TGI^{4} Ore Systems

SEDEX deposits in the Cordillera: Current concepts on their geology, genesis, and exploration

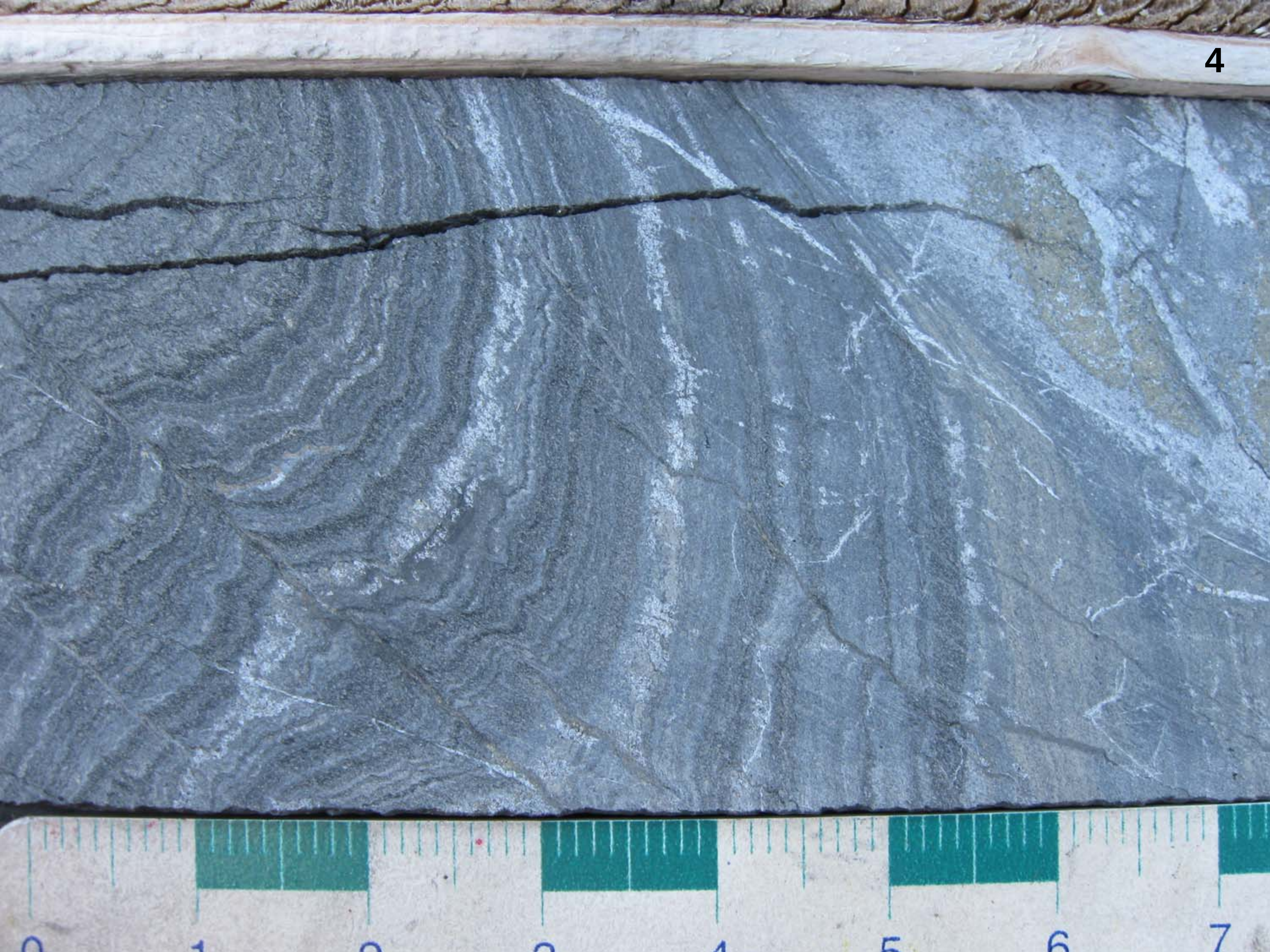
Suzanne Paradis and Wayne Goodfellow
Geological Survey of Canada

Definition of SEDEX Deposits

- SEDEX deposits are tabular bodies composed predominantly of syn-sedimentary sphalerite and galena.
- They occur in basinal sedimentary rocks consisting primarily of carbonaceous black shale, mudstone, chert, and coarser grained-clastic rocks.
- In Canada, there are 31 deposits with geological resources, of which 6 are past producers including the giant Sullivan deposit.

Photo of Mineralization

Photograph (see **slide 4**) of a drill core sample of the high-grade sulphide mineralization at the Howards Pass deposit in Yukon showing the deformed laminae of fine-grained sulphides, dark grey mudstone, and calcite (white). Sulphides consist of pale to dark grey sphalerite and galena with a minor amount of pyrite. Centimetre-scale for reference.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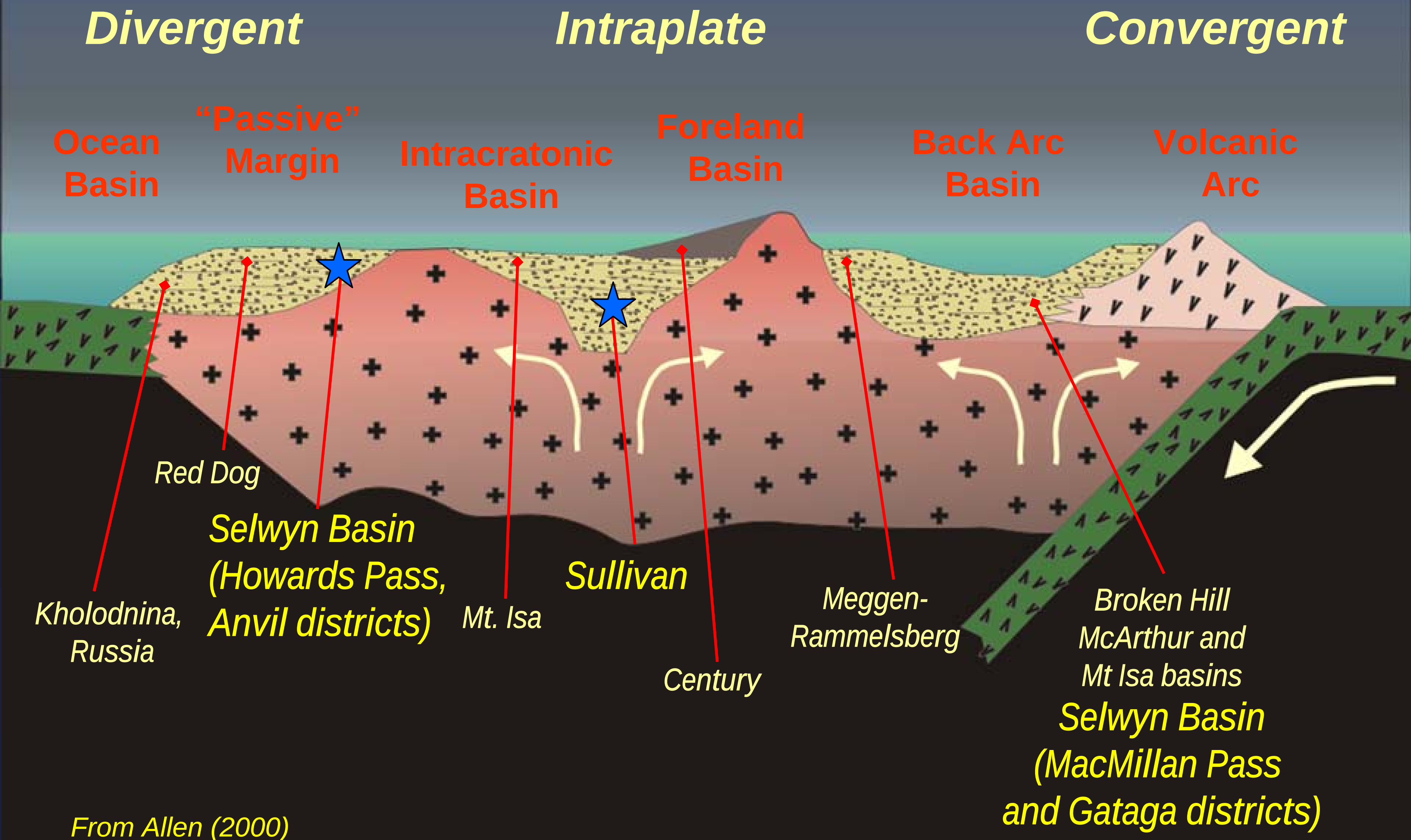
Tectonic Settings

Sedimentary basins occur in various tectonic settings (see **slide 6**, from Allen, 2000). Most SEDEX deposits formed in intracratonic and epicratonic sedimentary basins (Large, 1980) that were subjected to long periods of tectonism marked by fault reactivation, intrabasin clastic sedimentation, and, in many cases, magmatism represented by volcanism and/or sill emplacement (Goodfellow and Lydon, 2007). In the Cordillera, SEDEX deposits occur in rift-generated sedimentary basins that include:

- Reactivated rifted passive margin; such settings host the Red Dog deposit and deposits of the Selwyn Basin.
- Intracratonic and foreland basins; such settings host the Sullivan deposit, which formed in the rift phase of an intracratonic rift (compare with rift sag (cover) setting for Mt. Isa deposit).
- Back-arc basins may develop within divergent, intraplate, and convergent tectonic settings. Deposits of the MacMillan Pass and Gataga districts may have formed in a far-field back-arc rifting environment in Late Devonian time (Nelson et al., 2002).

Two of the best understood continental rifted basins hosting SEDEX deposits in the Cordillera are the intracontinental Middle Proterozoic Belt-Purcell basin and the rifted Paleozoic continental margin represented by the Paleozoic Selwyn Basin.
This is a composite of possible tectonic settings and is not to scale or intended to represent relative polarities of subduction or extension at the time of formation of the various Cordilleran deposits.

Tectonic Settings



From Allen (2000)

Basin Architecture

Slide 9 illustrates the ideal basinal architecture for the development of hydrothermal reservoirs leading to the genesis of metalliferous fluids and SEDEX formation (from Goodfellow, 2004):

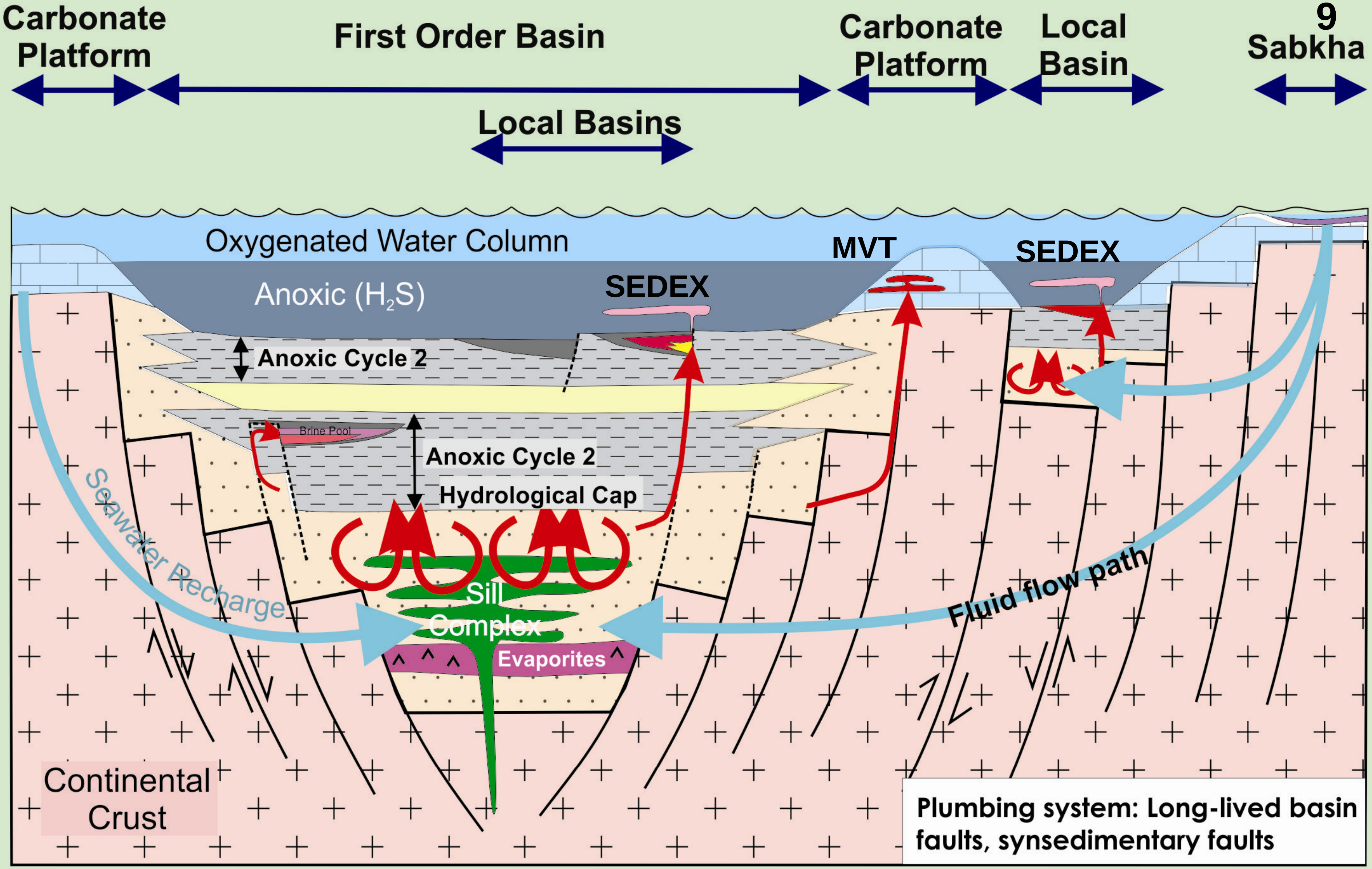
The basin architecture is a continental rifted margin basin or an intracontinental rift basin with at least 4 to 10 km of coarse-grained permeable sedimentary clastic rocks and related volcanic and/or volcaniclastic rocks that form the syn-rift phase. The syn-rift sequence is overlain by an impermeable cap or seal of sag-phase sediments consisting of basinal shale, mudstone, chert, carbonate, and coarser-clastic rocks (Lydon, 1983; Large, 1986).

The sources for the Zn and Pb are the syn-rift, dominantly clastic, sedimentary rocks (Lydon et al., 2000), whereas the ideal traps for the metals are reduced sub-basins with an adequate supply of bacteriogenic H_2S in the ambient water column (Goodfellow and Jonasson, 1984; Goodfellow, 1987; Cooke et al., 1998, 2000; Goodfellow and Lydon, 2007).

Basin Architecture, continued

The accumulation of sediments in the basins is associated with the development of second or third order basins via tectonism, subsidence and faulting. Therefore, tectonism, represented by long-lived basin-bounding faults, is an essential process in the development of a basin rich in SEDEX deposits. Evidence of local tectonism can be shown by abrupt changes in sedimentary facies and thicknesses, occurrence of intraformational debris flows and breccias, local unconformities, and offsets of major faults.

Other important features that should be present within or proximal to basins are: 1) coeval evaporative carbonate platform margins, which are needed to produce the fluid drive and the volumes of saline brine require to form SEDEX deposits (Emsbo, 2009); and 2) evidence of anoxic conditions to aid accumulation and preservation of sulphides (Goodfellow and Jonasson, 1984; Goodfellow, 1987; Cooke et al., 1998; Goodfellow and Lydon, 2007).



Plumbing system: Long-lived basin faults, synsedimentary faults

Rift fill sequence (4-10 km thick, >3 km deep): coarse oxidized clastic rocks

From Goodfellow (2004)

Metal trap:
Anoxic/Euxinic carbonaceous sediments with >1% TOC

Criteria for Anoxic Seafloor Environment

Important criteria for the recognition of anoxic environments in basinal environment (Goodfellow and Peter, 2010) include:

- Carbonaceous pelagic and hemipelagic sedimentary rocks (e.g., black shale/mudstone, chert, carbonate; variable input of coarser clastic rocks; Lydon, 1983; Large, 1986).
- Laminated, non-bioturbated sedimentary textures (restricted to the Phanerozoic examples).
- Laminated and graded pyrite framboids in black carbonaceous shales/mudstones.
- Absence of benthic fauna in Phanerozoic sedimentary rocks.
- Organic-rich black shale/mudstone with high contents of organic carbon (Corg) ; a sedimentary unit with greater than 1 weight % Corg is considered an indicator of a favourable host rock. High contents of Corg are essential for the production of sulphur, a requirement for precipitation of ore metals (Emsbo, 2009).

Criteria for Anoxic Seafloor Environment, con’t

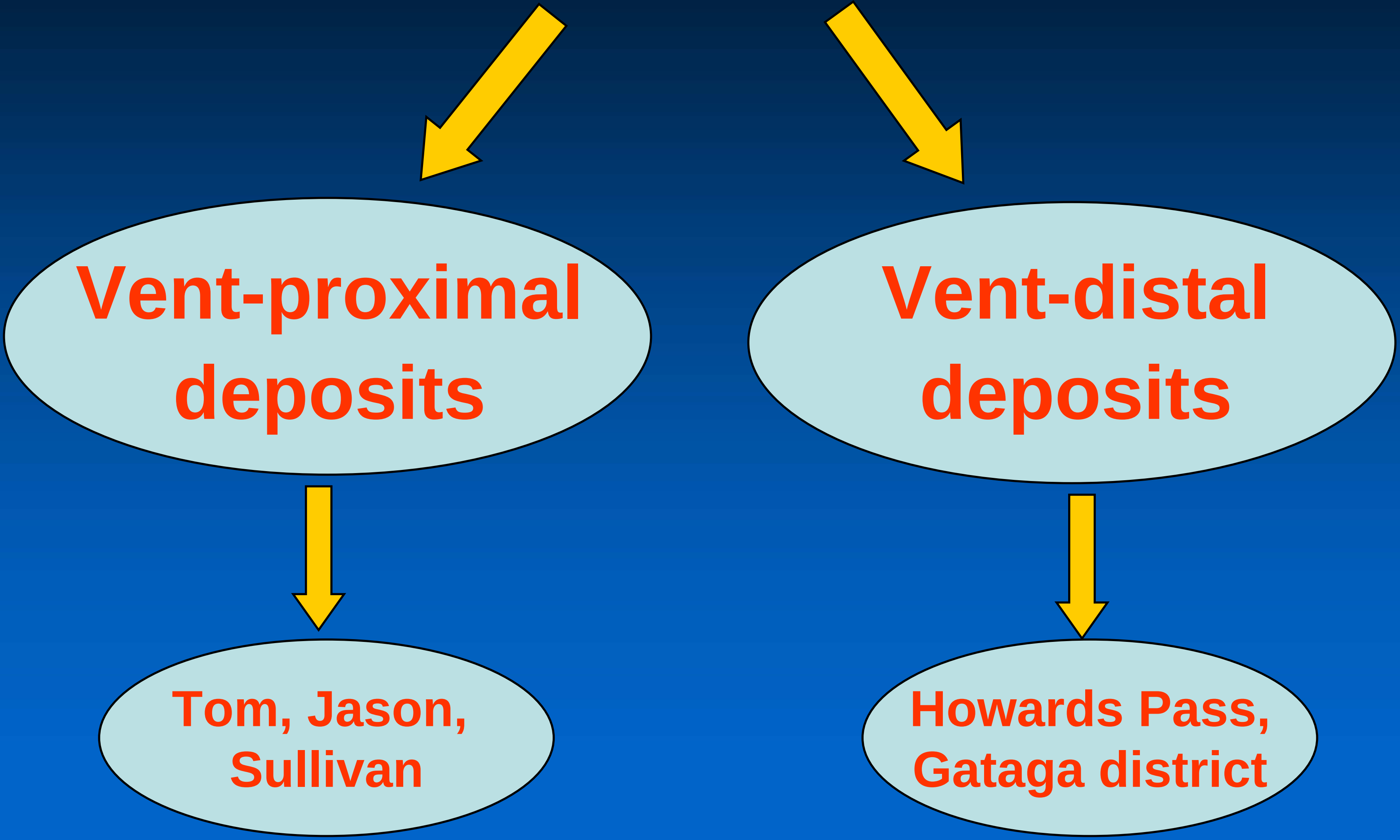
- Highly anomalous sulphur/carbon ratios; atomic S/C ratios greater than 0.13 for rocks of the Selwyn Basin suggest that the water column was stratified with anoxic bottom waters during the formation of the SEDEX deposits (Goodfellow and Jonasson, 1986; Goodfellow, 2007).
- Very low Mn (<1000 ppm) and V (average = 0.15%) contents (Quinby-Hunt and Wilde, 1994; Goodfellow, 2000).
- Anomalous concentrations of redox-sensitive trace element ratios [e.g., Mo, U, Tl Ni/Co, V/Cr, V/(V+Ni), Cr/Mo, V/Mo, Re/Mo], which can be used to record ambient marine conditions at the time of mineralization.
- Ce/Ce* less than one. (Goodfellow, 2000).
- Upward increasing of the sulphur isotope secular curves for pyrite and barite in the Selwyn Basin reflecting a restricted reduced water column (Goodfellow, 1987; Shanks et al., 1987).

Deposit Morphology

An important aspect in SEDEX-ore genesis is the physical behaviour of fluids at the seawater or sediment interface which is, in turn, influenced by the proximity of the vent to the fluid pathways. This will have an influence on the morphology of the sulphide ore body.

Sangster (2002) divided SEDEX deposits into two categories, the vent-proximal and the vent-distal deposits (**slide 13**). Sullivan, Tom, and Jason are good examples of vent-proximal deposits and deposits of the Howards Pass and Gataga districts are good examples of the vent-distal category.

Deposit Morphology



Vent-proximal deposits

Tom, Jason, Sullivan

Vent-distal deposits

Howards Pass, Gataga district

Vent-proximal Deposits

The vent-proximal deposits (**slide 15**) typically form from buoyant hydrothermal fluids. As a result, the sulphide accumulation has a mound or lens-shaped with a low aspect ratio (i.e., the ratio of the lateral extent of the body to its maximum stratigraphic thickness). They have a footwall alteration zone and stockwork zone near the center of fluid up-flow, and four distinct sulphide facies are usually present:

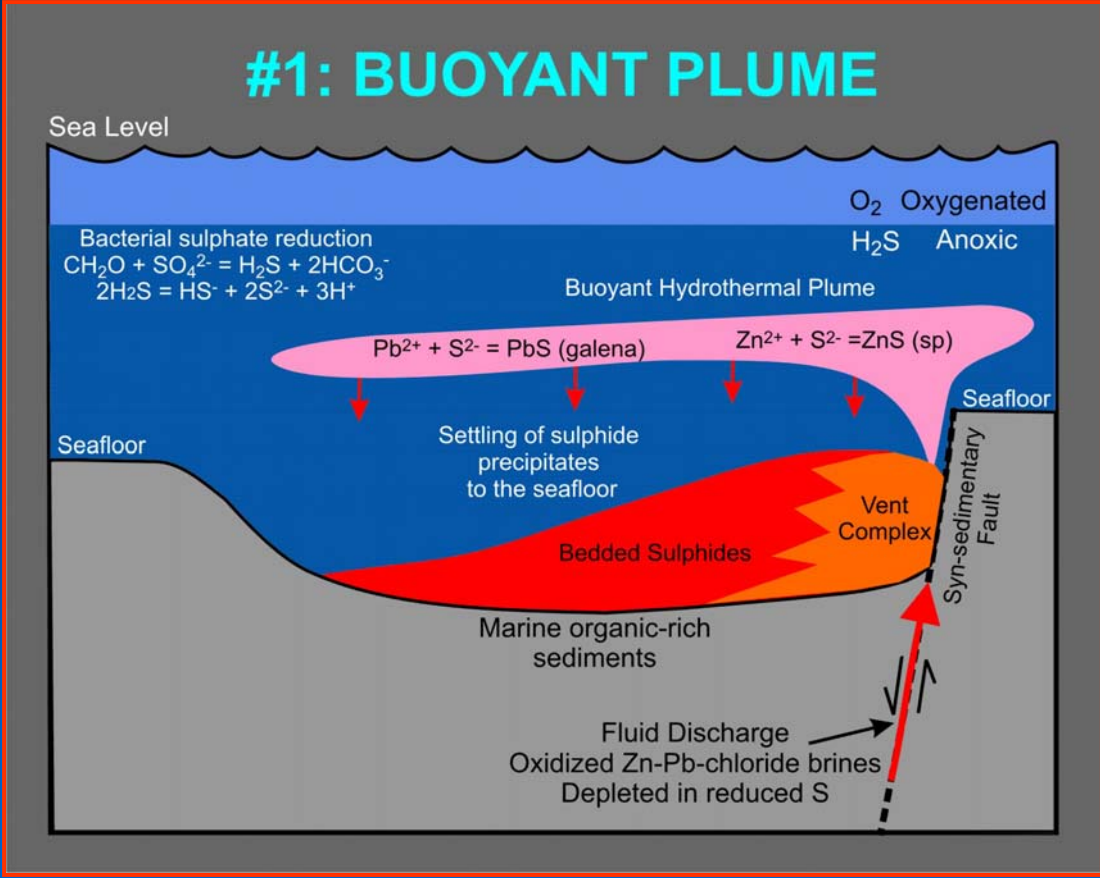
1) vent complex, 2) bedded sulphides, 3) stringer zone, and 4) distal hydrothermal sediments.

These deposits are characteristically zone-refined due to the reaction of hydrothermal fluids with the stratiform sulphides overlying vents (modified from Goodfellow and Peter, 2010). Diagram is not to scale.

Vent-proximal Deposits

Key characteristics:

- Fluids form buoyant hydrothermal plumes and discharged along extensional, syn-sedimentary faults.
- Fluids: Pb-Zn-chloride, H_2S-depleted and relatively high fO_2 .
- Source of reduced S: bacteriogenic H_2S in the lower part of a stratified ambient water column.
- Precipitation of sulphides in the plume by the reaction of Zn and Pb with H_2S in the reduced water column.



- Delicately interlaminated sulphides and organic-rich sediments in the vent-distal part.

Modified from Goodfellow and Peter (2010)

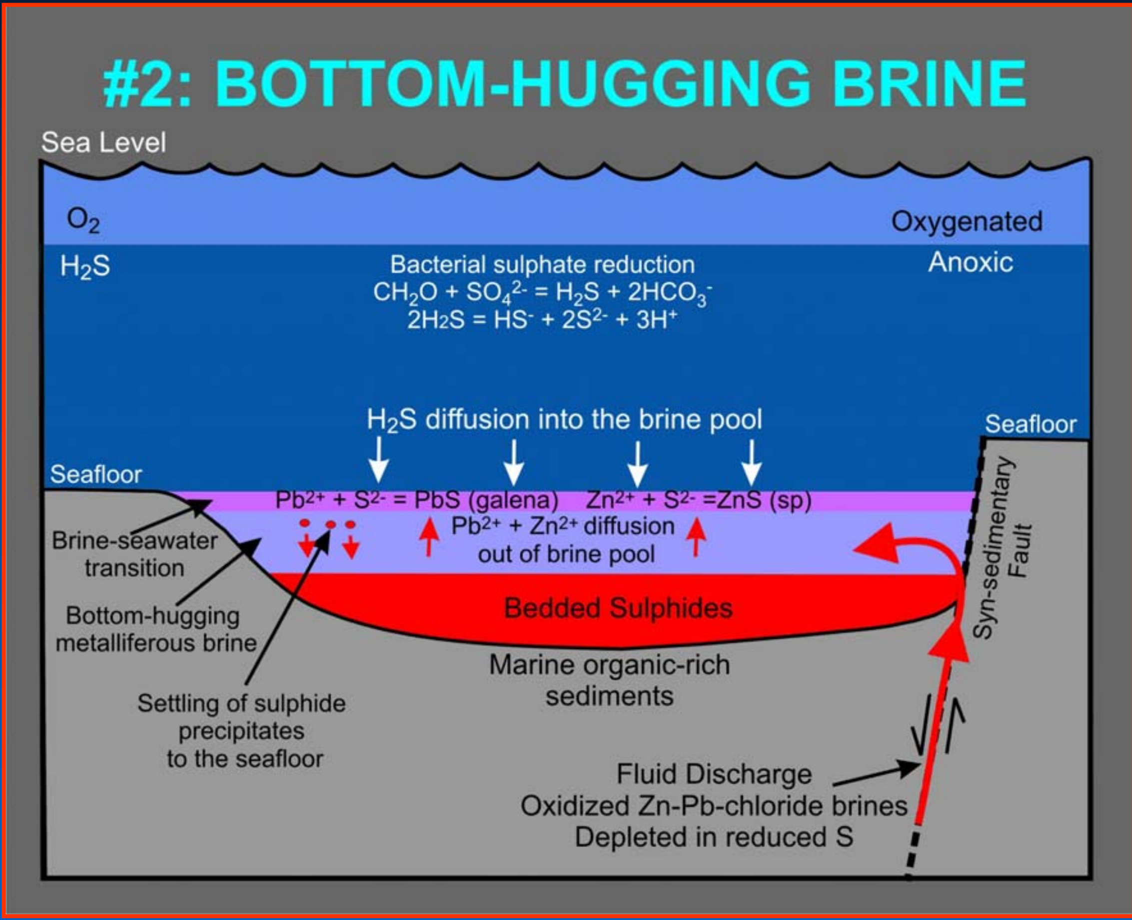
Vent-distal Deposits

The vent-distal deposits (**slide 17**) form from bottom-hugging brines in depressions on the seafloor. As a result, the sulphide accumulation has a tabular and sheet-like morphology with a high aspect ratio of >20 (i.e., the ratio of the lateral extent of the body to its maximum stratigraphic thickness). They are laterally extensive (up to 40 km) with maximum thicknesses in the range of 5 to 20 metres (Goodfellow and Jonasson, 1986; Goodfellow and Peter, 2010) and form conformable to semi-conformable stratiform lens or lenses of well-bedded sulphides. There is no evidence of vent complex and discordant footwall hydrothermal alteration is subtle.

Vent-distal Deposits

Key characteristics:

- Metalliferous brines accumulate in bathymetric depressions.
- Fluid discharged along extensional, syn-sedimentary faults.
- Fluids: Pb-Zn-chloride brines, H_2S-depleted and high fO_2 .
- Source of reduced S: bacteriogenic H_2S in the lower part of a stratified water column.
- Precipitation of sulphides by the interaction of hydrothermal Zn and Pb in the hydrothermal brine pool with H_2S in the overlying reduced water column.



- Bedded sulphides = Delicately interlaminated sulphides and organic-rich sediments.
- No major discordant footwall hydrothermal alteration.

Modified from Goodfellow and Peter (2010)

Alteration

The long-lived hydrothermal system and large volume of fluids required to form SEDEX deposits leave hydrothermal alteration footprints that can be occasionally recognized in the pre- and post-ore host rocks.

It includes dolomitization of platform carbonate rocks, pervasive alkali-alteration of clastic sediment aquifers (Emsbo, 2009), and the following alteration in the SEDEX ore systems:

Vent Complex (see slides 19 and 20):

- The nature and extent of alteration and mineralization depends on the mineralogy and physical properties of footwall sediments, temperature and composition of hydrothermal fluids and water depth (Goodfellow et al., 1983).
- Chlorite-pyrrhotite ±quartz (e.g., Sullivan, Anvil deposits), tourmalinite (e.g., Sullivan), ferroan carbonates and quartz (e.g., Tom and Jason).

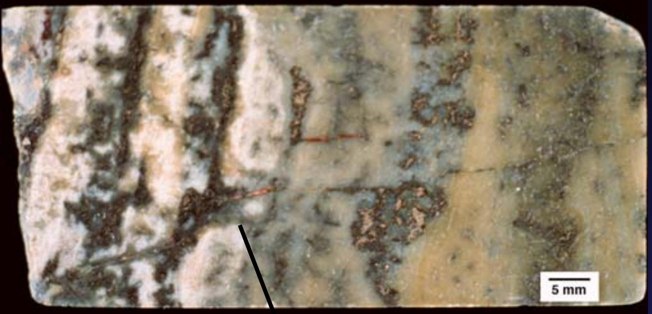
Hanging-wall rocks (see slides 19 and 20):

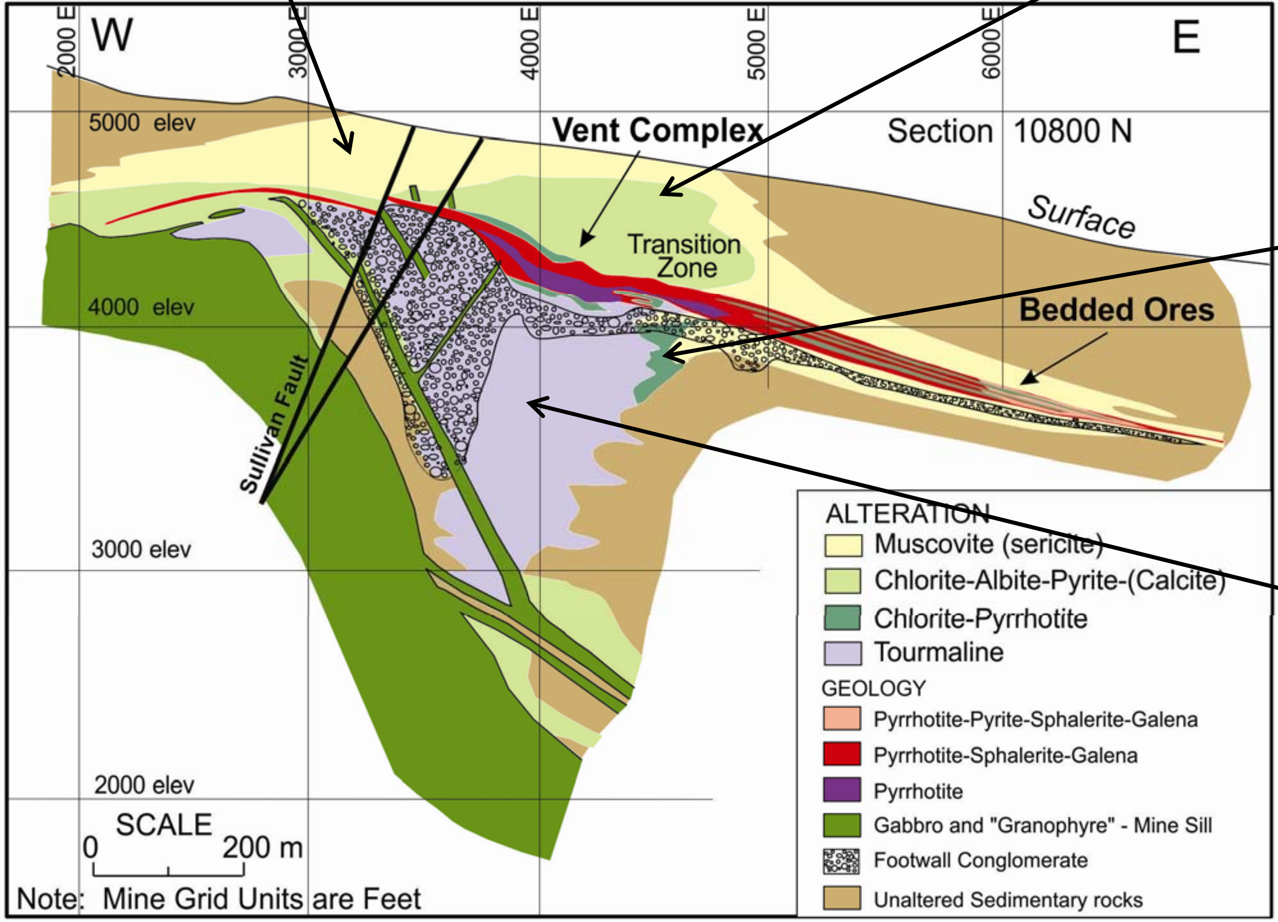
- Hydrothermal alteration can extend for hundred of metres into the post-ore sedimentary sequence and up to several kilometres laterally from the deposits.
- It may consist of sericite alteration (e.g., Sullivan), iron carbonate alteration (e.g., Jason, Tom, Australian deposits), chlorite-albite-pyrite (e.g., Sullivan), barite-pyrite (e.g., Tom and Jason), phosphatic-rich mudstone (e.g., Howards Pass).

Alteration

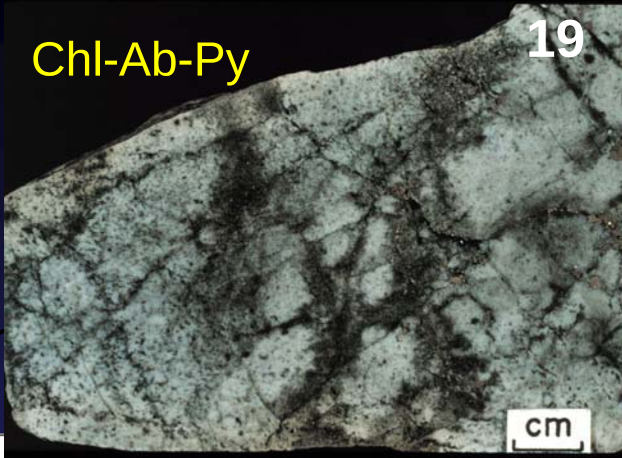
Sullivan Deposit

Ser-Ab

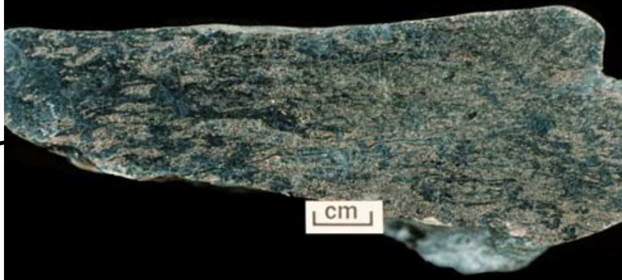




Chl-Ab-Py



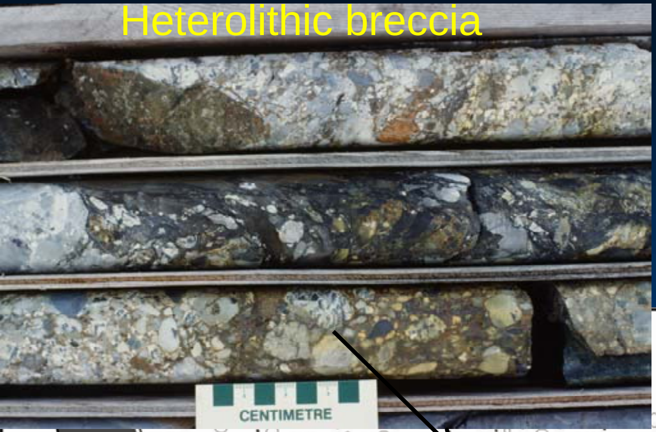
Chl-Po



Tourmaline

From Lydon (2007)

Alteration and Hydrothermal Facies, Jason deposit


Heterolithic breccia


Laminated sph (orange), ba (white) and siltstone

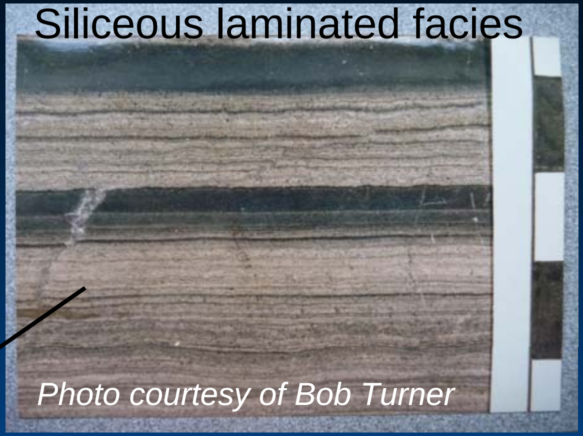

Siliceous laminated facies

Photo courtesy of Bob Turner

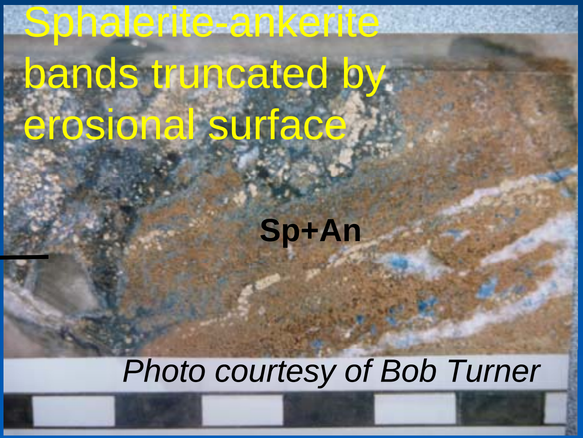

Sphalerite-ankerite bands truncated by erosional surface

Photo courtesy of Bob Turner

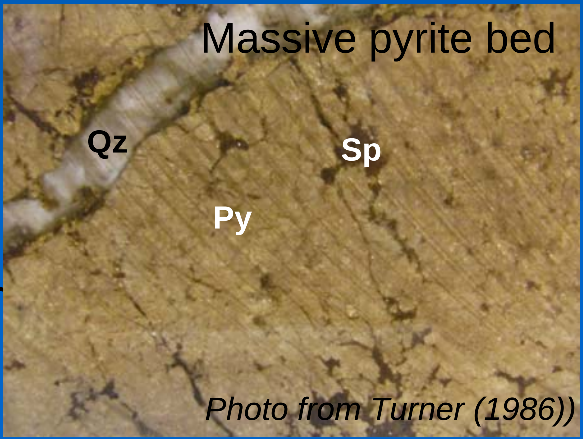
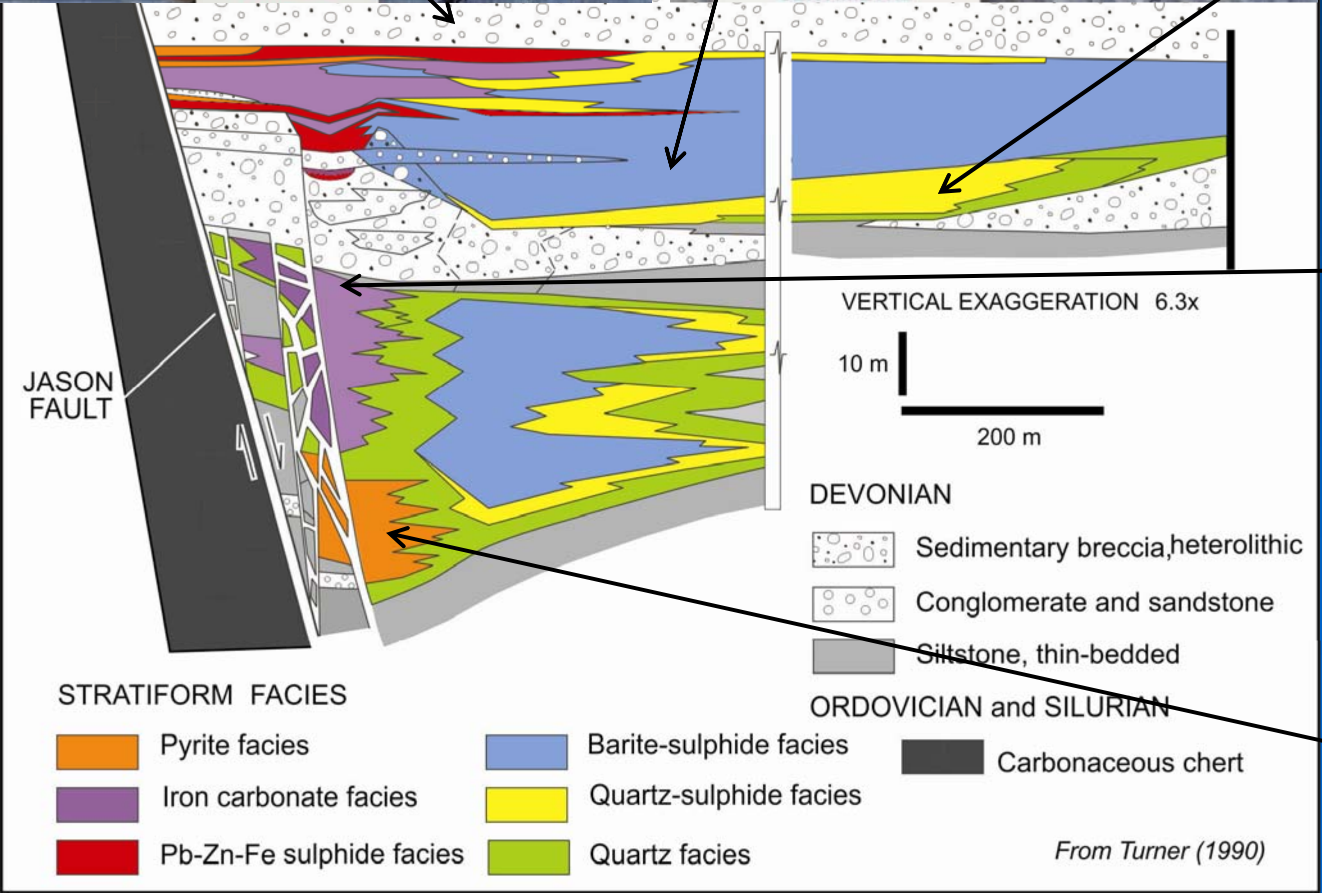

Massive pyrite bed

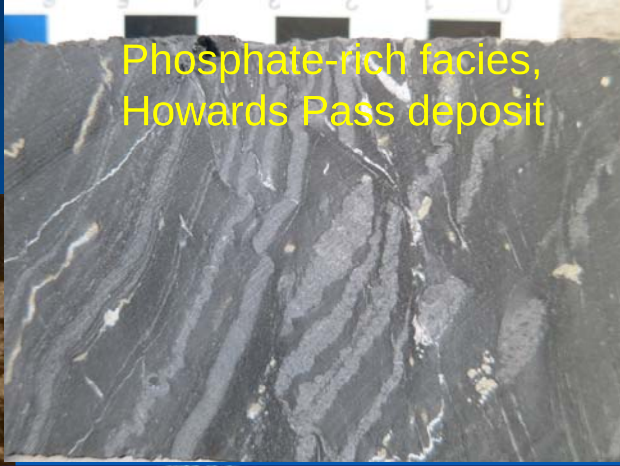
Photo from Turner (1986))



From Turner (1990)

Distal Hydrothermal Sediments

- They are spatially and temporally widespread as lateral sub-economic equivalents of the “bedded ores”; consequently they can be strong indicators of SEDEX deposits.
- They consist of chemical sediments of hydrothermal origin, such as disseminated pyrite and/or sphalerite, exhalative chert, hematite-chert iron formation, sedimentary barite and phosphate, and Mn-Fe-Ca-Mg carbonates.


Phosphate-rich facies, Howards Pass deposit

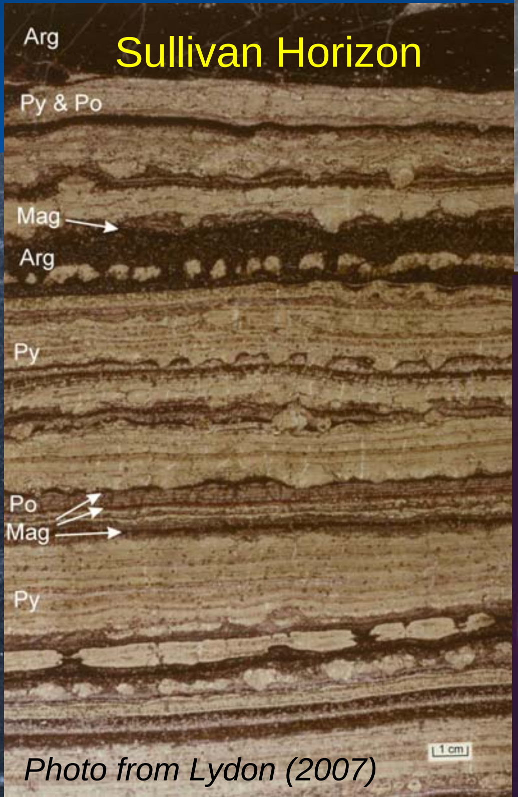
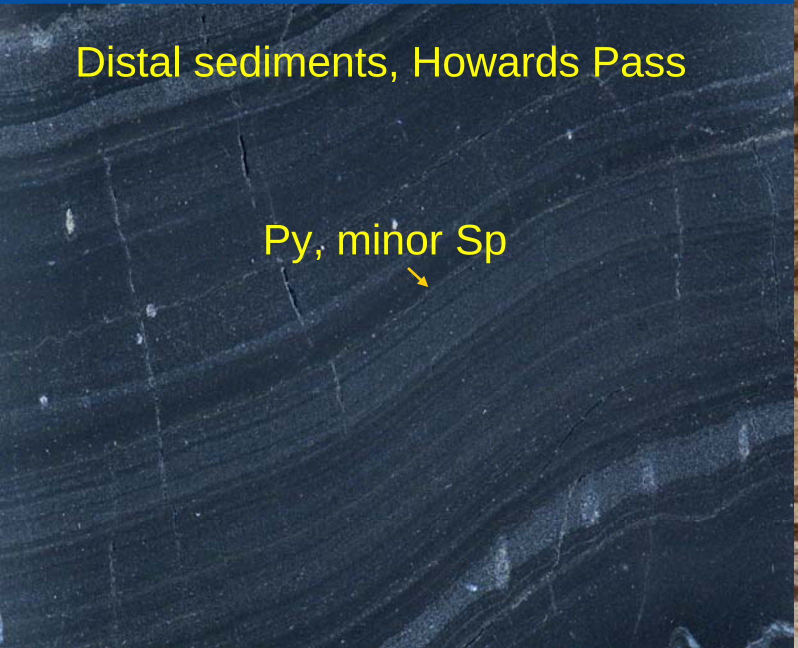

Sullivan Horizon

Photo from Lydon (2007)


Distal sediments, Howards Pass

Py, minor Sp


Bedded barite, Cirque deposit

Geochemical Anomalies

Widespread geochemical halos that extend several kms laterally and up to 100s of m into the hanging wall of SEDEX ore systems. These geochemical halos can be:

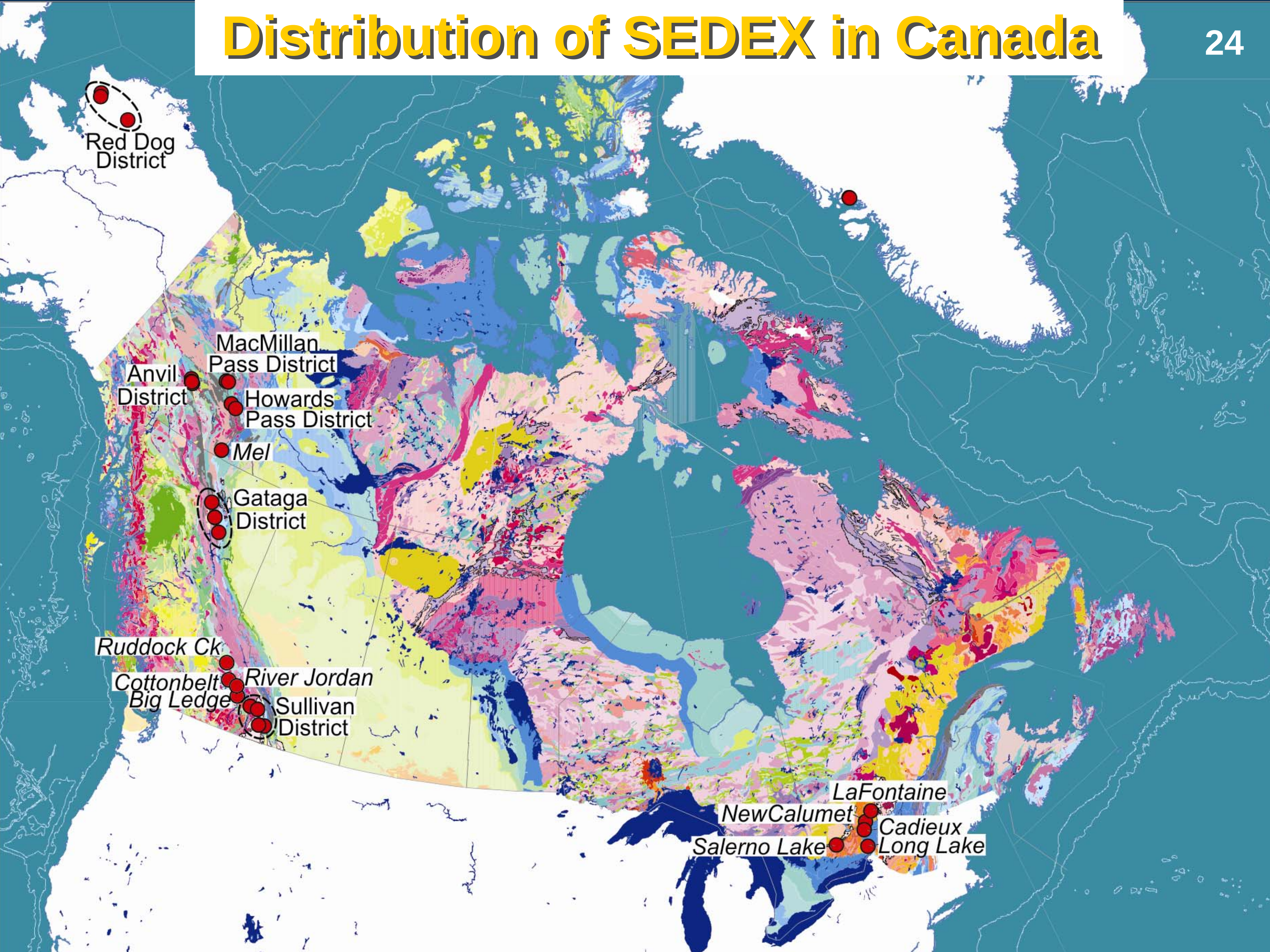
- Decrease of Pb/Pb+Zn ratios away from the vent complex.
- Increase of Pb:Ag, Fe:Zn, Ba:Zn, (Zn+Pb):Cu and SiO_2:Zn ratios away from the vent complex.
- The host stratigraphic succession may be enriched in base metals and ore-associated elements (e.g., As, Sb, Cd, Mn, P, Ba, Hg, Tl).
- Barite, exhalative chert, and hematite-chert iron formation, if present, are usually found in distal facies of the ore systems.
- Surficial geochemical anomalies in sediment and water samples can also be represented by abundant ore-forming and ore-associated elements over a large area of the basin.

Distribution of SEDEX in Canada

Slide 24 shows the distribution of SEDEX deposits in Canada. Most SEDEX deposits occur in districts in western Canada, including the Anvil, MacMillan Pass, Howards Pass, Gataga, and Sullivan districts.

There are six past producers and most production has been obtained from the Sullivan mine in British Columbia and deposits in the Anvil district in Yukon. No Canadian SEDEX deposit is currently in production.

Distribution of SEDEX in Canada



Selwyn Basin

The Selwyn Basin (**slide 27**) is a large oblong sedimentary basin that occupies the western margin of ancestral North America and it extends for 1000s of km from Alaska through the Yukon, western Northwest Territories, and British Columbia (Goodfellow et al., 1993; Nelson and Colpron, 2007).

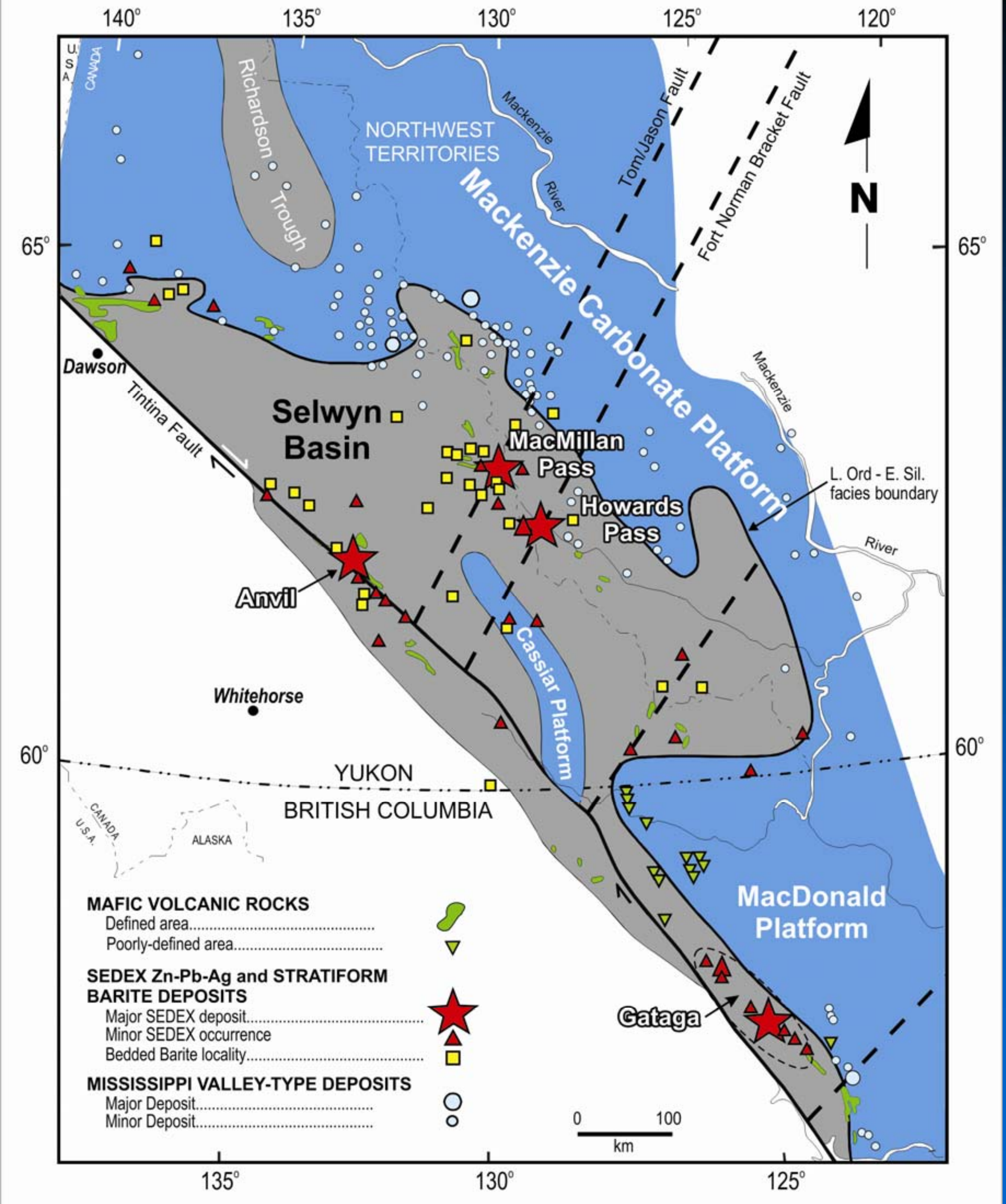
The Selwyn Basin contains the greatest abundance of SEDEX deposits of sedimentary basins in the world. Four major SEDEX mining districts are known in the basin: Anvil (Faro, Grum, Vangorda, DY, and Swim deposits), Howards Pass (XY Nose, XY, XY West, Brodel, HC, HC West, Don East, Don, Anniv East, Anniv Central, OP, OP West, Pelly North and Abbey deposits), MacMillan Pass (Tom, Jason, Nidd deposits), and Gataga (Cirque, Elf, Fluke, Driftpile, Akie deposits).

Selwyn Basin, continued

It hosts several major deposit types that are the products of basin-forming processes, including the past-producers in the Anvil district (i.e., Faro, Vangorda, and Grum SEDEX deposits) and sedimentary barite deposits. Numerous Mississippi Valley-Type (MVT) Zn-Pb (±Ag) deposits occur in the adjacent Mackenzie and Macdonald carbonate platforms (e.g., Paradis and Nelson, 2007; Paradis et al., 2007) as well.

The basin has a complete sedimentary architecture of an extensional basin located near a continental margin, which includes thick sequences of Late Proterozoic coarse- and fine-grained clastic rocks overlain by a Paleozoic basinal sedimentary sequence consisting mostly of black and carbonaceous pelagic and hemipelagic shale, mudstone, chert, carbonate, and coarser-clastic rocks.

Selwyn Basin



- Has more abundant Zn-Pb-Ag SEDEX deposits than any other sedimentary basin in the world.

  4 mining districts:
  - Howards Pass
  - MacMillan Pass
  - Anvil
  - Gataga (Kechika Trough)

- 12 major SEDEX deposits
- Stratiform Ba
- MVT Zn-Pb-Ag deposits in the adjacent carbonate platforms

- Comprises complete sedimentary architecture of an extensional basin near a continental margin, including clastic and basinal sequences.

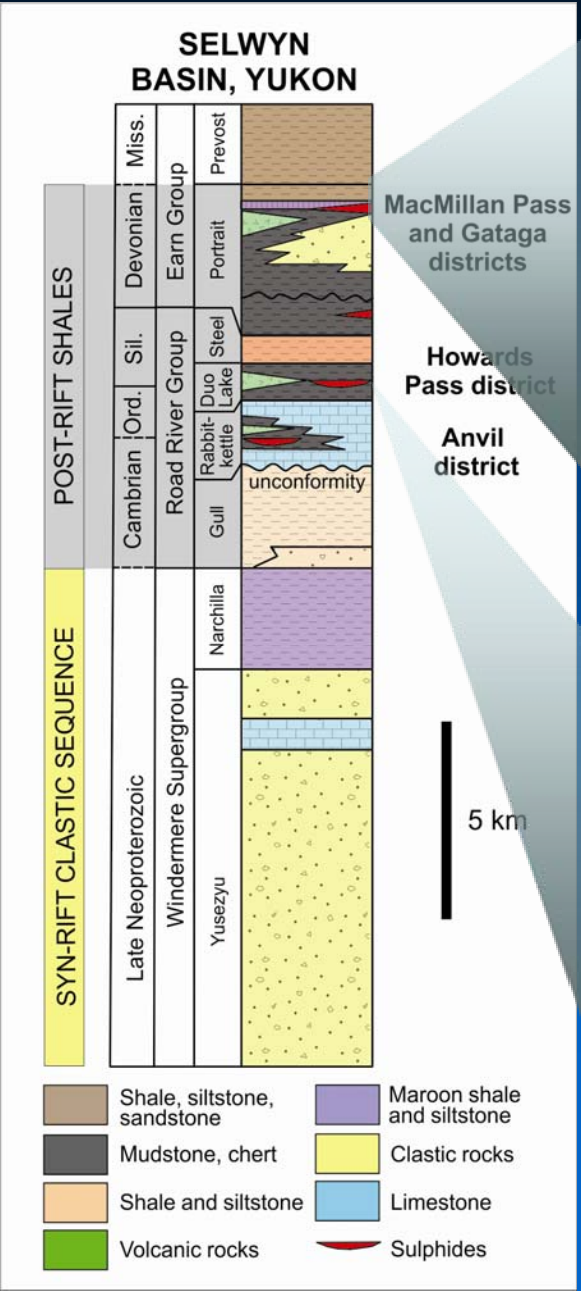
Multiple SEDEX Events, Selwyn Basin

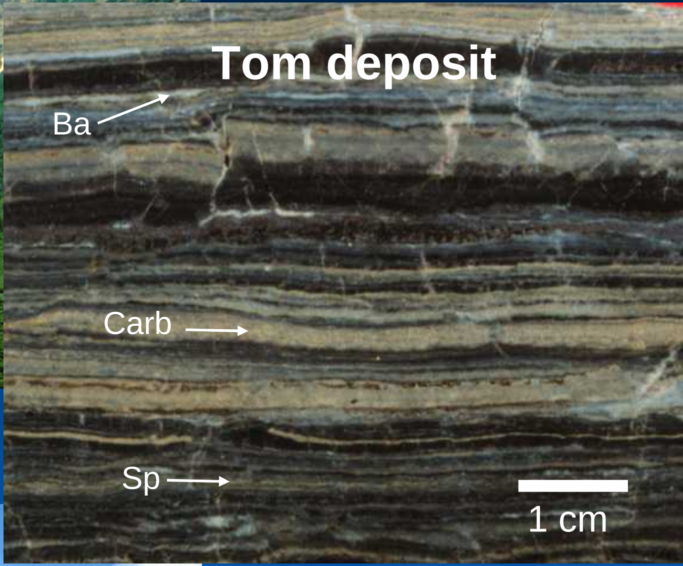
Major metallogenic events in the Canadian Cordillera are Cambrian, Early Silurian and Middle Devonian to Mississippian in age. SEDEX districts of the Selwyn Basin occur in strata which represent these prospective time intervals and host deposits of these ages (**slide 29**). Deposits of the Anvil district are Late Cambrian, Howards Pass district are Early Silurian, and Macmillan Pass and Gataga districts are Late Devonian-Early Mississippian in age (Goodfellow and Peter, 2010).

- Photo of laminae of fine-grained sulphides (sphalerite and galena) interlayered with carbonaceous mudstone at Howards Pass (XY) deposit, Yukon.

- Photo of finely laminated black carbonaceous chert with white barite (Ba), cream carbonate (Carb), and sphalerite (Sp) and galena (not visible), Tom deposit, MacMillan Pass district, Yukon.

Multiple SEDEX Events, Selwyn Basin





From Goodfellow and Peter (2010)

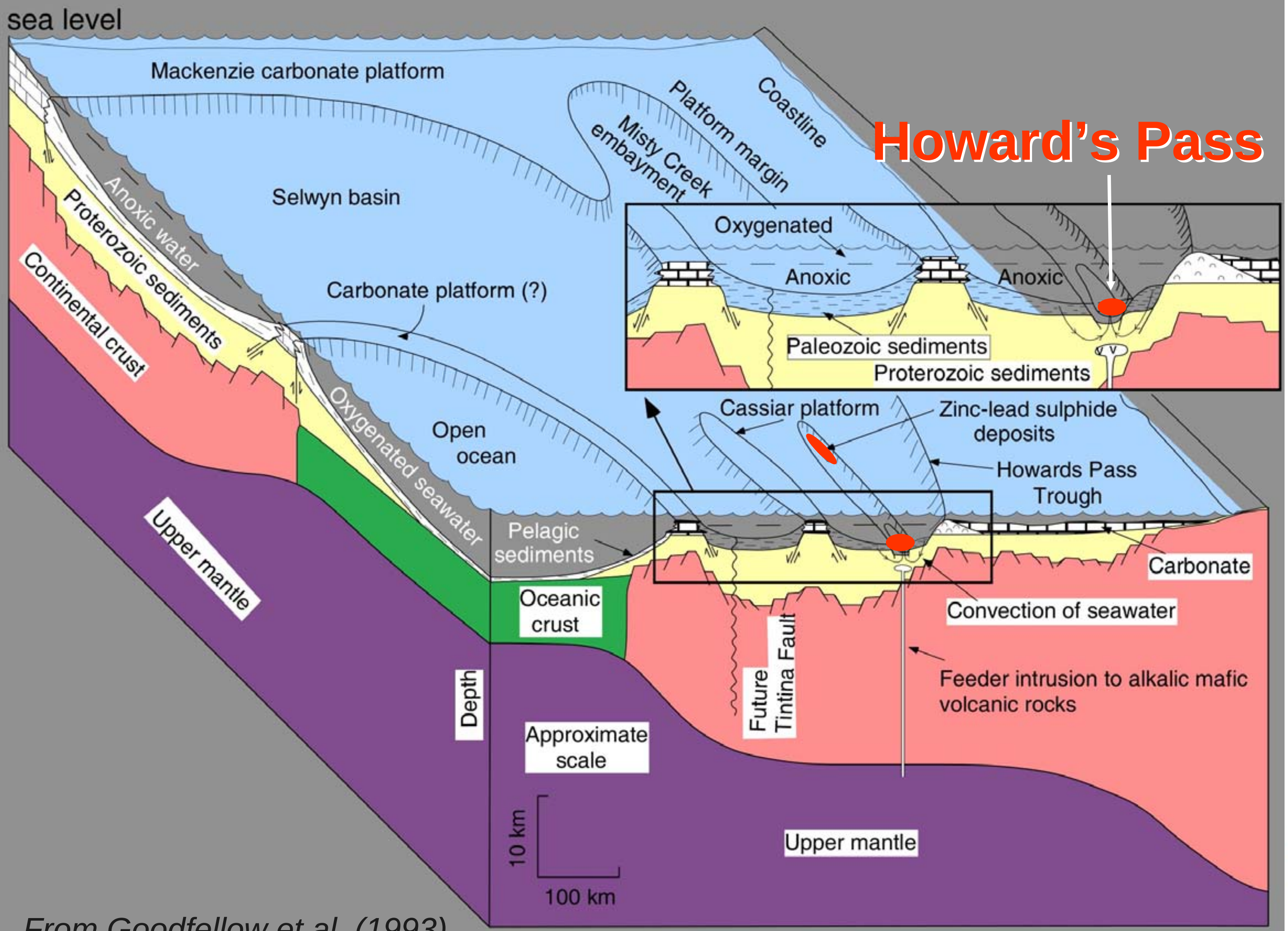
Howards Pass District

Slide 31 shows a conceptual block diagram of the rifted Paleozoic continental margin of northwestern Canada at the time of formation of the Howards Pass SEDEX deposit, Selwyn Basin, Yukon (from Goodfellow et al., 1993).

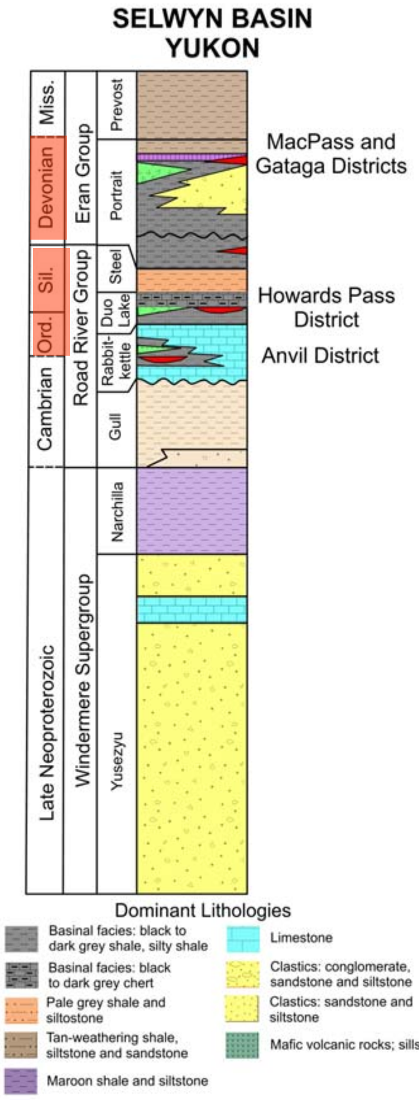
The deposits are hosted in post-rift basinal, reduced facies carbonaceous mudstones and cherts in restricted fault-controlled sub-basins near the margins of major depocenters. The sub-basins corresponded to local bathymetric lows that were euxinic, low-energy depositional environments dominated by organic-rich, pyritic, fine-grained carbonaceous mudstone and chert. This depositional environment provided ideal conditions for dense metalliferous brines to accumulate and react with locally derived H_2S to form sulphide minerals.

These basins are characterized by the occurrence of intraformational debris flows, breccias, and faults. The latter most likely served as fluid conduits that focused hydrothermal brines.

Howards Pass District, Selwyn Basin



From Goodfellow et al. (1993)



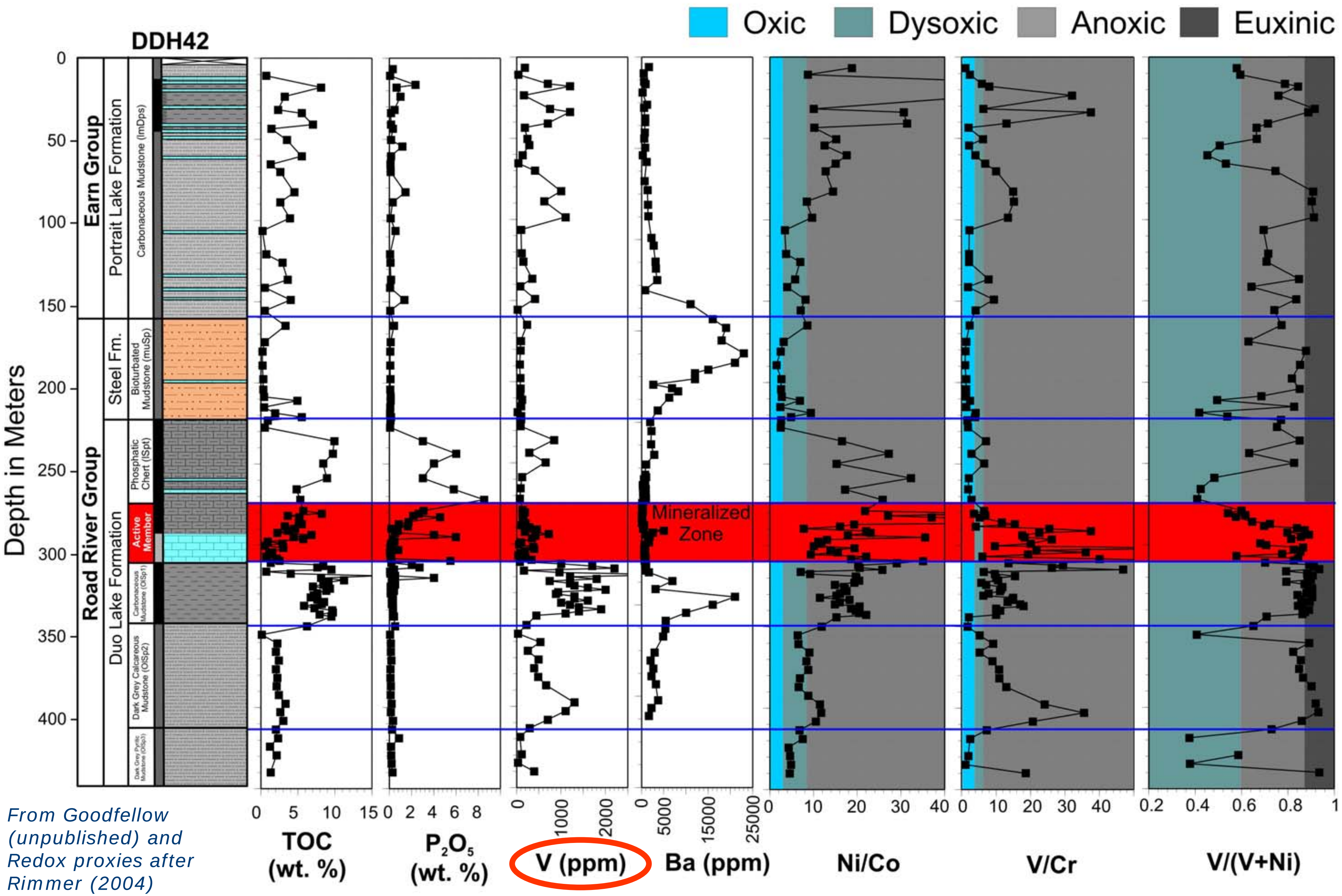
Redox Proxies, Selwyn Basin

Slide 33 illustrates the stratigraphy from a drillhole (DDH42) spanning the Howards Pass (Yukon) deposit interval and variations of some redox-sensitive elements and ratios along the stratigraphy (from Goodfellow, unpublished data; and redox proxies after Rimmer, 2004). The following observations can be made:

- Vanadium is high in the calcareous mudstone member (OlSp1) of the Duo Lake Formation, implying that sedimentation was near the suboxic-anoxic boundary.
- Ni/Co, V/Cr, V/V+Ni ratios are high in the calcareous mudstone member (OlSp1) and Active member of the Duo Lake Formation, the latter is host to the sulphide mineralization, implying that anoxic conditions prevailed prior to and during Zn-Pb mineralization, aiding accumulation and preservation of sulphides.

Slack et al. (2011) showed that Re/Mo ratio with values <0.001 is considered the best paleo-redox proxy at Howards Pass. It records sulphidic or anoxic conditions in bottom waters during deposition of the pyritic mudstone, calcareous mudstone, and Active members.

REDOX Proxies, Selwyn Basin



From Goodfellow (unpublished) and Redox proxies after Rimmer (2004)

Sedimentary Textures, Selwyn Basin

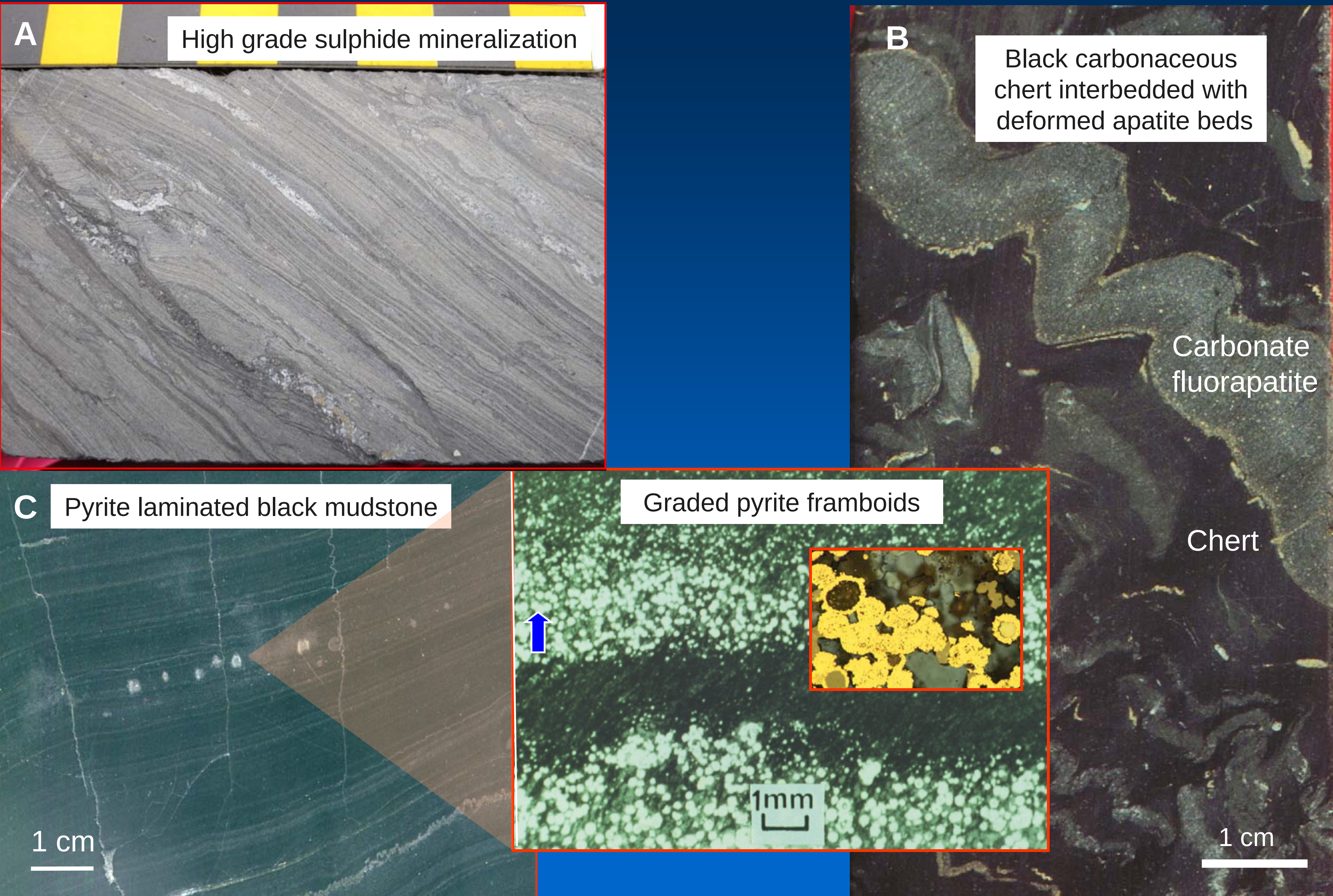
Slide 35 shows photographs of sedimentary textures and facies of rocks which hosted SEDEX deposits:

A. High grade sulphide mineralization, Active member of the Duo Lake Formation, Howards Pass deposit: Sphalerite with trace amounts of pyrite and galena delicately interlaminated with black carbonaceous chert and cut by axial planar pressure dissolution cleavages filled with mostly sphalerite and galena.

B. The phosphatic chert unit of the Duo Lake Formation at Howards Pass. The phosphatic chert consists of pale to medium grey carbonate fluorapatite-rich laminae and bands in carbonaceous chert or cherty mudstone (dark grey).

C. Photograph of pyrite laminated black mudstone, which comprises graded fine-grained pyrite framboids (inset photographs). Sample is from calcareous carbonaceous mudstone (CCMS) unit in Howards Pass deposit.

Sedimentary Textures, Selwyn Basin



A High grade sulphide mineralization

B Black carbonaceous chert interbedded with deformed apatite beds

Carbonate fluorapatite

Chert

1 cm

C Pyrite laminated black mudstone

1 cm

Graded pyrite framboids

1mm

Vent Distal, Howards Pass

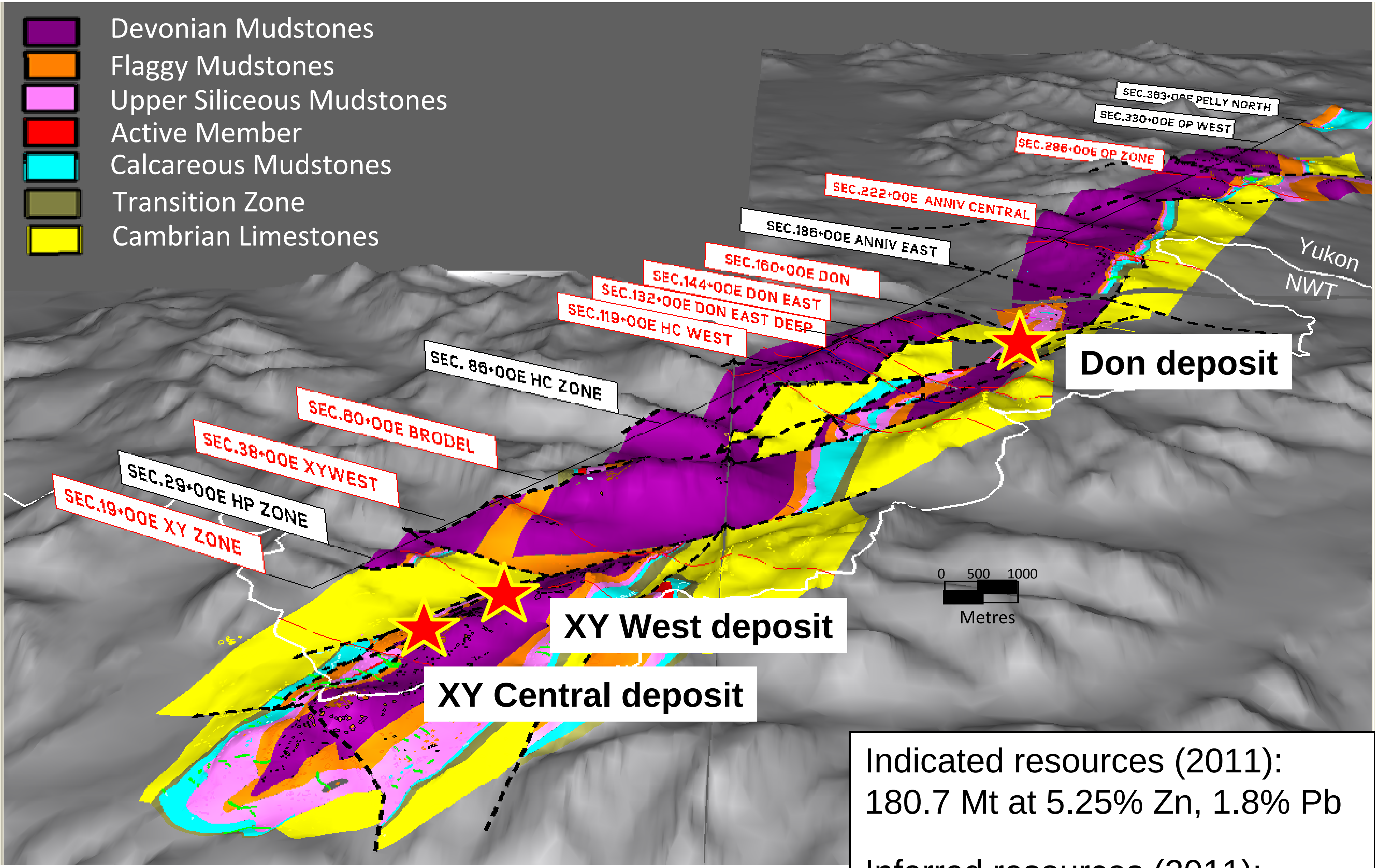
Slide 38 is a view south along a 3D model of the vent-distal Howards Pass deposits (from Selwyn Resources Ltd). The Howards Pass district is host to 15 known deposits (XY Central, XY Nose, XY West, Brodel, HC, HC West, Don, Don East, Anniv East, Anniv Central, Anniv West, HP, OP, OP West, Pelly North; only some of them are shown on the slide and the main deposits are shown by the red stars) that are hosted in the Active Member of the Middle Ordovician to Early Silurian Duo Lake Formation, which has been defined northwest-southeast over a distance of more than 38 kilometres and exhibits remarkable continuity. In this section, it is visible at the XY West and Brodel localities.

The NI 43-101 compliant global mineral resources are estimated at 180.7 Mt million tonnes of indicated mineral resources grading 5.25% Zn and 1.83% Pb, and 216.0 million tonnes of Inferred mineral resources grading 4.47% zinc and 1.38% lead based on drilling completed to September 12, 2011 (Selwyn Resources Ltd: http://www.selwynresources.com/en/index.cfm).

Vent Distal, Howards Pass – con’t

There are several lines of evidence, such as the sheet-like morphology of the deposits, the delicately laminated sulphides textures, and the lack of a pronounced zoning within the deposits, that suggest that bottom-hugging fluids flowed into several sub-basins within an elongated northwest-southeast second-order basin controlled by extensional faults oriented parallel to the hinge line separating the Selwyn Basin from the Mackenzie carbonate platform (Goodfellow, 2007).

Vent Distal - Howards Pass District, Selwyn Basin



Indicated resources (2011):
180.7 Mt at 5.25% Zn, 1.8% Pb

Inferred resources (2011):
216 Mt at 4.5% Zn, 1.4% Pb

Exhalative Vectors at Howards Pass

Slide 41 shows a schematic regional cross-section of Howards Pass with the local stratigraphy and the vertical and lateral zonation of elements. Diagram is not to scale.

Stratabound Zn-Pb sulphide deposits of the Howards Pass district occur in the Active Member of the Middle Ordovician to Early Silurian Duo Lake Formation, Road River Group. From the base to the top, the Duo Lake Formation comprises four principal members: 1) Pyritic Siliceous Mudstone (PSMS), 2) Calcareous Carbonaceous Mudstone (CCMS), 3) Active Member (ACTM), and 4) Upper Siliceous Mudstone (USMS; (drill core image with centimetre scale)). In the Howards Pass district, it tectonically overlies limestone-rich strata of the Ordovician Rabbitkettle Formation (not shown on slide) and was overlain conformably by bioturbated dolomitic mudstone of the Silurian Steel Formation (image with centimetre scale).

Sulphide mineralization consists of layered, laminated and massive aggregates of sphalerite and galena with minor amounts of pyrite that have been variably deformed.

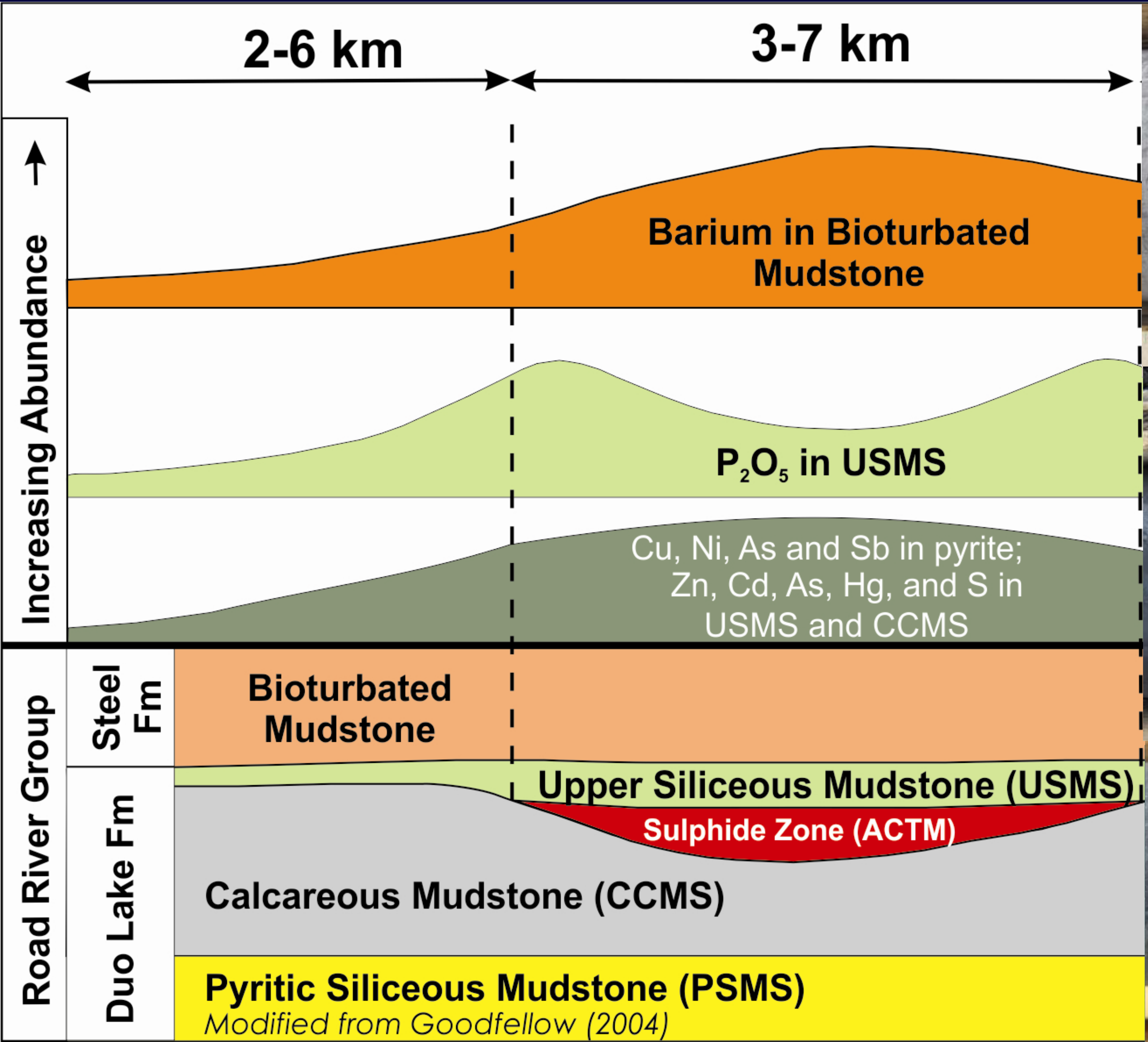
Exhalative Vectors at Howards Pass – con't

Goodfellow (2004, 2007) recognized widespread subtle geochemical halos that extend several kilometres laterally from the mineralized zone of ACTM and up to 100s of metres into the stratigraphic hanging wall. For the most part, these geochemical halos are not mineralogically recognized in the rocks.

Some significant geochemical variations are:

- Barium increases in bioturbated mudstone of the Steel Formation up to values of 2.8 wt% near the center of the sub-basin that hosts the XY deposit.
- P_2O_5 increases in USMS toward the Zn-Pb sulphide mineralization.
- The pyrite content of the unit hosting the mineralization increases toward the Zn-Pb sulphide zone.
- This pyrite increase is accompanied by an increase of total sulphur, Zn, Pb, Cu, Ni, Co, As, Sb, Se, Cd, and Hg in CCMS and USMS with proximity to the mineralization.
- Analyses of pyrite separates show that Cu, Ni, As, and Sb (which occur mostly in pyrite) reach values up to 2000 ppm in units hosting the XY deposit, compared to 500 ppm in correlative rocks distal from the sulphide mineralization.

Exhalative Vectors at Howards Pass



Modified from Goodfellow (2004)

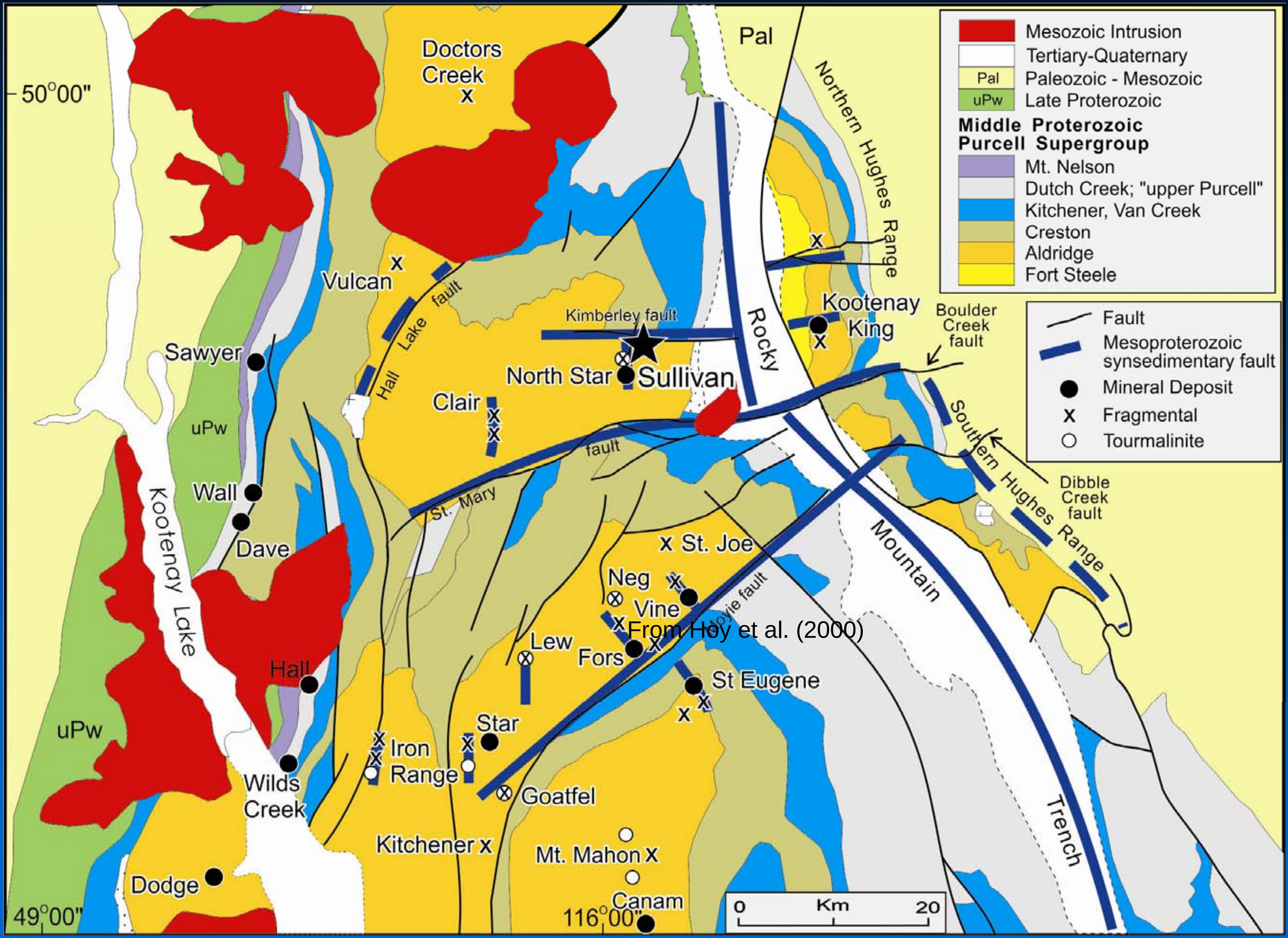
Purcell Basin

- The Purcell Basin in southern British Columbia (**slide 43**; from Höy et al., 2000) and its southern extension in U.S.A. (Belt Basin) is a Mesoproterozoic intracratonic NW-striking rift that comprises about 16 km-thick succession of marine and fluviatile sediments, and lesser amount of volcanic and carbonate rocks.

- Rocks of the rift basin have an unusually high metal endowment resulting from both Mesoproterozoic and Jurassic-Cretaceous metallogenetic events. Mineral deposit types include: SEDEX (e.g., Sullivan, B.C.) and Besshi (e.g., Blackbird, Idaho) types; syndiagenetic disseminated sulphides of Cu (e.g. Spar Lake, Montanore and Rock Creek, Montana) and Zn-Pb (e.g. Star, Canam, B.C.) types; Pb-Zn-Ag veins (e.g., Coeur d'Alene district, Idaho); Mesozoic porphyry deposits (e.g., Butte, Montana); and placer gold (Lydon, 2007).

- SEDEX deposits are spatially associated with synsedimentary faults that trend approximately N to NW rift-parallel faults and E to NE transfer faults (Höy et al., 2000; Chandler, 2000; Turner et al., 2000).

Purcell Basin



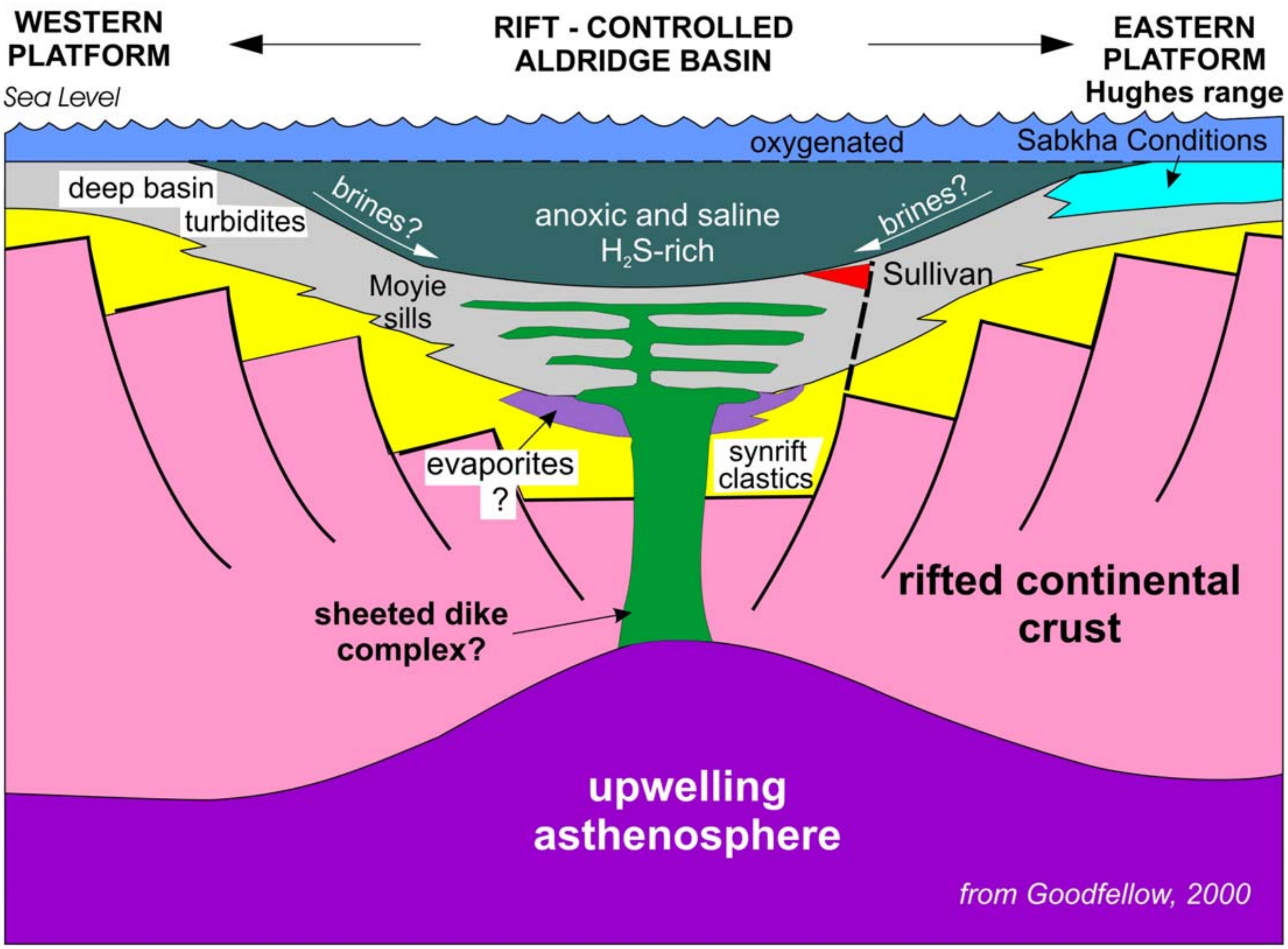
From Höy et al. (2000)

From Höy et al. (2000)

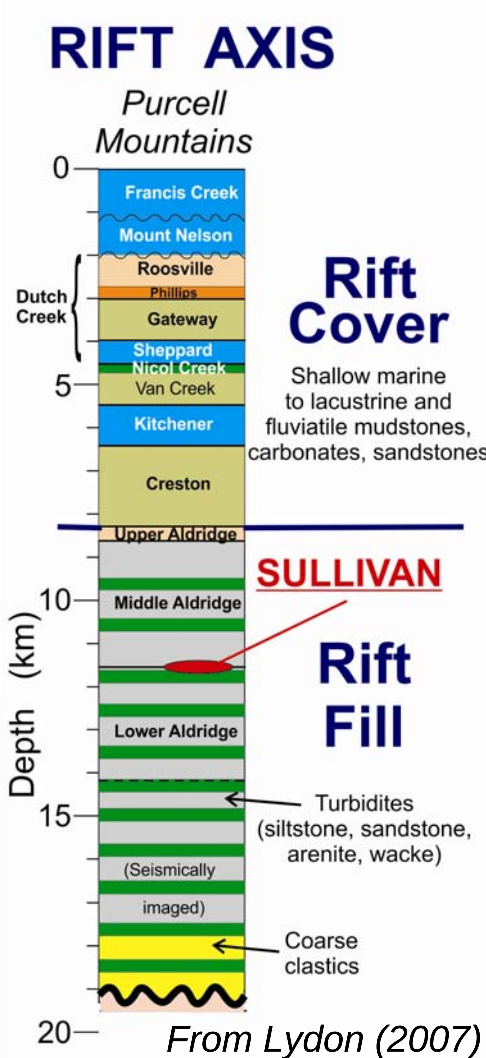
Intracratonic rift, Purcell Basin

Slide 45 shows a model, not to scale, of the Mesoproterozoic intracratonic rift basin (Purcell Basin, southern BC) at the time of formation of the Sullivan deposit (Goodfellow and Peter, 2010). On the right portion of the slide, a stratigraphic column of the rift-fill and rift-cover sedimentary sequences of the Belt-Purcell Supergroup is shown (from Lydon, 2007). This rift-controlled basin developed above an attenuated continental crust and an upwelling asthenosphere. It is filled by approximately 12 km of clastic sedimentary rocks (shown in yellow and grey) consisting mainly of deep-water turbidites and calcareous argillites intruded by numerous mafic sills (shown in green). This rift-fill sequence is overlain by a thinner rift cover sequence consisting of shallow marine to lacustrine and fluviatile mudstones, carbonates, and sandstones (Lydon, 2007). The Sullivan deposit occurs just below the contact between the Lower and Middle Aldridge Formation within turbidites of the rift-fill sequence. This setting is unusual as most SEDEX deposits occur in the stratigraphically higher rift-sag or rift-cover sequence. During deposition of the Aldridge turbidites, the deepest part of the water column may have been anoxic, saline and H_2S-rich (Goodfellow, 2000).

Intracratonic Rift: Purcell Basin



from Goodfellow, 2000



From Lydon (2007)

Sedimentary Textures, Purcell Basin

Photographs (**slide 47**) of sedimentary textures and facies of rocks, which host SEDEX deposits:

A. Middle Aldridge Formation, Purcell Basin, British Columbia. Photo courtesy of John Lydon.

B. The Sundown marker bed in the middle Aldridge Formation, Purcell Basin. The laminated carbonaceous siltite consists of alternating light and dark layers, 1 to 10 mm thick, whose relative thicknesses remain constant over distances in excess of 300 km. The diagnostic sequence of laminae can be correlated up to 300 km across the Purcell Basin (Huebschman, 1973; Edmunds, 1977; Höy, 1989, 1993) and have been used by exploration geologists to establish stratigraphic correlations within the otherwise monotonous sequence of turbidites. More than a dozen of these “marker” intervals have been recognized in the Purcell basin. Rock hammer is 30 cm long.

C. Polished slab of layered pyrrhotite-galena-sphalerite ore and fine-grained siliciclastic rocks (dark colored) typical of the upper part of the Main Band in Bedded Ores at the Sullivan deposit.

Sedimentary Textures, continued

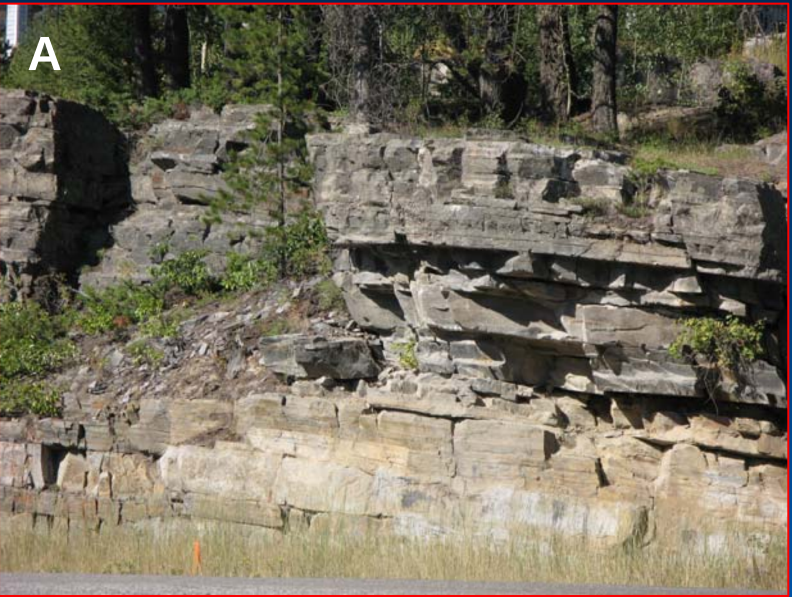
Photographs (**slide 47**) of sedimentary textures and facies of rocks which hosted SEDEX deposits:

D. Polished slab from the “B” Band, 3200 SE Crosscut, Sullivan mine, showing the typically laminated nature of the “*Bedded Ores*”. Note the layer of durchbewegt pyrrhotite-rich sulphides, which reflects bedding-parallel tectonic movement – a common feature of the Bedded Ores. From Lydon and Reardon (2000) and Lydon (2007).

E. Laminated pyrite variably replaced by pyrrhotite interlayered with argillite (dark coloured), and thin layers of magnetite, in the Ramp Extension, Southeastern Fringe of the Sullivan orebody. The small “spots” in the laminated pyrite layers are porphyroblasts of manganifereous garnet. From Lydon et al. (2000).

Sedimentary Textures, Purcell Basin

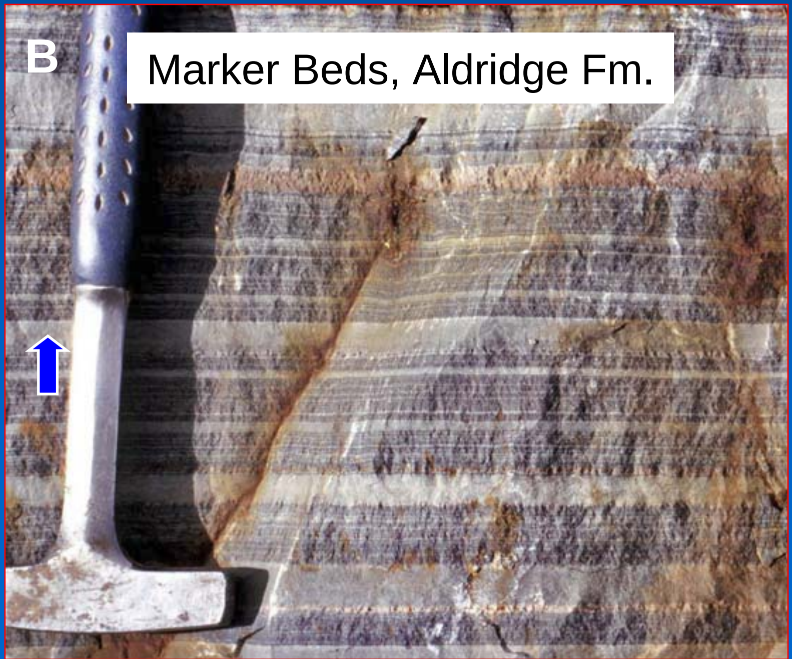
A



C

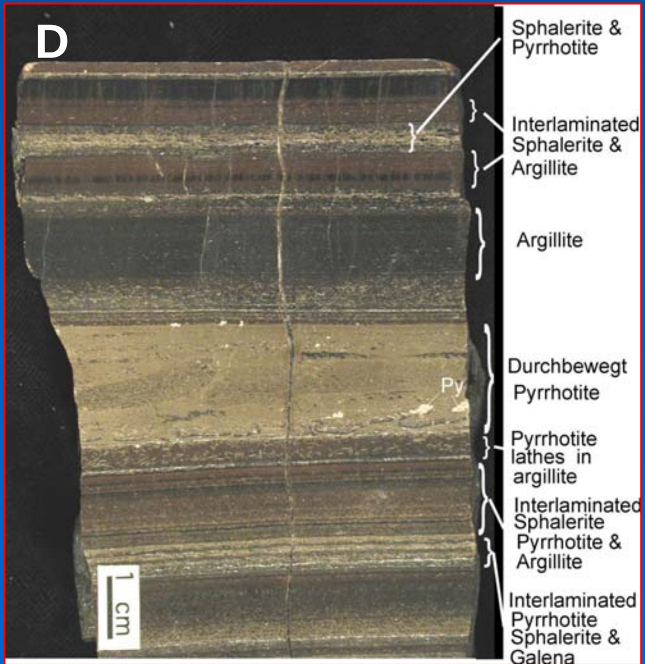
Folded layered sulphides, Sullivan deposit

B

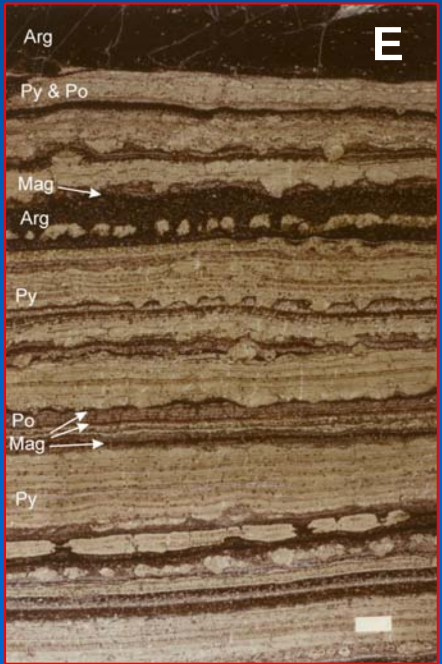


Marker Beds, Aldridge Fm.

D



E



Geological Cross-section of Sullivan Deposit

Slide 50 shows a schematic W-E cross section of the vent-proximal Sullivan deposit (from Lydon et al., 2000) and the distribution of local stratigraphy, major sulphide facies, and major alteration types. Mine grid units are feet. Corresponding photographs of the vent complex, bedded sulphides, and distal hydrothermal sediments are shown on **slide 51**.

The vent complex at Sullivan encompasses about 70% of the total ore tonnage (Lydon, 2007). It consists of the main sulphide lens, which is up to 100 m thick and coarsely layered with a lower uneconomic pyrrhotite (Po)-rich sulphide zone with local layers rich in galena (Gn) and sphalerite (Sp), a middle zone of tectonically layered pyrrhotite-galena-sphalerite, and an upper zone of massive galena, sphalerite, and pyrrhotite interlayered with sediments (from Lydon, 2004, 2007). Photo of the vent complex (**slide 51**) is from Lydon (2007); vertical field of view about 1.5 metres.

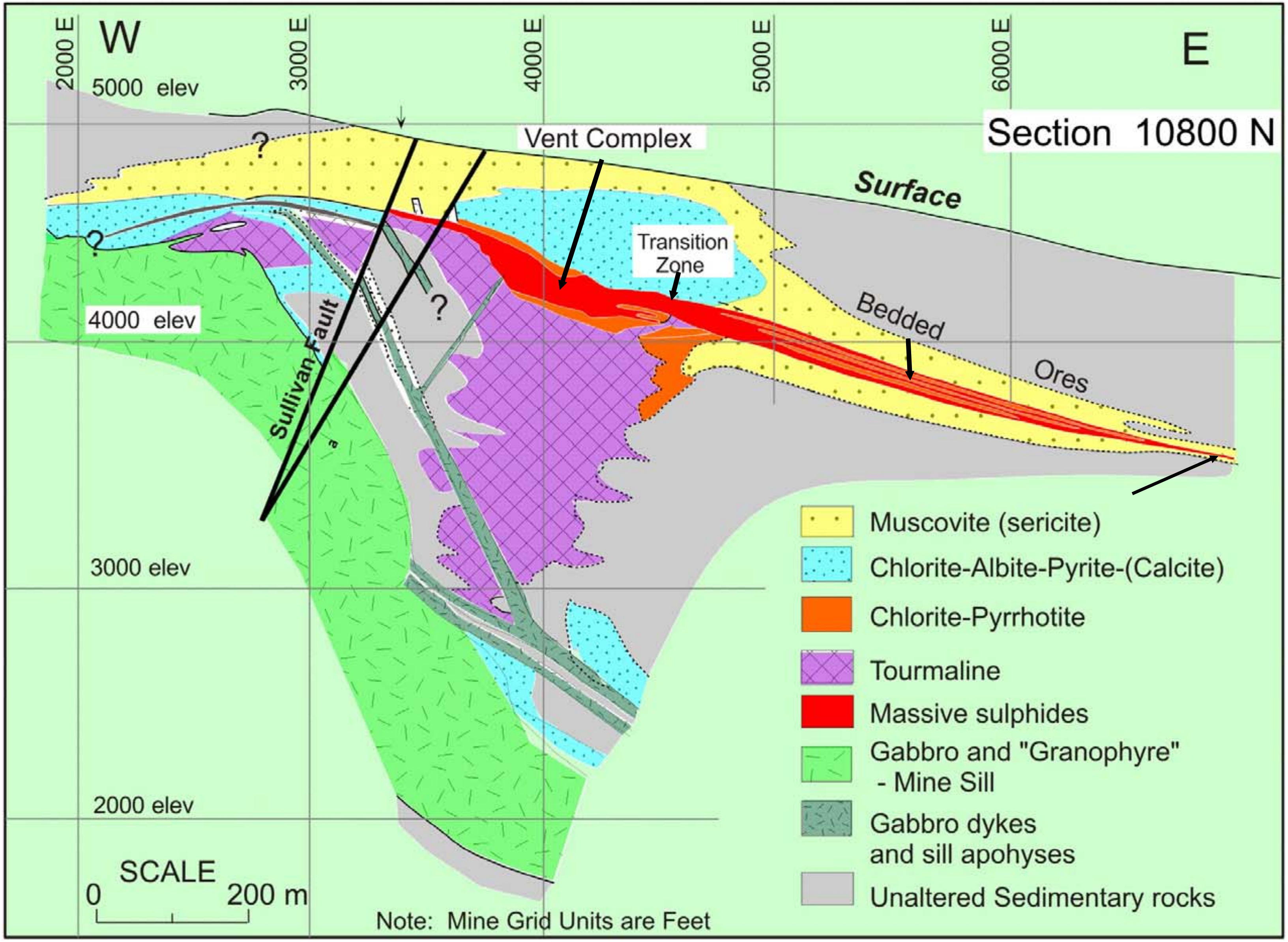
Geological Cross-section of Sullivan Deposit
- continued

The bedded sulphides consist of concordant layers of interlaminated sulphides [i.e, sphalerite (Sp), galena (Gn), pyrrhotite (Po)] and argillite (**slide 51**).

The distal sediments are spatially and temporally widespread as lateral sub-economic equivalents of the “bedded ores”; consequently they can be strong indicators of SEDEX deposits. They consist of chemical sediments of hydrothermal origin, such as disseminated pyrite and/or sphalerite, exhalative chert, hematite-chert iron formation, sedimentary barite and phosphate, and Mn-Fe-Ca-Mg carbonates.

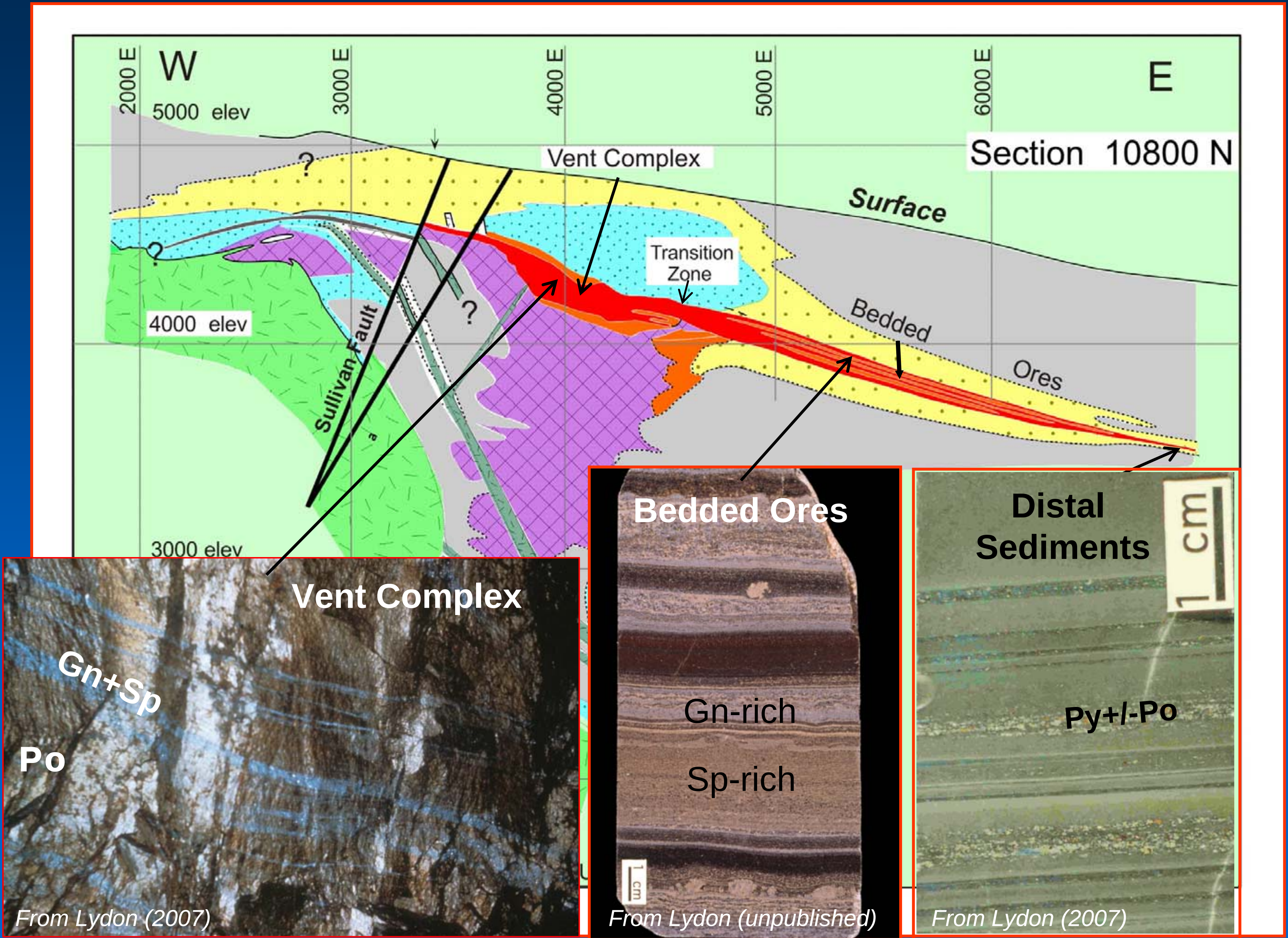
At Sullivan (**slide 51**), the distal sediments consist mainly of a muscovite-rich argillite and siltite with thin pyrite-pyrrhotite layers. The photograph of **slide 51** is a polished slab of drill core from the distal hydrothermal sediments of the Concentrator Hill Horizon (CHH).

Geological Cross-section of Sullivan Deposit



From Lydon (2007)

Geological Cross-section of Sullivan Deposit



From Lydon (2007)

From Lydon (unpublished)

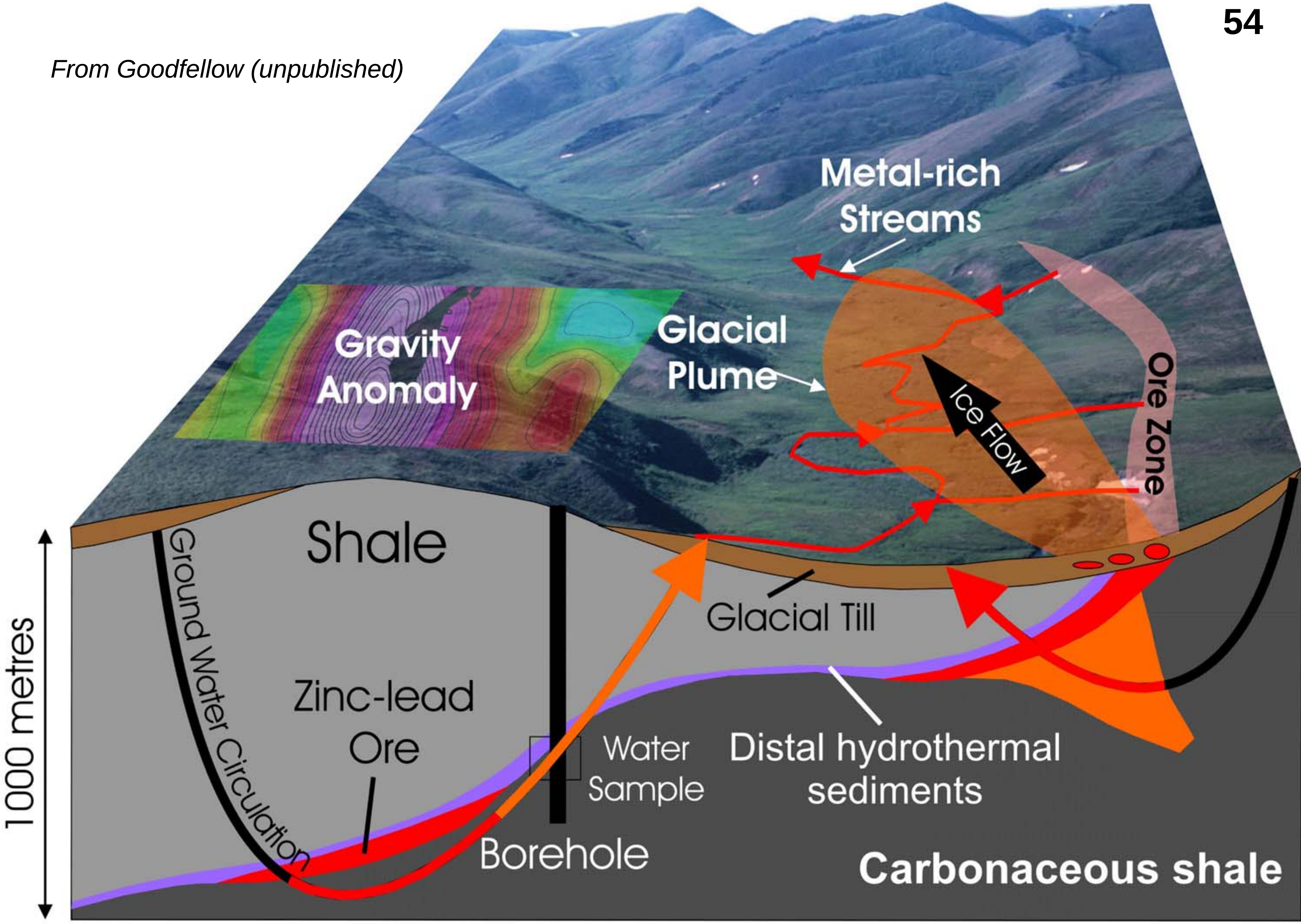
From Lydon (2007)

Key Exploration Criteria

- **Tectonic and sedimentary setting:** Thick (> 4 km) marine sedimentary sequences in fault-controlled intracratonic or epicontinental rifts.
- **Basin architecture:** Syn-rift and post-rift stages + coeval evaporative carbonate platforms, and syn-sedimentary faults.
- **Seafloor Environment:** Stratified with lower anoxic to sulphidic water column; no bioturbation; no benthic fauna; high C_{org}, etc.
- **Alteration:** Associated with pre- and post-ore host rocks. It includes dolomitization of platform carbonates, alkali-alteration of clastic rocks, silicate alteration halos and Fe-Mn carbonate alteration halos.

Key Exploration Criteria

- **Distal hydrothermal sediments** are spatially and temporally (syn- to post-ore) widespread. They consist of disseminated Py and/or Sph, chert, iron formation, sedimentary Ba and PO_4 deposits, Mn-Fe-Ca-Mg carbonates.
- **Geochemical anomalies:**
  - Regionally anomalous shales: Enriched in base metals and ore-associated elements (e.g., As, Sb, Cd, Mn, P, Ba, Hg, Tl).
  - Surficial geochemical anomalies: Soil & stream sediments and water enriched in SEDEX-forming elements (**slide 54**).
- **Others:** Presence of coeval MVTs and already discovered SEDEX deposits.



From Goodfellow (unpublished)