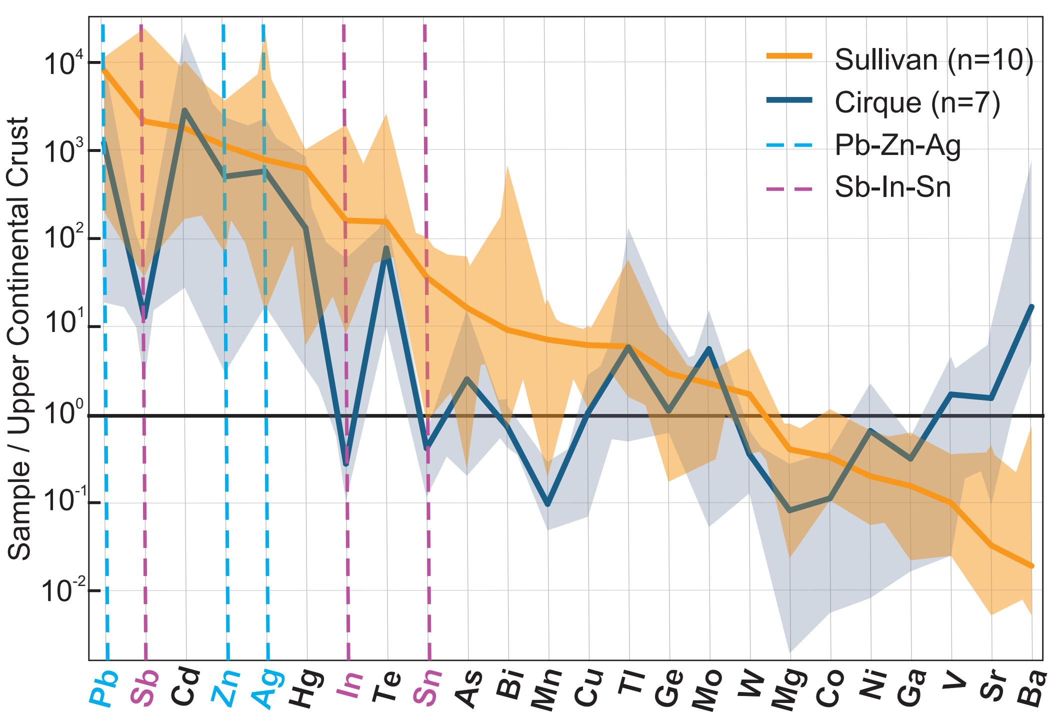

Fig. 6. Elemental enrichments for samples from Sullivan (n=10) and Cirque (n=7) (ioGAS™). Median (line) and range (shaded area) of metal enrichment of samples by deposit relative to average upper crust of Rudnick and Gao (2014), in order of enrichment in Sullivan samples.

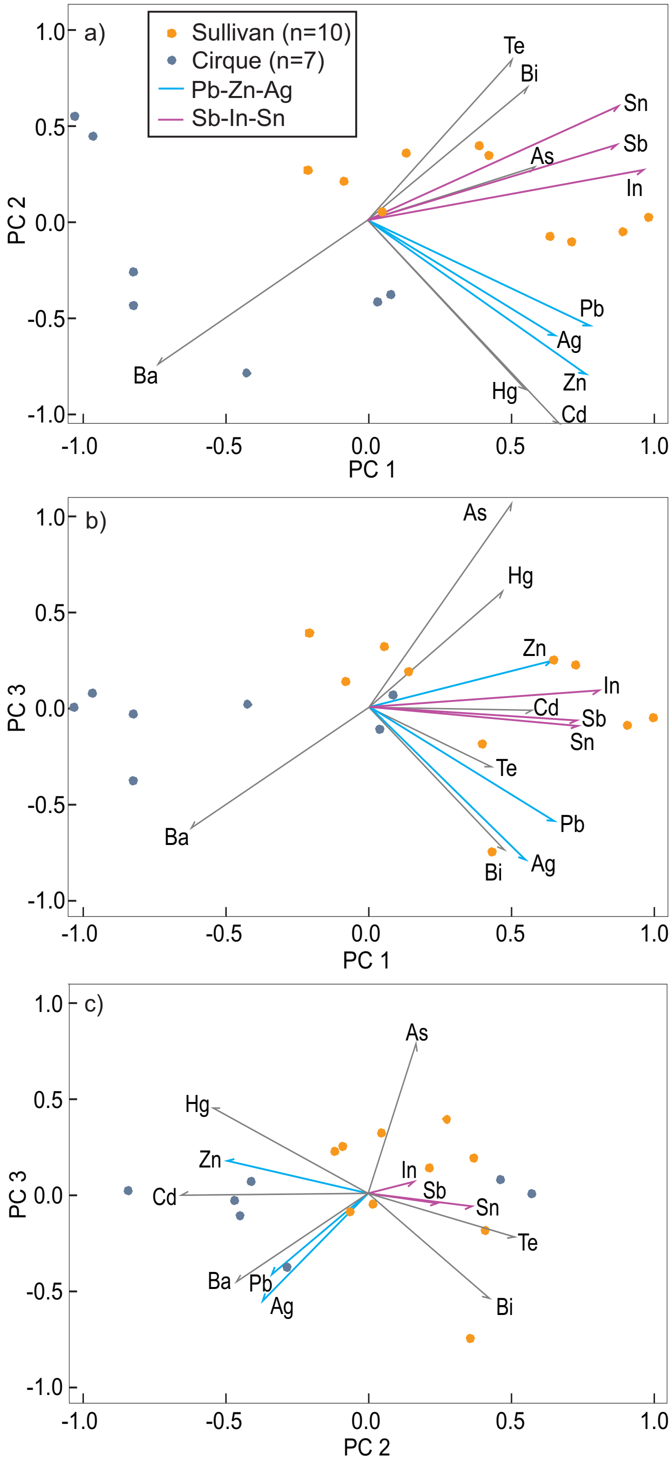

Fig. 7. Principal Component Analysis (PCA) bi-plots from ioGas™. **a)** PC1 versus PC2 for samples (dots) with elemental enrichment vectors. **b)** PC1 versus PC3. **c)** PC2 versus PC3.

4.2. Mineral potential modeling for SEDEX deposits, northeast British Columbia

Combining critical mineral investigations with mineral potential mapping enables identification of provincial domains with both traditional metal endowments (e.g., Pb-Zn-Ag) and poorly quantified companion metal opportunities. Known mineralization received the highest correlation with training data, by combining areas with medium to high density of SEDEX mineral occurrences with sedimentary Ba mineral occurrences, and outcrop grab samples with anomalous Pb or Ba (Wearmouth et al., 2024b). The Kechika trough is the most prospective area for SEDEX deposits (A on Fig. 5). Additionally, an area ~100 km northeast of Dease Lake (B on Fig. 5) contains narrow (<0.5 by 10 km) northwest-trending areas of ‘highest’ to ‘high’ prospectivity. A third northwest-trending area west of Cirque and Akie (C on Fig. 5) contains areas (up to 40 km x 3 km) of ‘high’ to ‘moderate’ prospectivity but lacks favourable trap processes (e.g., strata deposited in anoxic environments; Table 3) to warrant a higher ranking.

5. Conclusion

The preliminary work presented herein indicates that ore from the Sullivan SEDEX deposit is variably enriched in In, which is strongly correlated with other companion metal concentrations such as Sn, Sb, and Cd and that the Cirque project is enriched in Cd. Mineral potential modelling of the SEDEX mineral system indicates that northeastern British Columbia holds potential for SEDEX mineralization, both in the Kechika trough and in smaller areas along what was the western flank of Ancestral North America.

Ongoing work is incorporating scanning electron microscopy-mineral liberation analysis (SEM-MLA) to identify the occurrence and distribution of companion metals either as stand-alone minerals or as micro-inclusions or solid solutions in other mineral phases.

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