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Scientific Presentation 42

UPDATE ON THE SEDEX MODEL FOR DEPOSITS OF THE CANADIAN CORDILLERA YUKON AND BRITISH COLUMBIA

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Abstract

SEDEX (SEDimentary EXhalative) deposits are important resources of Zn and Pb. In addition to Zn and Pb, other potentially economic commodities are: Ag, Au, Cu, Cd, Sb, Sn, and barite. Major metallogenic districts in the Canadian Cordillera that host SEDEX deposits are:

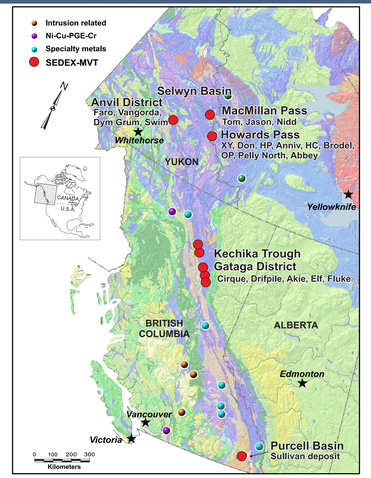
- Mesoproterozoic Sullivan district in southeastern British Columbia, which hosts the world-class Sullivan deposit and other smaller deposits such as North Star and Kootenay King.
- Late Cambrian Anvil district in the Selwyn Basin of central Yukon, which hosts the Faro, Grum, Vangorda, DY, and Swim deposits.
- Early Silurian Howard's Pass district in the Selwyn Basin of the northeastern Yukon, which hosts the world-class Howard's Pass deposits (XY, Brodel, HC, Don, Anniv, OP, Pelly North).
- Late Devonian Gataga district of the Kechika Trough (southern extension of Selwyn Basin) in northeastern British Columbia, which hosts the Cirque, Driftpile, and Akie deposits.
- Late Devonian MacMillan's Pass district in the Selwyn Basin of northeastern Yukon, which hosts the Tom and Jason deposits.

SEDEX deposits are defined as being predominantly composed of Zn and Pb hosted in sphalerite and galena that were deposited at or near the seafloor from basinal metalliferous fluids discharged into rift-controlled anoxic sedimentary basins. They consist of vent-distal and vent-proximal facies. The former is composed of interbedded sphalerite, galena, iron sulphides and clastic sediments, and the latter of variably veined, infilled and replaced bedded sulphides.

Cordilleran SEDEX deposits formed in settings with dynamic redox fronts controlling sulphide and sulphate precipitation within carbonaceous sediments. Zinc, Pb, Cu and other metals are leached from deeply buried clastic sediments during metamorphic mineral reactions and transformations driven by increasing temperature and pressure during burial. At the Howard's Pass (HP) deposits (Yukon), sulphides precipitated from dense bottom-hugging metalliferous brines that accumulated in a bathymetric low, distal to vent complex(es), and percolated into porous unconsolidated sulphidic carbonaceous muds. At the MacMillan Pass (MP) deposits (Yukon), hydrothermal sulphides precipitated sub-seafloor, proximal to vent complex(es), due to interaction of hot (>250°C), acidic (pH ≤ 4.5) metal-bearing hydrothermal fluids with H_2S generated during a number of processes (bacterial and thermochemical sulphate reduction, barite dissolution, and sulphate reduction coupled with anaerobic methane oxidation) in the carbonaceous mudstones. At HP and MP, most of the Zn-Pb mineralisation was precipitated below the seafloor as replacement of early barite (at MP) and fine-grained sediments during early diagenesis. Close proximity to a carbonate platform may have been an important factor for the mineralising systems, enhancing access to sources for saline, metal complexing brines.

Factors that have potential application in the search for SEDEX include the presence of:

1. Deep-seated synsedimentary faults expressed as abrupt changes in facies and isopachs, intraformational breccias, slumps, debris flows, and fault scarp talus.
2. Sedimentary basins hosting organic-rich sediments with > 1% C_{org} adjacent to carbonate platform.
3. Ore-stage diagenetic pyrite that are texturally sooty (i.e. inclusion-rich) and anomaleous in Tl, As, Sb and possibly Mn.
4. Anomalous concentrations of redox-sensitive trace elements (e.g. V, Tl, Cd, U, V/Mo, Re/Mo) Mo, Re/Mo, and Ce/Ce* in the host rocks.
5. Widespread hydrothermal alteration (muscovite, carbonates, and silicates).
6. Laterally and vertically extensive distal sediments that are mineralogically and chemically zoned around seafloor vents.
7. Regional exinic condition is not a prerequisite for the formation of SEDEX deposits.
8. Basin has high biological productivity; should include outer shelf and slope settings and not focus exclusively on anoxic or sulphidic basins.



DEPOSIT MORPHOLOGY

Vent-proximal deposits → **MacMillan Pass district, Sullivan**

Vent-distal deposits → **Howards Pass, Gataga districts**

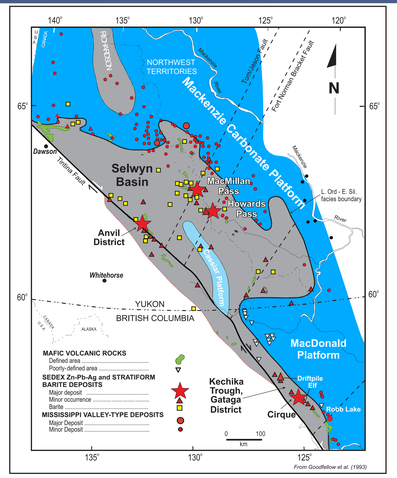
There are two major types of SEDEX deposits in the Selwyn Basin: 1) vent-proximal, with bedded ores overlying vent complexes (e.g. MacMillan Pass deposits), and 2) vent-distal, with laterally extensive bedded ores and no evidence of a vent complex (e.g. Howards Pass and Gataga districts).

Key characteristics of vent-proximal deposits:

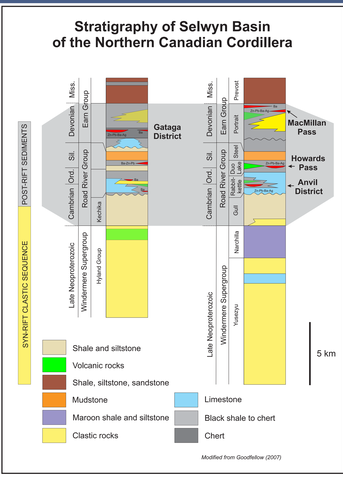
- Consist of bedded sulphides overlying vent complexes;
- Display a mound-like (or lensoidal) morphology;
- Vent complexes consist of a zone of stockwork-style carbonate, quartz, and sulphide veins that cross-cut the altered host sediments; they transition upwards through a zone of massive sulphides and minor barium carbonate into more bedded, stratiform and stratabound sulphide and barite mineralisation.
- Bedded sulphides consist of delicately interlayered sulphides and organic-rich sediments;
- Vent complexes form the primary conduits of hydrothermal fluid upflow; located in proximity to syn-depositional faults.

Key characteristics of vent-distal deposits:

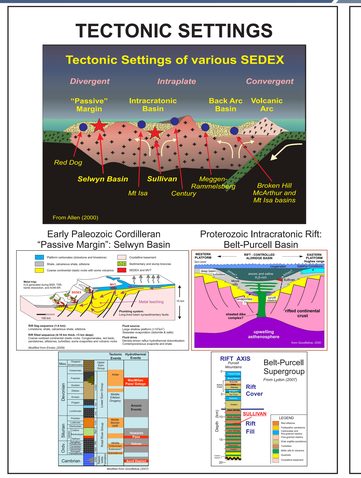
- Consist of bedded sulphides with no discordant footwall hydrothermal alteration and no vent complexes;
- Display a sheet-like or tabular morphology; up to a few tens of metres in thickness and >1 km in length;
- The bedded facies consist of delicately laminated and layered fine-grained sulphides (sphalerite, galena, iron sulphides), organic-rich clastic sediments, and occasionally other components, such as carbonates, chert, barite, and apatite);
- The bulk of the ore is contained in the bedded ore facies.



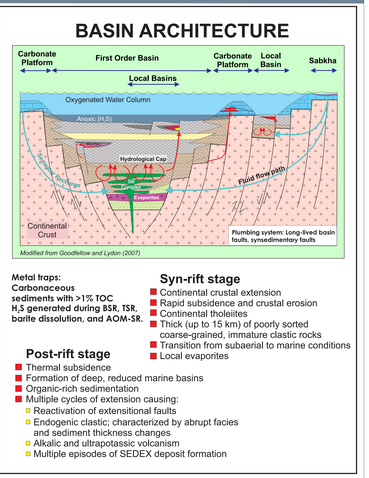
Stratigraphy of Selwyn Basin of the Northern Canadian Cordillera



TECTONIC SETTINGS



BASIN ARCHITECTURE



Metal traps:
Carbonaceous sediments with >1% TOC
H_2S generated during BSR, TSR,
barite dissolution, and AOM-SR.

Syn-rift stage

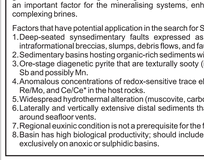
- Continental crustal extension
- Rapid subsidence and crustal erosion
- Continental tholeiites
- Thick (up to 15 km) of poorly sorted coarse-grained, immature clastic rocks
- Transition from subaerial to marine conditions
- Local evaporites

Post-rift stage

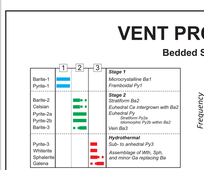
- Thermal subsidence
- Formation of deep, reduced marine basins
- Organic-rich sedimentation
- Multiple cycles of extension causing:
  - Reactivation of extensional faults
  - Endogenic clastic; characterized by abrupt facies and sediment thickness changes
  - Alkalic and ultrapotassic volcanism
  - Multiple episodes of SEDEX deposit formation

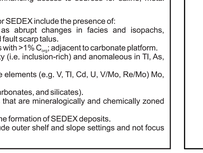
VENT PROXIMAL SEDEX deposits of the Macmillan Pass district, Yukon

Bedded Sulphides



Mineral paragenesis in the bedded sulphides. Stages 1 and 2 predate hydrothermal mineralization. There are 3 generations of Ba and 2 generations of Py associated with Ba. Py1 is framboid; Py2 occurs as stratiform accumulation and euhedral crystals within Ba2; hydrothermal Py (Py3) overprints earlier Py and Ba.



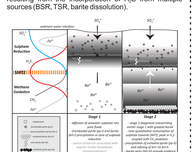


Sulphur Isotopes:

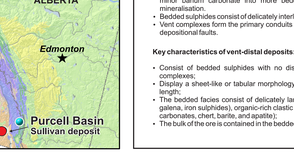
- Early diagenetic framboidal Py1 (-23 to -28‰), euhedral Py2 (8 to 26‰), and barite (24 to 34‰).
- Hydrothermal pyrite Py3 = 3 to 18.6‰. Sphalerite (not shown) = 8.5-22.5‰ (avg.14.5), Galena (not shown) = 8.5-20.2‰ (avg. 13.9).

The isotopic values of Py2 and Ba2 ($\delta^{34}S_{pyrite}$-$\delta^{34}S_{barite}$) are the result of formation of a diagenetic redox front, via anaerobic methane oxidation coupled sulphate reduction (AOM-SR).

Hydrothermal Py3 displays a wide range of $\delta^{34}S$ values, resulting from the incorporation of H_2S from multiple sources (BSR, TSR, barite dissolution).



Vent Complex

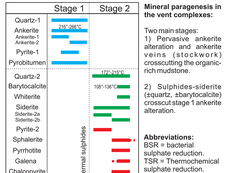


Samples from Tom and Jason vent complexes. A. Stockwork of ankerite veins crosscutting altered mudstone. B. Thick ankerite veins crosscutting altered mudstone. C. Discrete ankerite veins crosscutting unaltered mudstone.

Fluid Inclusions:

- Small fluid inclusions (<10µm) in quartz, ankerite, and barytocalcite.
- CO, rich inclusions in quartz
- Salinity in quartz-2: 3.4-5.7 wt.% NaCl; n=5
- >275°C of fluid entering vent complexes.

Genetic Model



Mineral paragenesis in the vent complexes:

Two main stages:
1) Pervasive ankerite alteration and ankerite veins (stockwork) crosscutting the organic-rich mudstone.

2) Sulphides-siderite (quartz, ± barytocalcite) crosscut stage 1 ankerite alteration.

Abbreviations:
BSR = bacterial sulphate reduction.
TSR = Thermochemical sulphate reduction.
AOM-SR = sulphate reduction coupled with anaerobic methane. oxidation

Schematic model:

- Bedded barite-pyrite assemblage formed along diagenetic redox front where BSR coupled with AOM-SR occurred.
- Hydrothermal stockwork sulphides (pyrite, sphalerite, galena) post-date diagenetic bedded barite-pyrite. They precipitated sub-seafloor due to interaction of hot (>250°C), acidic (pH ≤ 4.5) metal-bearing hydrothermal fluids with H_2S generated during a number of processes (bacterial and thermochemical sulphate reduction, barite dissolution) in the carbonaceous mudstones.
- Metal deposition occurred upon interaction with carbonate altered host-rock (pH increase and fluid cooling).
- Metals are sourced from basement-derived clastic rocks, whereas Ba comes from reduced pore fluids in carbonaceous mudstones at shallow level in the basins.
- High biological productivity, host rock organic matter content, fluid mobility in partially lithified sediments, deep basin penetrating faults, hot fluids (metal transport) and concentration of sulphur in the host rock played important roles in SEDEX formation.

VENT DISTAL SEDEX deposits of the Howard's Pass district, Yukon

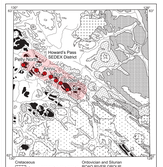


Figure 1: Geologic map of Howard's Pass district showing locations of SEDEX deposits and zones (modified after Goodfellow, 2004).

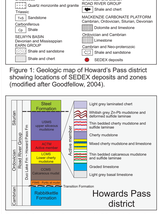


Figure 2: Stratigraphic column of HPD with informal unit names within their designated formation (after Morganti, 1979). Active member hosts all the sulphide mineralisation.

The Howard's Pass Zn-Pb district (HPD) in the Selwyn Basin (Fig. 1) comprises 14 SEDEX Zn-Pb deposits that contain an estimated 400 Mt of Zn and Pb grading at 5% and 2%, respectively (Goodfellow, 1993). The deposits consists of stratabound accumulation of bedded sulphides (no hydrothermal vent complex has been found) in Upper Ordovician-Lower Silurian Road River Group succession (Fig. 2).

Pyrite is a minor but ubiquitous component of the ore mineralogy, which is dominantly comprised of sphalerite and galena.

Objectives and methods:
This study aims to develop geochemical methods to identify favourable strata that host mineralization using micro-analytical instruments. We used petrography, La-ICP-MS and SIMS analytical methods on texturally and paragenetically complex pyrite (Fig. 2) in order to differentiate between ore-stage pyrite and pyrite not associated with ore formation, and to revise the model for SEDEX in HPD.

Figure 3: Pyrite paragenesis with representative photomicrographs of pyrite generations and textures. Framboidal **py1** is the earliest generation to form. Abbreviations: sph=sphalerite; cpy=chalcopyrite.

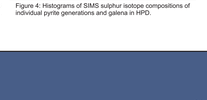


Figure 4: Histograms of SIMS sulphur isotope compositions of individual pyrite generations and galena in HPD.

- Framboidal pyrite (py1) occurs as disseminated to laminated and polyframboidal aggregates. They are the earliest to form.
- Banded (bedded) pyrite (py2a) occurs as banded to bedded subhedral and euhedral aggregates. Overprints and recrystallizes py1.
- Nodular and concretionary pyrite (py2b) occurs as rounded masses. Overprints and recrystallizes polyframboidal py1.
- Euhedral pyrite (py3): overgrowths on pre-existing pyrites.

Results:

Microscopy reveals multiple generations of pyrite growth. Pyrite occurs as framboids, polyframboidal clusters (Fig. 3A), micro-euhedra, bedding parallel bands (Fig. 3B), nodules (Fig. 3C), porphyroblasts and metamorphic overgrowths (Fig. 3D).

$\delta^{34}S$ values of **py1** = -26.1 to -7.5‰ (Fig. 4).
Bedded (**py2a**) and nodular pyrite (**py2b**) are isotopically indistinguishable = 10.3 to 49.7‰.

$\Delta^{34}Spy2\text{-}py1 = 40‰$ over distances <50 µm.

$\delta^{34}S$ values of **py3** = 17 to 27.3‰.

$\delta^{34}S$ values of **ga** = 17 to 27.3‰.

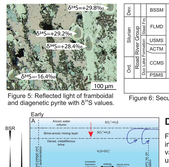


Figure 5: Reflected light of framboidal and diagenetic pyrite with $\delta^{34}S$ values.

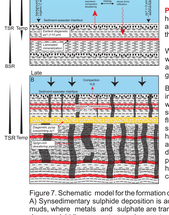


Figure 6: Secular distribution of sedimentary pyrite and seawater sulphate.

Discussion and Model:

Framboidal **py1** formed either in the euxinic water column or in the uppermost sulphidic sediment porewaters. Its isotopic value is consistent with derivation of sulphide from unfractionated seawater sulphate (Fig. 6).

Pyrite2, sphalerite, and galena $\delta^{34}S$ values are much heavier than **py1**. By inference, the base metal sulphides and framboids do not have a common source of sulphur and they are not coeval (Ohmoto and Goldhaber, 1997).

We propose that additional (oxidized) sulphur was delivered with base metals to the ambient euxinic (?) water column and that both BSR and TSR are responsible for the generation of reduced sulphur in SEDEX deposits.

BSR was the most important process prior to the introduction of metalliferous fluids and these sulphidic waters provided a necessary catalyst for TSR. TSR superseded BSR following the introduction of metalliferous fluids because these fluids were too warm to support significant bacterial activity. In the early stage of hydrothermal activity, BSR occurred in the water column and in the shallow sediments (Fig. 7A). Continued venting of dense brine resulted in its downward percolation into porous unconsolidated muds, where TSR reduced hydrothermal sulphate by the oxidation of labile organic carbon (Fig. 7B).

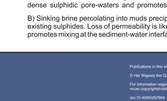


Figure 7. Schematic model for the formation of SEDEX deposits in the HPD.
A) Syngenetic/early sulphide deposition is accompanied by dense brine sinking into permeable muds, where metals and sulphate are transported together. Dense brine sinking displaces less dense sulphidic pore-waters and promotes early TSR.

B) Sinking brine percolating into muds precipitates diagenetic sulphides that form overgrowths on pre-existing sulphides. Loss of permeability is likely followed by vertical compaction and dewatering, which promotes mixing at the sediment-water interface (adapted and modified from Ireland et al. 2004).

SYNTHESIS

also see GSC OF 7838:
Paradis et al. (2015): Sediment-Hosted Zn-Pb Deposits: Processes and Implications for Exploration

Major metallogenic districts in the Canadian Cordillera hosting SEDEX are located in the **Purcell Basin** of southeastern BC (e.g., Sullivan) and **Selwyn Basin** of Yukon, NT, and BC (e.g., Anvil, Howards Pass, MacMillan Pass, Gataga).

- SEDEX deposits formed in settings with dynamic redox fronts controlling sulphide and sulphate precipitation within permeable sediments of the shallow succession.
- Zinc, Pb, Cu and other metals are leached from deeply buried clastic sediments during metamorphic mineralogical transformations driven by increasing temperature and pressure during burial.
- Proximity to a carbonate platform may be an important requirement for some mineralising systems, enhancing access to sources for saline and metal complexing brines, and providing the fluid drive.

Howards Pass District (HPD):

- Vent distal deposits with stratabound bedded sulphides in siliceous to carbonaceous, calcareous mudstones.
- There are multiple generations of pyrite, from syngenetic to metamorphic.
- Sulphur isotope data indicate two different sources of sulphur: bacterially reduced seawater sulphate (BSR) for early framboidal pyrites (negative $\delta^{34}S$ values), and thermochemically reduced sulphate (TSR) for later pyrite overgrowths, Sphalerite, and galena have positive $\delta^{34}S$ values.
- Zn, Pb, Mn, As, Ag, Sb and Tl were delivered in the mineralising fluid.
- Immediate host rocks and mineralisation contain abundant fine-grained layers of apatite that has rare earth element (REE) compositions identical to marine upwelling phosphorites, indicating hydrogenous deposition under suboxic conditions.
- Hydrothermal mineralising event (ie. SEDEX) is **early diagenetic and mostly recurred in the subsurface.**

Genetic model:

- Dense, bottom-hugging brines exhaled from submarine vents in pulses related to the reactivation of early growth faults.
- Hydrothermal sulphides (pyrite, sphalerite and galena) precipitated from dense bottom-hugging brines, which accumulated in bathymetric lows, distal to vent complex(es), and percolated into porous unconsolidated sulphidic carbonaceous muds.

MacMillan Pass District (MDP):

- Vent proximal deposits (Tom and Jason) with stratabound bedded sulphides and vent complexes in siliceous to carbonaceous mudstones.
- Hydrothermal mineralising event (Py3, Sph, Ga) post-dates diagenetic pyrite (Py1, Py2) and barite, and ankerite alteration → **sulphide mineralisation is diagenetic and mostly occurred in the subsurface.**

Genetic model:

- Bedded sulphides: Bedded barite-pyrite assemblage formed along diagenetic redox front where sulphate reduction coupled with anaerobic methane oxidation (AOM-SR) occurred.
- Vent complexes: Hydrothermal sulphides were precipitated in the shallow subsurface during diagenesis due to interaction of hot (>250°C), acidic (pH ≤ 4.5) metal-bearing hydrothermal fluids with H_2S generated during a number of processes (bacterial and thermochemical sulphate reduction, barite dissolution) in the carbonaceous mudstones.

High biological productivity, host rock organic matter content, fluid mobility in partially lithified sediments, deep basin penetrating faults, hot fluids (metal transport) and concentration of sulphur in the host rock played important roles in SEDEX formation.

Collectively, the data from HDP and MDP show that mineralisation was precipitated below the seafloor in the shallow subsurface during diagenesis, and euxinic conditions were not a requisite for SEDEX formation.

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