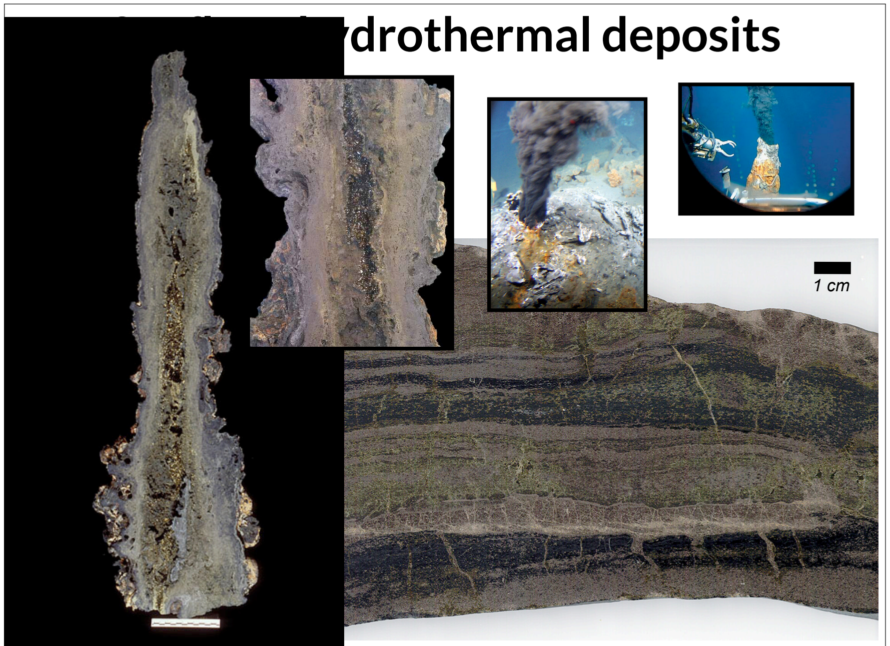
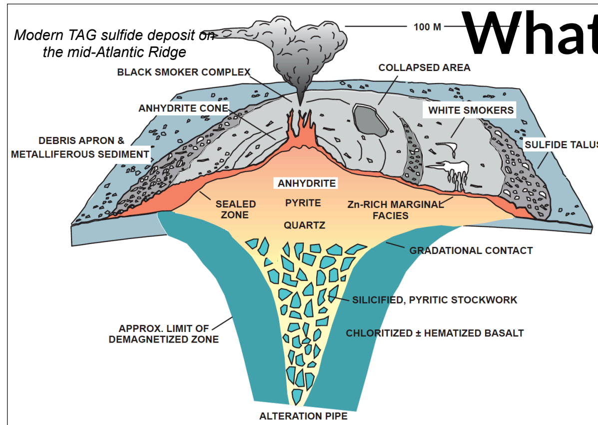
drothermal deposits



What is a VMS?



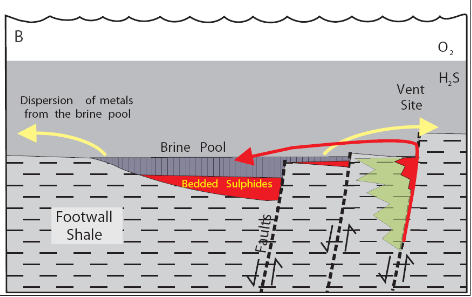
VMS
Volcanic-associated
Volcanic-hosted
Volcanic-sedimentary-hosted

- **Volcanogenic massive sulfide (VMS) deposits occur as lenses of polymetallic massive sulfide that form at or near seafloor in submarine volcanic environments:**
  - Form from metal-enriched fluids associated with seafloor hydrothermal convection (“exhalative”).
  - Host rocks can be either volcanic or sedimentary.
  - Major sources of Zn, Cu, Pb, Ag, and Au (± many others).
- **Mound-shaped to tabular, stratabound bodies of massive sulfide (>40%)**
  - underlain by stockwork veins or “pipes” and disseminated sulfides.

What is a SEDEX deposit?

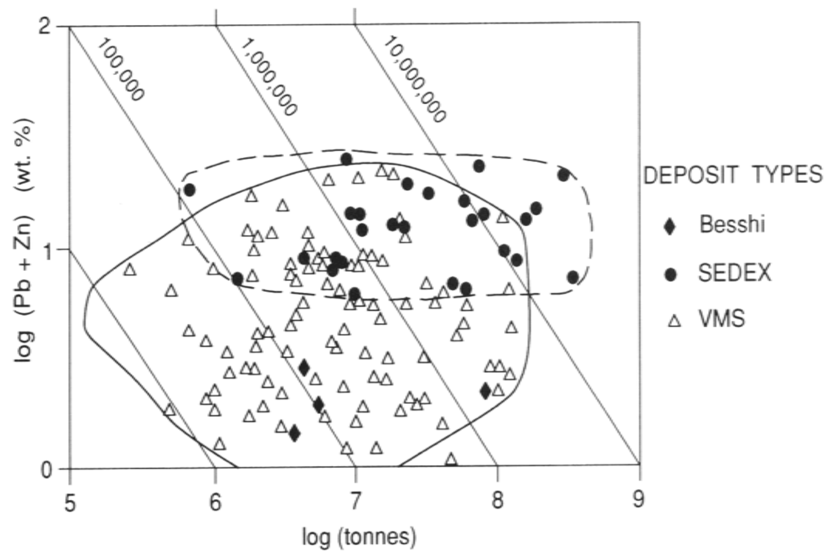
- **SEDimentary EXhalative (SEDEX) deposits**
  - STRATIFORM
  - sphalerite, galena and pyrite (± pyrrhotite) with abundant Ag
  - assoc. w/ bedded barite
  - interbedded with basinal sediments
    - *usually fine grained clastic*
- **Form in reduced sedimentary basins in <u>continental</u> rift settings.**
  - deposited on seafloor, and
  - as replacement of fine-grained clastic sediments

Stratiform =
concordant with bedding; usually in sheets but may be ribbon-like.



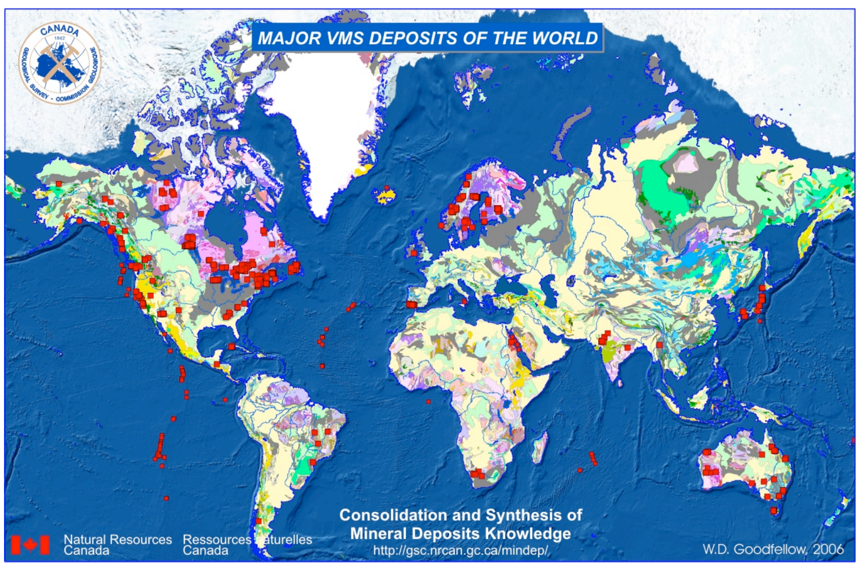
VMS vs. SEDEX

- VMS
  - At or very near black smoker vent
  - Extensional settings
    - *mid-ocean ridges*
    - *rifts*
    - *back-arc basins*
  - Rapid formation
- SEDEX
  - Generally far from any source vent
    - *vent probably not a black smoker*
  - Continental rifting-related
  - Slow (millions of yrs) formation
  - ~10X bigger than VMS
  - Pb-Zn
    - *50% of world resources*
    - *~25% of production*
      - fine-grained



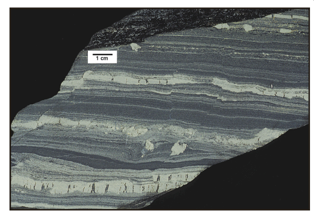
VMS Geologic Setting

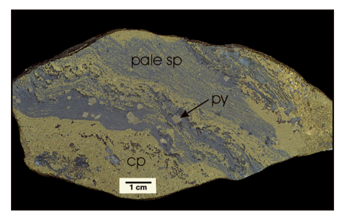
- **VMS deposits are formed/ found at/in**
  - Divergent plate margins (ophiolite-associated deposits)
  - Convergent plate margins in island arcs or continental margins (Kuroko-type deposits)
    - *localized extensional settings*
  - Associated with intra-plate oceanic islands
  - Archean greenstone belts
- **VMS deposits range in age from about 3500 Ma in the Pilbara craton (NW Australia) to the modern sulfide deposits of the East Pacific Rise and Juan de Fuca Ridge.**

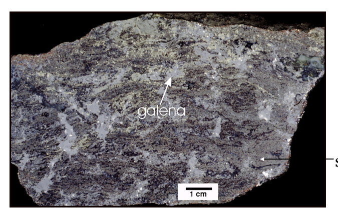


- **~850 known VMS deposits worldwide**
  - reserves of over 200,000 tonnes
  - found in submarine terranes
  - range from 3.4 Ga (Pilbara, Australia) to actively forming deposits (ocean ridges, back arcs).

VMS Major Ore Minerals





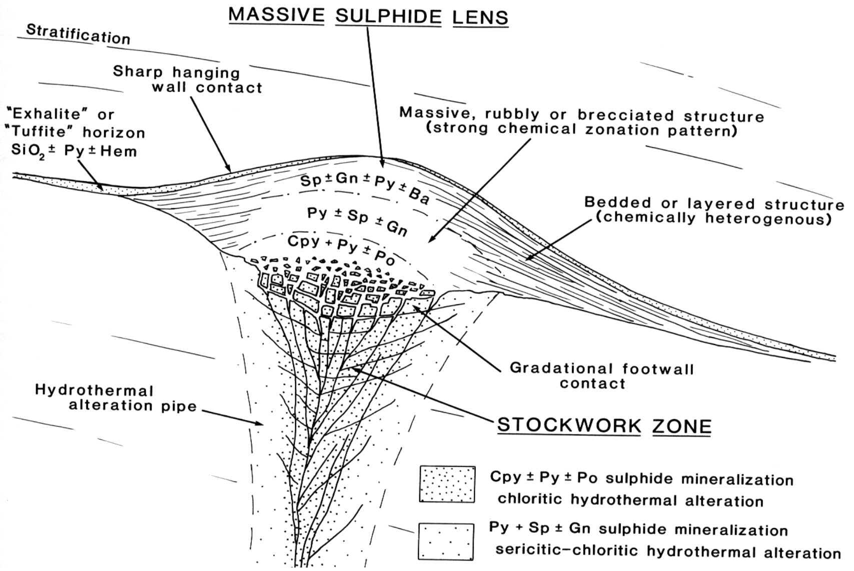


sph

2.71 Ga Kidd Creek ores (bimodal-mafic VMS)

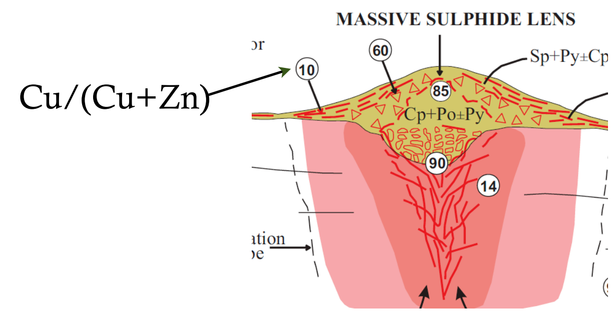
- **Sphalerite (sph or sp) = (Zn,Fe)S**
  - White, yellow, brown, black in hand sample (darkening with increasing Fe); grey in polished section
  - Resinous luster as crystals, earthy to submetallic in colloform or massive habits
- **Chalcopyrite (cp) = $CuFeS_2$**
  - Brassy yellow in hand sample; brass yellow in polished section
  - High reflectance in polished section (not as high as pyrite)
- **Galena (gn) = PbS**
  - "Lead grey" with a bluish tint in hand sample; white in polished section
  - Very dense (~7.5 g/cm3) and soft (H=2.5)
  - Perfect cleavage results in cubes or octahedra.

VMS schematics



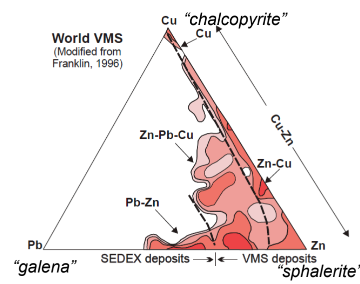
VMS Metal Zonation

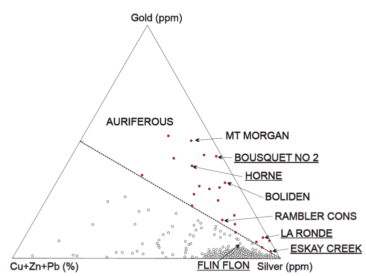
- **Increase in Zn:Cu ratio upward and outward from the core of the massive sulfide lens**
  - Local physicochemical gradients affect mineral precipitation from (and alteration by) an ore fluid
  - Progressive local cooling of the solutions causes the Cu-dominant to Zn-dominant zonation.



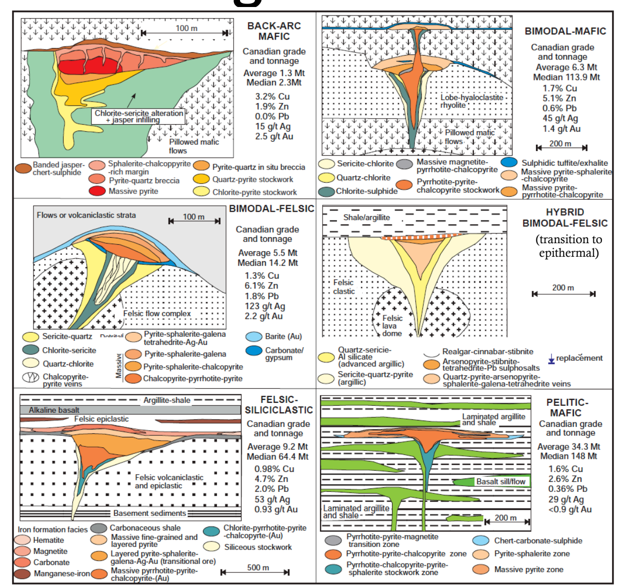
VMS Classification

- **VMS deposits are divided groups according to their contained ratios of the Pb, Cu, & Zn:**
  - Zn-Cu or Cu-Zn
    - *Precambrian primitive oceanic arcs*
  - Zn-Pb-Cu
    - *Pb-rich rifts and arcs*
- **Some are particularly gold-rich:**
  - Arbitrarily defined as:
    - *Au (ppm) > Zn+Cu+Pb (in wt%)*
- **Also classified by host lithologies (relate to tectonic settings)**
  - Bimodal-mafic (+ultramafic)
  - Back-arc-mafic
  - Pelitic-mafic
  - Bimodal-felsic
  - Hybrid bimodal-felsic
  - Felsic-siliciclastic
- **Older classification scheme:**
  - Kuroko-type deposits (felsic volcanics)
  - Cyprus-type deposits (mafic volcanics)
  - Besshi-type deposits (mafic volcanics + clastic sediments)



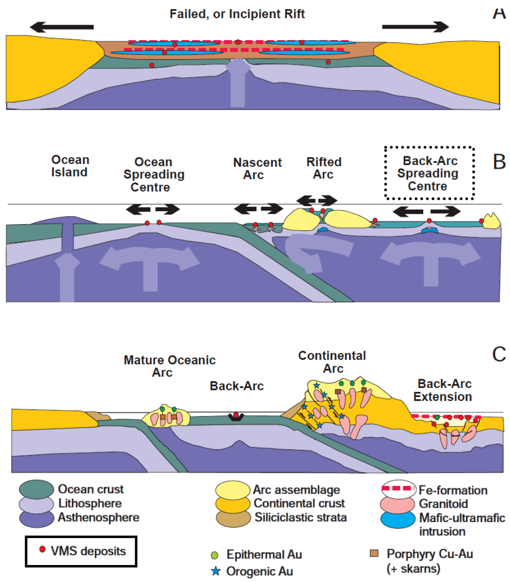


VMS Lithological Classification



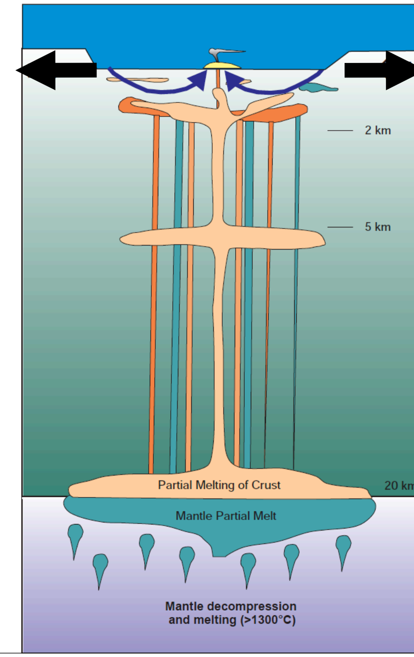
Note the shapes and sizes of sulfide deposits compared to alteration footprint.

VMS : Extensional Settings

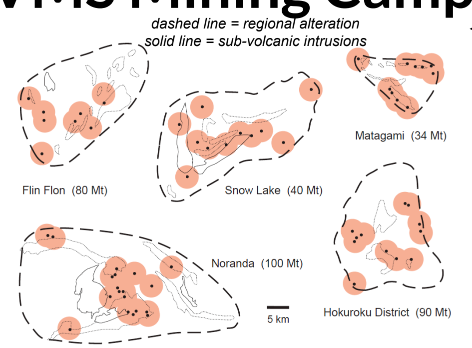


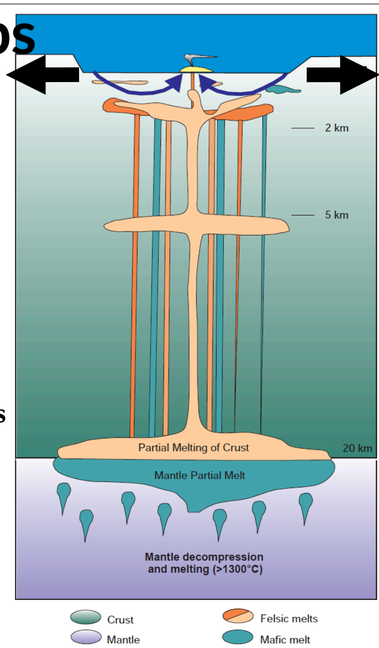
- **Incipient or failed rift settings:**
  - Abundant mafic volcanic rocks/ komatiites and sills with clastic sedimentary rocks (pelitic-mafic, bimodal-mafic)
- **Active spreading centres (mid-ocean ridges, spreading back-arcs and rifted oceanic arcs):**
  - Formation of "calderas" dominated by bimodal mafic extrusive successions
- **Continental margin arcs and back-arcs:**
  - Volcaniclastic-rich bimodal felsic deposits

Bimodal volcanism



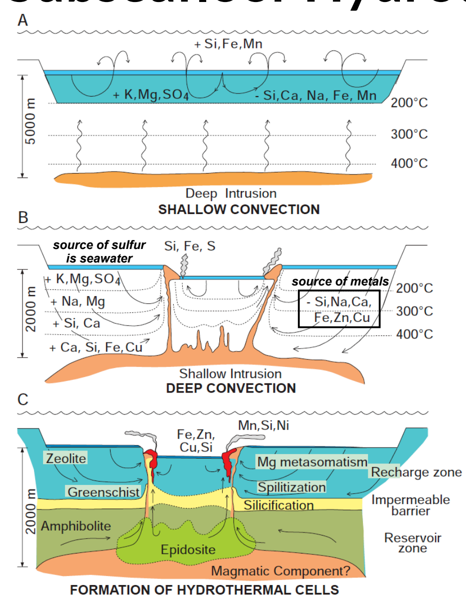
VMS Mining Camps





- **Most VMS deposits occur in clusters that define major *mining camps*:**
  - Clusters restricted to linear vents or calderas
    - *generated by regional thinning*
    - *elongate sills few 1000m below the seafloor*

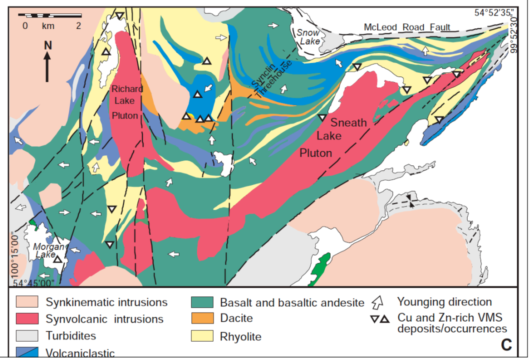
Subseafloor Hydrothermal Systems



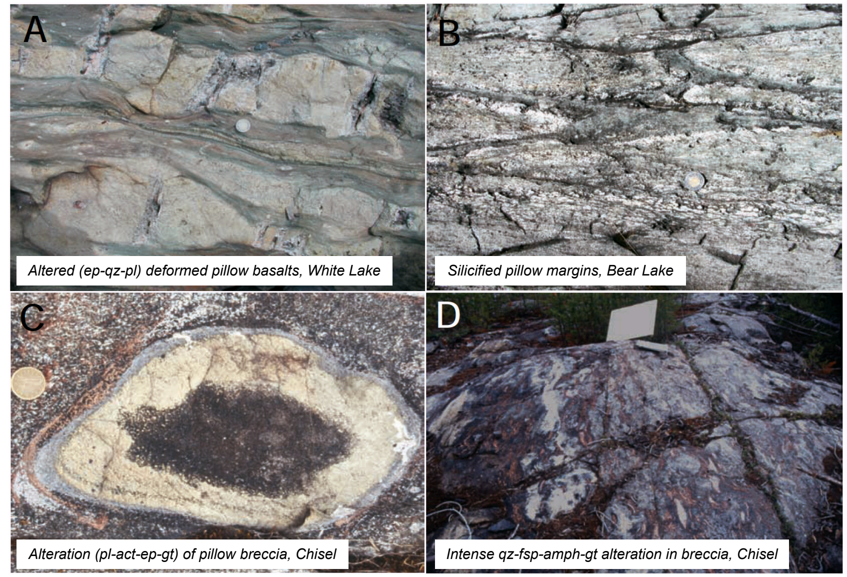
- **Convection system**
  - driven by emplacement of mafic or composite intrusions
  - seawater heated; becomes buoyant
  - rises up syn-volcanic fault structures
  - cold, near-neutral pH fluids are heated and interact with surrounding rocks.
- **Alteration zones**
  - stratified, district-scale alteration zone
  - mineral assemblages mimic regional metamorphic facies (zeolite to amphibolite)
  - high-temperature, acidic metal-laden hydrothermal fluids rise along faults
    - *proximal "pipe-like" alteration systems beneath deposits.*
  - hydrothermal fluids emitted at the seafloor through chimneys ("black smokers")
    - *reaction with cold seawater causes the metals to precipitate.*

Syn-volcanic Intrusions

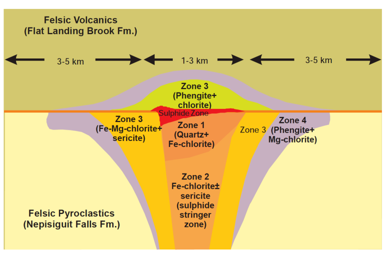
- **Syn-volcanic intrusions: heat source for hydrothermal convection:**
  - Snow Lake:
    - *8 bimodal-mafic deposits*
    - *underlain by two subvolcanic intrusions (Richard Lake and Sneath Lake)*
      - two separate hydrothermal events



VMS Semi-Comformable Alteration Styles

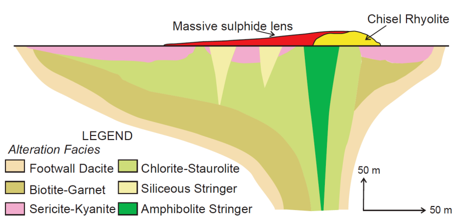


Proximal Alteration Systems



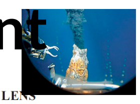
Above: VMS alteration system metamorphosed to greenschist-grade mineral assemblages (Bathurst)

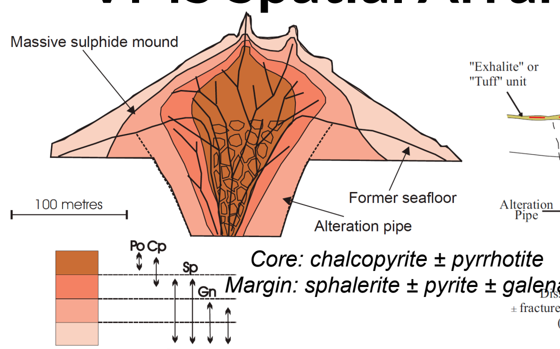
Below: VMS alteration system metamorphosed to amphibolite-grade regional metamorphism (Snow Lake)

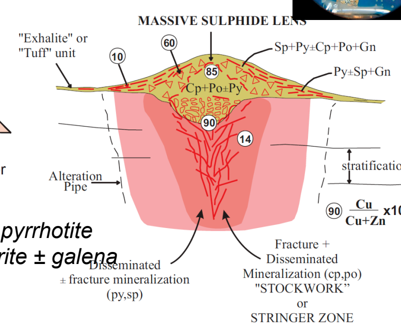


- **Proximal alteration beneath the massive sulfide lenses in VMS deposits**
  - chlorite core, sericite margins
  - associated with stockwork vein systems
  - alteration zones or "pipes" can extend 100s of metres below the massive sulfide
  - alteration halo can be up to twice diameter of the massive sulfide lens.
  - hanging wall alteration can extend for 10s to 100s of metres above the deposits reflecting continued hydrothermal activity after burial of the deposit.
  - alteration zones (and associated mineralization) can be a series of stacked massive sulfide lenses
    - *sequential phases of ore formation*
- **The proximal alteration halo makes an excellent exploration target.**
  - may extend for kms from sulfide!

VMS Spatial Arrangement

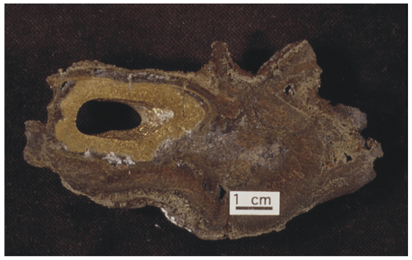






- **Massive sulfide lenses can be >100 m thick, tens of metres wide, and hundreds of metres long**
  - form as sulfide-silicate-sulfate chimneys on seafloor.
  - continued growth and collapse results in breccia mound
- **Circulation of hydrothermal fluids seals mound from seawater**
  - precipitates silica, clay and/or sulfate cap
  - progressive deposition of metals occurs within sealed mound to make massive sulfide.
- **Flow of hydrothermal fluid through mound can remobilize and replace sulfide**
  - seafloor sediments can be replaced unit-by-unit by sulfide due to hydrothermal flow

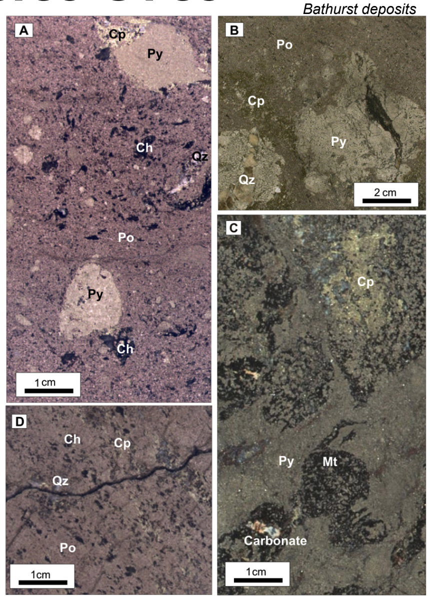
Vent Facies Ores



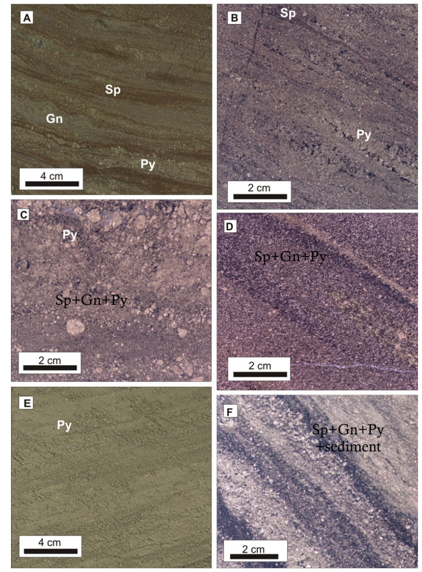
Above: zoned sulfide chimney, Endeavour Ridge vent field

Above: sample of massive sulfide mound, Juan de Fuca Ridge, Main vent field

Bathurst deposits

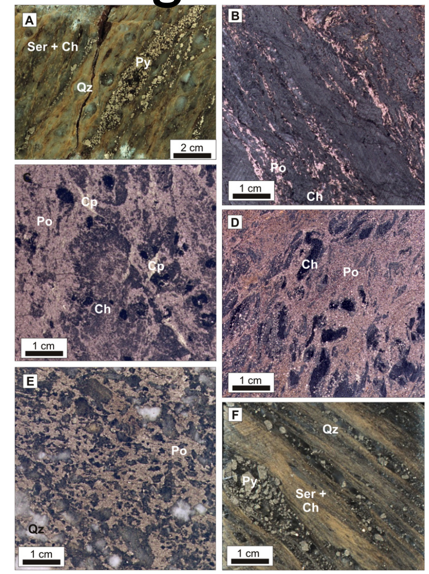


Bedded Ores



Bedded ores: fine-grained and distal from vent

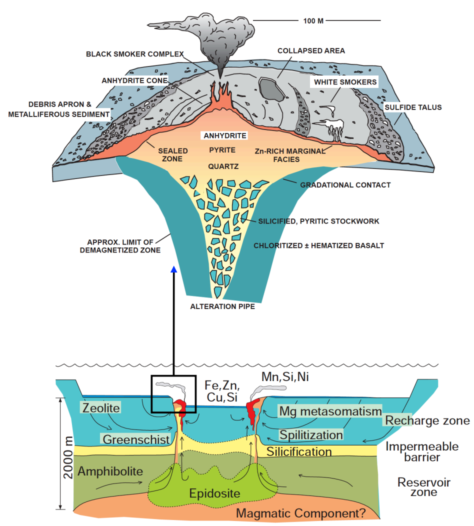
Stringer Zone



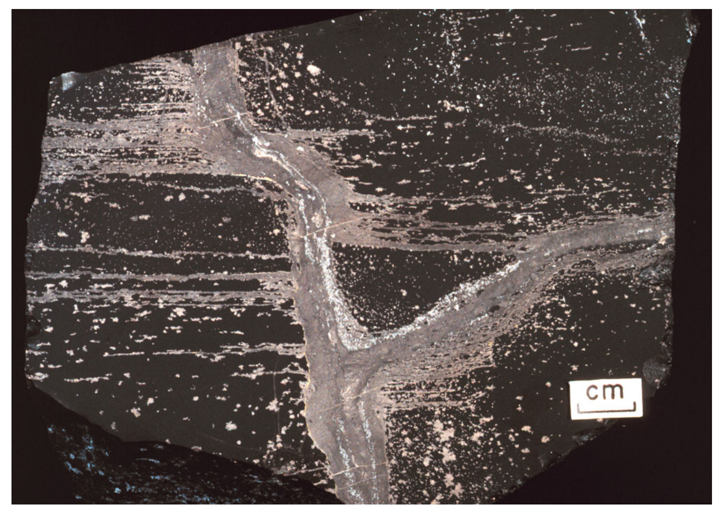
Sulfide stringer zone: complex, typically po+py & cp veins

VMS: Source-Transport-Trap

- **Source of S**
  - mostly seawater sulfate
- **Source of metals**
  - underlying host rock (volcanic + sediments)
- **Source of fluid**
  - seawater
- **Transport**
  - metals (Zn-Cu-Pb ± Au-Ag-others) leached and transported in solution
    - *acidic hydrothermal fluids*
- **Trap**
  - seafloor vent
  - or water-saturated zone just below the seafloor
  - hot hydrothermal fluids interact with cold seawater and precipitate the metals.



SEDEX

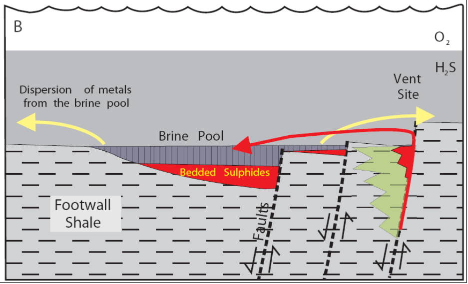


Sulphide veins cutting footwall tourmalinite pipe, with selective replacement along bedding in tourmalinitized siltstone. Note that the vertical vein is along a fracture that displaces bedding. Sullivan deposit - from Leitch et al., 2000.

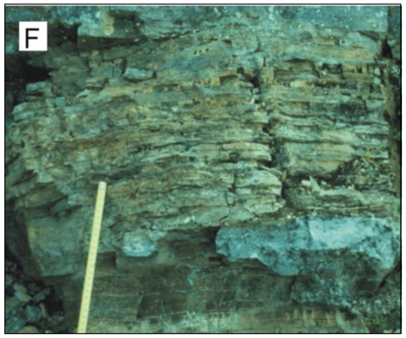
What is a SEDEX deposit?

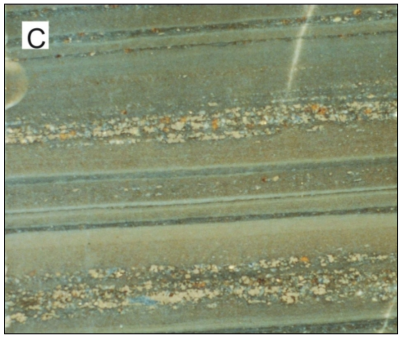
- **SEDimentary EXhalative (SEDEX) deposits**
  - STRATIFORM
  - sphalerite, galena and pyrite (± pyrrhotite) with abundant Ag
  - assoc. w/ bedded barite
  - interbedded with basinal sediments
    - *usually fine grained clastic*
- **Form in reduced sedimentary basins in <u>continental</u> rift settings.**
  - deposited on seafloor, and
  - as replacement of fine-grained clastic sediments

Stratiform = concordant with bedding; usually in sheets but may be ribbon-like.



SEDEX





Well-bedded barite ore from the Tom deposit in Yukon (left) and a close-up of finely laminated massive sulfide ore from the Gataga District in NE BC (right)

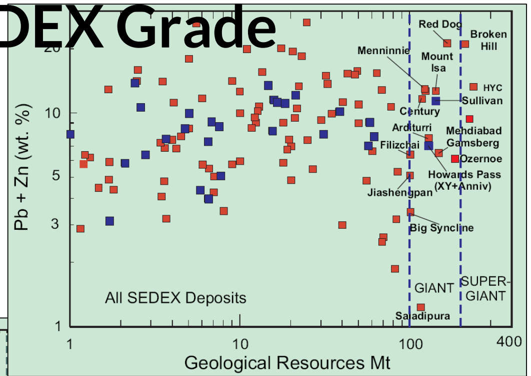
Howards Pass deposit, Selwyn Basin, Yukon – Active Member-upper unit: sphalerite and galena with minor pyrite delicately interlaminated with black carbonaceous chert and cut by axial planar pressure dissolution cleavages filled with mostly sphalerite and galena.

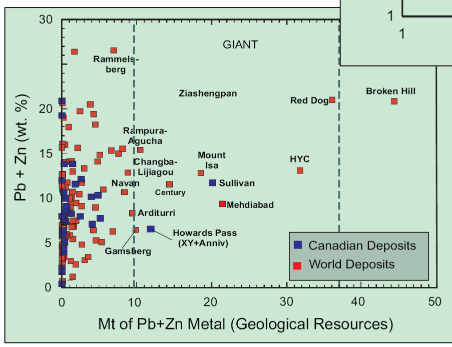
Australia - Mount Isa → spectacular banded Pb-Zn-Ag ore and brecciated banded ore
http://www.geodiscovery.com.au/slideb/index.html

SEDEX Grade

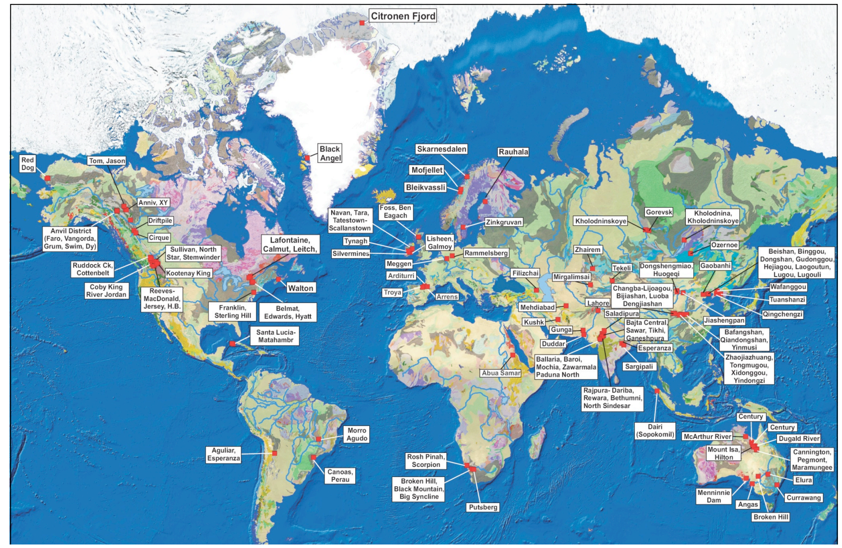
Grade vs. tonnage plots for SEDEX (including Irish and BHT) deposits world wide

Max size SEDEX vs Porphyry
- Porphyry $10^8 - 10^7$ tonnes Cu
- SEDEX ~1-4 x 10^7 tonnes Pb+Zn





SEDEX deposits are typically larger and have higher Zn + Pb grades than VMS deposits. They commonly have quite high Ag contents but relatively low Au contents.



Global SEDEX deposits

Goodfellow and Lydon, 2007

SEDEX Tectonics

- **Extensional basins**
  - Failed epi- and intra-cratonic (continental) rifts and Atlantic-type rifted continental margins.
- **Most formed during periods of tectonism**
  - fault reactivation
  - intra-basin clastic sedimentation
  - sometimes volcanism and/or sills
- **Most in reduced marine basins adjacent to deeply penetrating faults**
  - faults provide fluid conduits
- **Deposits commonly found in smaller, fault-controlled sub-basins within large sedimentary basins.**
- **Some Australian SEDEX deposits associated with basin contraction during diagenesis**

Epi-cratonic(continetal) rift →partially open to an ocean basin

SEDEX Tectonics

- **Continental extension**
  - Back-arc basin
  - Failed/incipient rift
  - Trailing margin (successful rift)

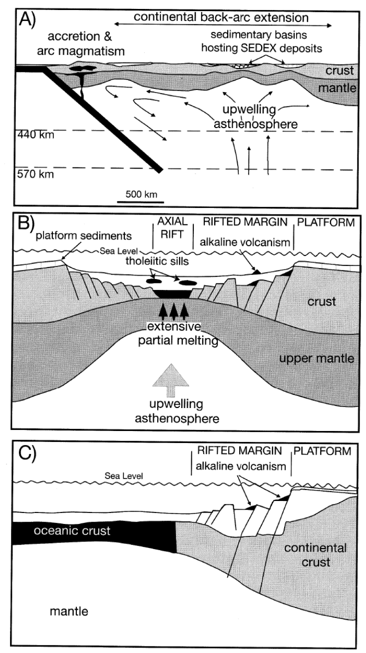
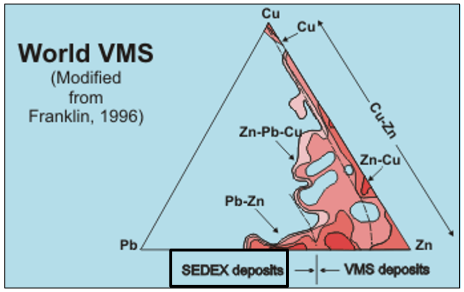


FIG. 20. Cartoons showing tectonic models for the development of sedimentary basins hosting SEDEX deposits. A. Intracontinental or failed rift setting where extensional basins are developed in the overriding plate related to a north-dipping subduction zone along the southern margin of the craton (e.g., northern Australia; Large et al., 2005). B. Continental rift floored by oceanic crust and filled with a thick sequence of clastic sediments (e.g., Selwyn basin; Goodfellow, 2004). C. Passive continental margin rift with oceanic crust outboard from continental crust and sedimentary basin (e.g., northern Alaska; Young, 2004).

Leach et al., 2005

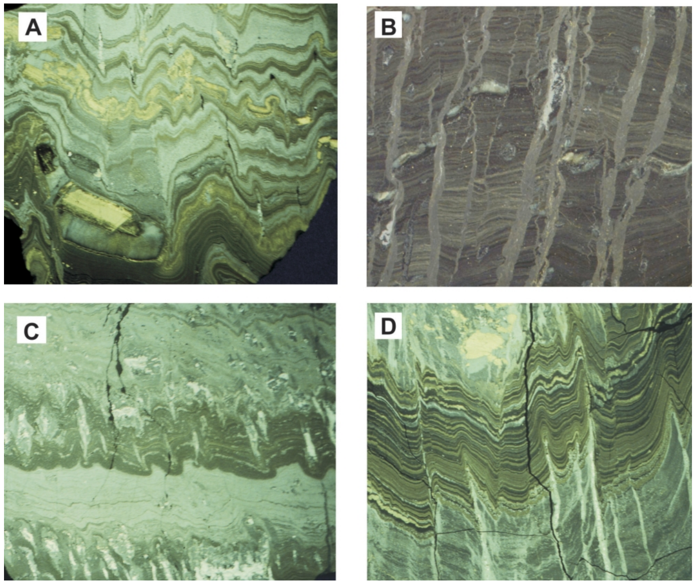
SEDEX-VMS continuum

- **Related processes**
- **Continuum of characteristics between SEDEX and VMS**
- **BUT: form in different geological environments**
  - SEDEX deposits typically occur within thick sedimentary basin sequences
    - *result from the migration of basinal saline fluids*
    - *generally no volcanics*
  - VMS deposits occur in submarine volcanic-sedimentary sequences
    - *formed from convecting seawater-derived fluids*
    - *driven by sub-volcanic intrusion*



SEDEX Mineralogy

- **Fairly simple mineralogy**
  - Base metals contained in sphalerite (Zn)and galena (Pb)
  - Barite common in some deposits, particularly those of North America
  - Gangue minerals include
    - *abundant pyrite (FeS_2)*
    - *sometimes pyrrhotite (FeS)*
      - esp. if deposit has been metamorphosed
  - Ore and gangue minerals are commonly very fine grained and intimately intergrown
    - *major problems in metal extraction*
- **Usually no distinct alteration halo**
  - unlike other deposit types such as porphyry or epithermal vein
  - subtle alteration can sometimes be discerned on a deposit scale

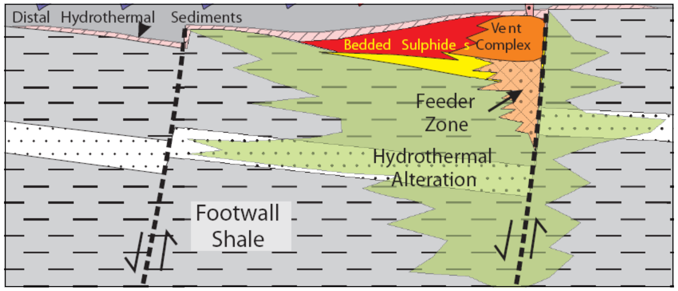


Cut and polished hand samples of delicately laminated ore from the Howards Pass deposit,

SEDEX Deposit Features

- **Most are large and tabular**
- **Typically are internally layered with stratiform sulfide-rich beds interlayered with sulfide-poor clastic units**
- **Some deposits have a distinct discordant Feeder Zone (Pipe)**
  - typically a fault
  - discordant zone composed of sulfide, carbonate and silicate veins and replacement
    - *overprints footwall sedimentary sequence*
  - zone of reaction between upflowing hydrothermal fluid and footwall sediments
  - analogous with VMS feeder pipes – zones of upflowing hydrothermal fluid

SEDEX Deposit Features



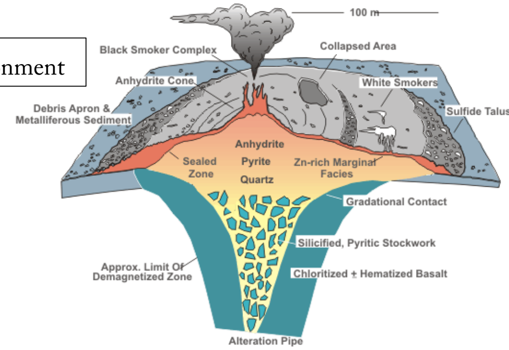
- **Vent-proximal deposits are characterized by four distinct facies:**
  - bedded sulfides
  - vent complex
    - *bedded sulfides are infilled, veined and replaced by a high-temperature mineral assemblage*
  - sulfide stringer zone (Feeder Zone)
  - distal hydrothermal sediments

After Goodfellow and Lydon, 2007

SEDEX Deposit Features

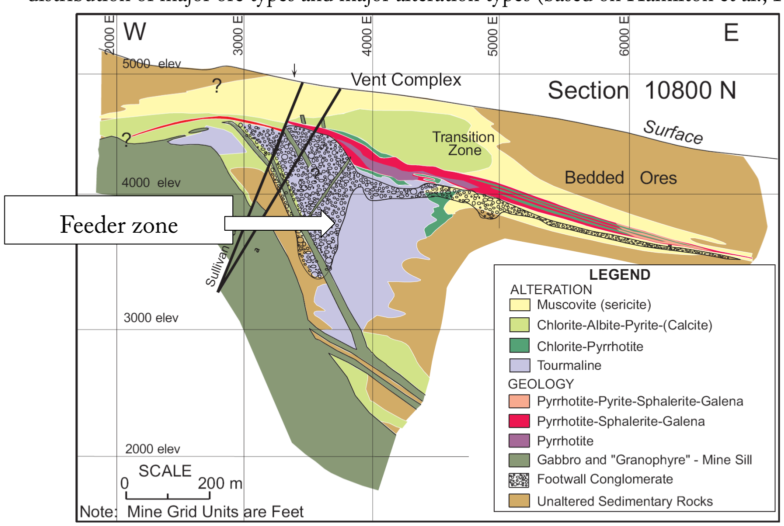
- **Proximal deposits**
  - Stratiform deposits directly above a feeder zone
- **Distal deposits**
  - Stratiform deposits without a feeder zone
- **NOTE: 80% of SEDEX deposits are distal**
  - no evidence for any feeder zones
  - very different from VMS deposits, which are typically proximal to a vent

VMS environment



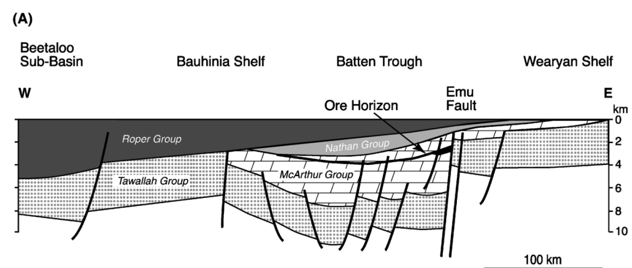
SEDEX Deposit Features

Semi-schematic west-east cross-section through the Sullivan deposit showing the distribution of major ore types and major alteration types (based on Hamilton et al., 1982).

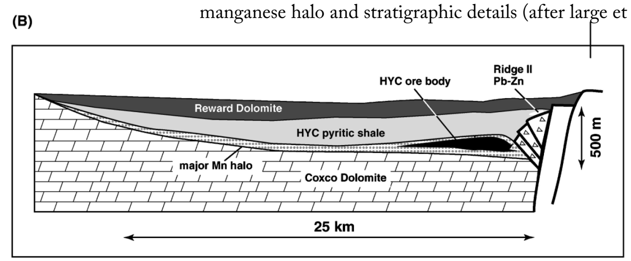


Goodfellow and Lydon, 2007

SEDEX Deposit Features

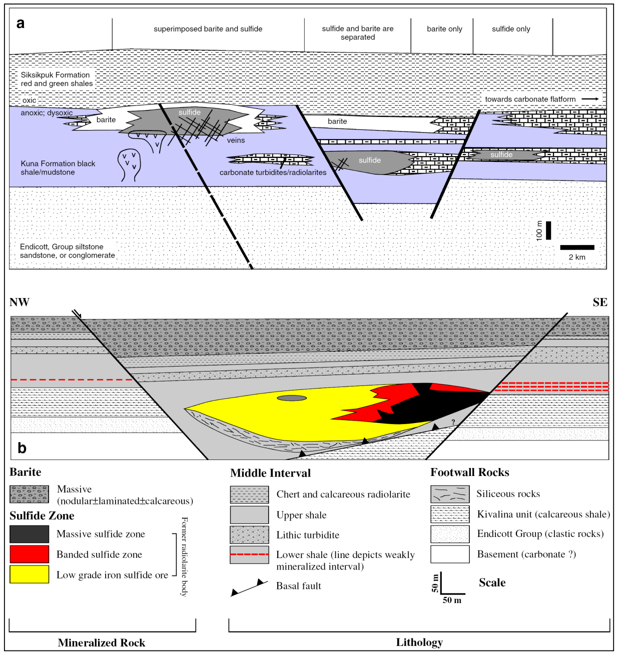


Geologic setting of the HYC ore deposit, McArthur Basin, Australia. (A) Regional geological profile across the Batten Trough (after Plumb 1987). (B) Expanded view of HYC showing reconstruction of manganese halo and stratigraphic details (after large et al. 1998).



Garven et al., 2001

Red Dog, AK



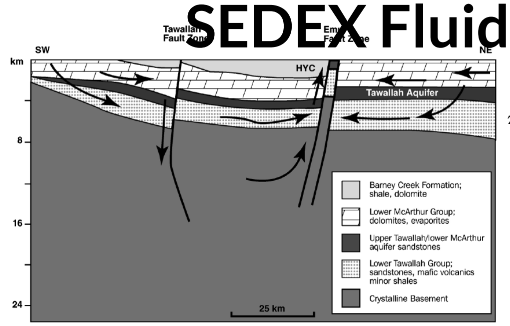
(a) Schematic diagram illustrating relative stratigraphic positions of barite and sulfide deposits in the Red Dog district.
(b) Restored schematic cross section showing the Ikalukrok unit hosting the Anarraaq deposit in Late Mississippian time. The sequence of the units is consistent from top to bottom based on drill core, but thickness of some units can differ significantly. The Kivalina and underlying units are not present at Anarraaq but are inferred to have existed prior to Brookian thrust faulting based on stratigraphic evidence.

From Kelley et al,. 2004 and Schardt et al., 2008

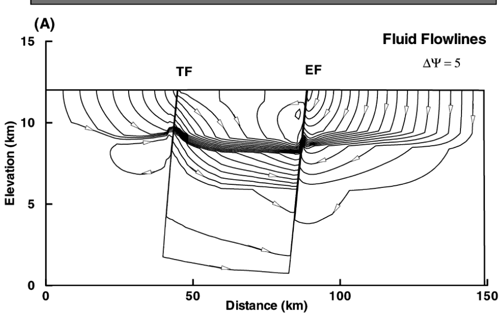
SEDEX Genesis

- **Deposited from Cl-rich fluids**
  - connate brines derived from sedimentary sequence
  - up to 20 wt% NaCl equivalent
- **Metals are derived from fluid flow through sedimentary sequence**
  - high solubility of base metals in high-salinity fluids
- **Fluids neutral to moderate acidity (pH 3.5-6)**
- **Fluid temperature 150-250°C**
- **Fluids generally oxidized (SO4- > H2S)**
- **BUT reduced fluids also occur (SO4- < H2S)**
- **Fluid flow**
  - large convection systems

SEDEX Fluid Flow

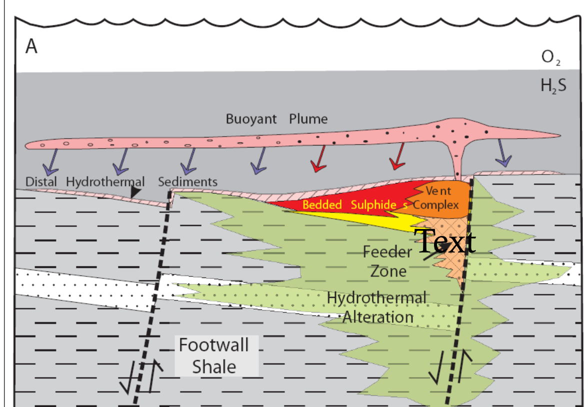


Conceptual model for hydrothermal flow and genesis of the stratiform HYC lead–zinc deposit at McArthur River, Northern Territory, Australia
(from Garven et al., 2001)



Fluid flowlines of density-driven flow model for thin Tawallah Group aquifer for the case in which only the Emu Fault is a permeable conduit. Fluid temperature on the sea floor reaches up to 140–150°C at the Emu Fault Zone due to upward convection. TF, Tawallah Fault; EF, Emu Fault.
HYC lead–zinc deposit at McArthur River, Northern Territory, Australia
(from Garven et al., 2001)

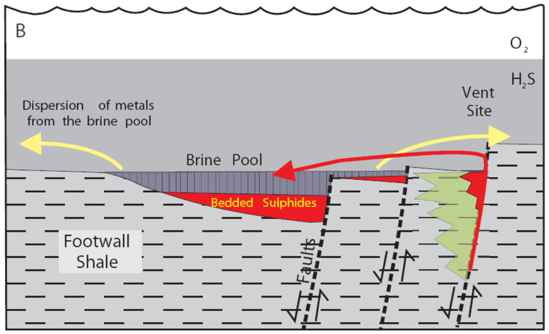
Older SEDEX Model



- **Model works best for proximal deposits**

- **Fluids vent up into anoxic (O_2-starved, reduced) seawater**
  - mixing causes Pb-Zn deposition by
    - *cooling*
    - *pH increase (for reduced hydrothermal fluids)*
    - *reduction (for oxidized fluids)*
    - *dilution*
      - salinity loss → lower Cl content → lower metal solubility
- **Metal sulfides then rain down onto seafloor**

Newer SEDEX Model



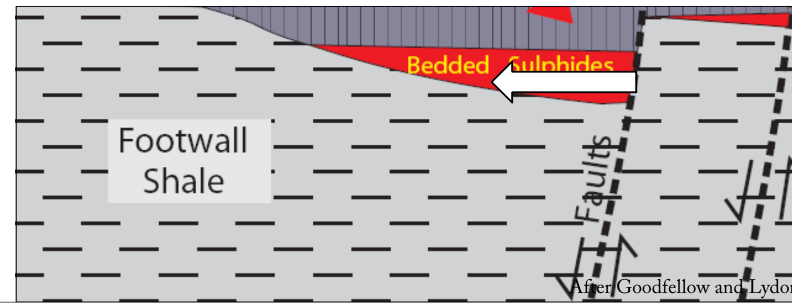
this model better explains distal deposits

Goodfellow and Lydon, 2007
Sangster, 2002

- **Highly saline hydrothermal fluid too dense to rise and mix with seawater**
  - flows as a ground-hugging plug, settling into local depressions ("brine pool").
  - Likely travelled km distances
- **Similar deposition process**
  - product of cooling and reaction with seafloor sediment pore water
  - little mixing with seawater
  - no need for anoxic water column
  - can settle into sediments replacing pore fluid and cause replacement-style mineralization
- **Multiple discharge events likely (tectonically driven or facilitated fluid flow)**

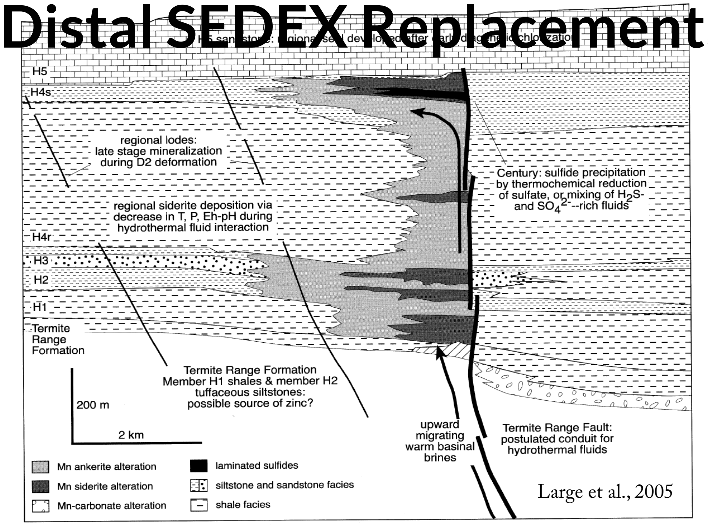
Distal SEDEX Replacement

- **Oxidized fluids flow along more reduced bedding layers**
  - reduction of fluid metals to sulfides and replacement of existing minerals
- **Reduced fluids flow along beds**
  - cooling and pH increasing from rock interaction
  - *sulfide replacement of existing minerals*
- **Early in diagenesis during rifting**
- **Late in diagenesis during contraction and basin inversion**



After Goodfellow and Lydon, 2007

Distal SEDEX Replacement



Large et al., 2005

Model for fluid flow, mineralization, and Fe-Mn carbonate alteration at Century (from Broadbent et al., 2002). The uppermost H5 sandstone was cemented during early burial by diagenetic chlorite and formed a barrier to subsequent upflow of metalliferous brines. The brines moved upward along the Termite Range fault and outward along favorable permeable horizons causing deposition of Mn siderite and Mn ankerite cements. The Century Zn-Pb-Ag lenses formed in the H4s siltstones below the impermeable cap of H5 chloritized sandstone due to reaction between hydrocarbons generated in the organic-rich H4s shales and sulfate and metal chlorides carried by the hydrothermal brines. The Mn siderite cements form a halo surrounding the deposit, being concentrated in areas of maximum temperature and fluid flow. Mn ankerite cements formed in the sediments more distal from the mineralization.

SEDEX Source-Xprt-Trap

- **Source of sulfur**
  - seawater sulfate
    - *either directly from seawater, from the brines, or from pre-existing marine sulfate (e.g., barite)*
- **Source of metals**
  - derived from fine-grained clastic sediments by circulating brines
- **Source of fluids**
  - connate brines commonly present within sedimentary sequences
- **Transport**
  - Hydrothermal circulation on basin scale
    - *during rifting (and/or basin inversion)*
    - *faults control upflow (vent) areas*
      - multiple upflow pulses
  - fluid largely flows as ground-hugging dense brines
    - *pools in depressions*
    - *near vent zones there might be increased mixing seawater*
    - *some subsurface flow along sedimentary layers*
- **TRAP**
  - *cooling*
  - *pH increase (for reduced hydrothermal fluids)*
  - *reduction (for oxidized fluids)*
  - *dilution*
    - salinity loss → lower Cl content → lower metal solubility