Sedimentary Exhalative (SEDEX) Deposits

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Abstract

There are 132 SEDEX (including Irish and BHT subtypes) deposits worldwide with known grade and tonnage, and of these, 50 have geological resources equal to or greater than 20 Mt. In Canada, there are 35 deposits, seven with measured geological resources of more than 20 Mt, including the Sullivan deposit with 162 Mt. Twelve Canadian deposits are past producers, the largest of which is the Sullivan deposit, which produced 149 Mt of 5.33 percent Zn and 5.64 percent Pb.

The morphology of SEDEX deposits is highly variable and includes mounds, lenses, and tabular or sheet-like bodies. Their internal architecture is controlled by the proximity of seafloor sulphides to fluid discharge vents. Vent-proximal deposits typically formed from buoyant hydrothermal fluids, whereas vent-distal deposits formed from fluids that are denser than seawater and pooled in bathymetric depressions that may be remote from seafloor vents.

Most SEDEX deposits are hosted by organic-rich sedimentary rocks that were deposited in basins during periods in the Earth's history when the oceans were stratified with a lower anoxic and H_2S-rich water column. In the Paleozoic Selwyn Basin, for example, there is a close temporal relationship between upward-increasing $\delta^{34}S$ secular trends in sedimentary pyrite, anoxic laminated carbonaceous shales and cherts, and three major SEDEX forming events in the Late Cambrian, Early Silurian, and Late Devonian.

The typical basinal architecture of most SEDEX deposits is a continental rift basin with at least 2 to 5 km of syn-rift, coarse-grained, permeable clastics and related volcanic rocks and/or volcaniclastics overlain by post-rift relatively impermeable basinal shales or carbonates. Hydrothermal discharge to the seafloor was commonly focused at the intersection of extensional and transform faults. There is close temporal and, in many cases, spatial association of SEDEX deposits with basaltic volcanic rocks, dykes, and sills. The low rigidity, permeability, and thermal conductivity of host sediments served to focus and prolong hydrothermal discharge at a restricted number of vent sites, thereby generating deposits that are an order of magnitude larger on average than VMS deposits.

SEDEX deposits most likely formed from oxidized and therefore H_2S-poor fluids generated in geopressured hydrothermal reservoirs within syn-rift clastic (and evaporitic) sediments sealed by fine-grained marine sediments. The large variability in the temperature, salinity, metal content, and redox conditions of SEDEX fluids was controlled by a number of parameters including the local thermal regime, the redox state of the reservoir sediments, and the presence or absence of evaporates. Because most of the fluids that formed SEDEX deposits were probably depleted in reduced S, an essential requirement for this deposit type is a sufficient supply of reduced S at the site of deposition. In the case of well-bedded deposits that formed at the seafloor, the most likely S source is bacteriogenic H_2S generated in an ambient anoxic water column.

Résumé

À l'échelle du monde, il existe 132 gîtes SEDEX, y compris les gîtes irlandais et de type Broken Hill avec teneurs et tonnages connus, et 50 d'entre eux renferment des ressources géologiques supérieures à 20 millions de tonnes. Le Canada possède 35 gîtes de ressources géologiques mesurées, dont sept renferment plus de 20 millions de tonnes, y compris le gisement de Sullivan avec 162 millions de tonnes. Douze gisements canadiens sont des producteurs passés et, le plus important d'entre eux, le gisement Sullivan, a produit 149 millions de tonnes avec 5,33 % de Zn et 5,64 % de Pb. D'une grande diversité, la géomorphologie des gîtes SEDEX comprend buttes, lentilles et corps tabulaires ou feuilletés.

La structure interne de ces gîtes est régie par la proximité des sulfures du plancher océanique par rapport aux évents relâchant des fluides. En général, les gîtes à proximité des évents se forment par l'intensité des fluides hydrothermaux; en revanche, ceux formés à distance des évents sont formés par des fluides plus denses que l'eau de mer et se concentrent dans les dépressions du plancher océanique qui peuvent être à l'écart des évents.

La plupart des gîtes SEDEX sont encaissés dans des sédiments carbonés déposés durant une période de l'histoire de la Terre au cours de laquelle les océans furent stratifiés avec une colonne d'eau anoxique plus basse et riche en H_2S. Dans le bassin de Selwyn du Paléozoïque, notamment, une relation étroite existe entre les tendances séculaires d'augmentation à la hausse de $\delta^{34}S$ dans la pyrite sédimentaire, les shales et les cherts laminés anoxiques et trois événements d'importance dans la formation des gîtes SEDEX au cours du Cambrien supérieur, du Silurien inférieur et du Dévonien supérieur.

La structure type des bassins de la plupart des gîtes SEDEX se caractérise par un bassin d'effondrement continental avec au moins 2 à 5 km de dépôts clastiques, volcaniques ou volcano-détritiques à gros grain, contemporains au rift, recouverts de shales ou de carbonates de bassins imperméables, lesquels sont postérieurs au rift. Les jaillissements hydrothermaux sur le plancher marin se produisaient habituellement à l'intersection des failles d'extension et de transformation. Il existe une association temporelle étroite et, en maints cas, spatiale des gîtes SEDEX avec les roches volcaniques basaltiques, les dykes et les filons-couches. La faible rigidité, la perméabilité et la conductivité thermale des sédiments hôtes ont servi à concentrer et à prolonger le jaillissement thermal dans un nombre restreint de sites d'évents, ce qui a créé des gîtes plus importants que les gîtes de sulfures massifs volcanogènes.

Selon toute probabilité, les gîtes SEDEX ont été formés de fluides oxydés, donc pauvres en H_2S produits par des réservoirs hydrothermaux géopressurés dans les sédiments clastiques (et évaporitiques), contemporains au rift, enveloppés

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par du carbonate ou des sédiments marins à grain fin. Un certain nombre de paramètres régissaient les grandes variations de température, de salinité, du contenu en métaux, des conditions de redox des fluides de SEDEX, soit le régime thermique, l'état de redox des sédiments du réservoir et la présence ou l'absence d'évaporite. Vu que la plupart des fluides qui ont formé les gîtes SEDEX étaient appauvris en souffre réduit, un élément essentiel de ce type de gîte est un approvisionnement suffisant de soufre réduit sur l'emplacement du dépôt. Dans le cas des gîtes bien lités qui ont formé le plancher océanique, la source de soufre la plus probable est le H_2S qui est habituellement enrichi dans les colonnes d'eau anoxiques.

Introduction

This synthesis of SEDEX deposits is intended as a synopsis of the major economic, geological, geochemical and genetic attributes of SEDEX deposits, with an emphasis on those that are considered important in mineral exploration. A great deal of the key attributes are based on research undertaken in the Selwyn Basin, Canada (e.g., Goodfellow, 2004; Goodfellow, 2007) and the Sullivan district, southeast B.C. (Höy et al., 2000; Lydon et al., 2000a; Lydon et al., 2007). This was augmented by major research programs on SEDEX deposits of the Northern Territories, Australia, by the Centre for Ore Deposits Research (CODES; e.g., Large et al., 1998; Bull and Rawlings, 1999) and on the Red Dog deposits, Brooks Range, Alaska by the U.S. Geological Survey (e.g., Kelley and Jennings, 2004; Young, 2004).

For a comprehensive analysis of this economically important deposit type, the reader is referred to reviews by Large (1981b), Goodfellow et al. (1993) and Leach et al. (2005).

Definition

Mineral Deposit Type

Sedimentary exhalative (SEDEX) deposits are typically tabular bodies composed predominantly of Zn, Pb, and Ag bound in sphalerite and galena that occur interbedded with iron sulphides and basinal sedimentary rocks, and that were deposited on the seafloor and in associated sub-seafloor vent complexes from hydrothermal fluids vented into mostly reduced sedimentary basins in continental rifts.

Mineral Deposit Subtypes

Subtypes of SEDEX deposits include the Broken Hill type (BHT) and those that formed below but near the seafloor (e.g., Irish-type deposits). The Irish type of SEDEX deposits (e.g., Hitzman and Beaty, 1997) is hosted predominantly by carbonate rocks and these deposits, either individually or collectively (district-wide), may show characteristics of both seafloor deposition and epigenetic features typical of Mississippi Valley-type (MVT) deposits (e.g., Sangster, 1990; Paradis et al., 2007). Irish-type deposits are considered to have formed by ore-forming processes similar to those of SEDEX deposits, but because carbonate platforms are highly soluble in mildly acidic ore fluids, the ores were also deposited in open space that commonly formed by hydrothermal karsting (e.g., dissolution voids, collapse breccias). BHT deposits (Beeson, 1991; Parr and Plimer, 1993; Walters, 1998) are characterized by high metamorphic grade, elevated base metal to S ratios, a spatial and temporal association with Fe-Si-Mn oxide exhalites, and bimodal felsic-mafic volcanic/intrusive and fine- to coarse-grained, mostly clastic sedimentary host rocks.

It is generally recognized that, especially at the deposit scale, no matter the criteria used to define a SEDEX deposit, there is a continuum of characteristics between SEDEX and VMS (volcanogenic massive sulphide) deposits on the one hand, and SEDEX and MVT deposits on the other hand. The distinction between the three classes of deposits is based not only on the typical physical, chemical, and geological attributes of member deposits and their respective geological environments, but also on genetic models for the class. Both SEDEX and MVT deposits occur within marine platforms of thick sedimentary basins and are thought to result from the migration of basinal metalliferous saline fluids, whereas VMS deposits occur in submarine volcanic-sedimentary sequences and are formed from convective hydrothermal fluids driven by, and/or magmatic fluids from, a subvolcanic magma body. Both SEDEX and VMS deposits were formed by hydrothermal systems that vented fluids onto the sea floor, so that the age difference between the ores and the immediate host rocks is by definition small. In contrast, MVT deposits formed in the subsurface and so the age difference between ores and host rocks can be much larger than for SEDEX deposits (Leach et al., 2001; Leach et al., 2005).

Associated Mineral Deposit Types

SEDEX-associated deposits include MVT (Paradis et al., 2007) and stratiform barite deposits (Goodfellow, 2004). The MVT deposits occur in platformal carbonate sequences that are the shallow-water facies equivalent of basinal, typically fine-grained sediments that host SEDEX deposits. Although there is debate regarding the genetic link between SEDEX and MVT deposits, the overlap in timing and the compositional similarities suggests that these deposits formed from similar basinal metalliferous fluids (Goodfellow, 1987; Sangster, 1990). The only major difference is that ore-forming fluids vented at the seafloor in the case of SEDEX deposits whereas most of the sulphide precipitation took place subsurface in the case of MVT deposits. The source of most of the reduced S in both deposit types is most likely bacterial reduced seawater sulphate (Goodfellow, 1987).

Economic Characteristics

Summary

SEDEX deposits are an important resource for Zn and Pb (Table 1). In 2004, SEDEX deposits accounted for 38.8% and 65.1% of the western world's Zn reserves and resources, respectively (Fig. 1; Hunt, 2006). By comparison, VMS and MVT deposits accounted for 30.2% and 15.3%, and 4.2% and 1.4%, of Zn reserves and resources, respectively. In addition, the percentage of SEDEX Zn reserves has shown a consistent increase over the past two decades. In 2004, SEDEX deposits also accounted for 32% of Zn production that was followed by VMS at 27%, Zn oxide at 12%, and MVT at 6%. The size (in tonnes of Pb + Zn metal) of SEDEX deposits is on average about an order of magnitude greater than that of VMS deposits (Goodfellow et al., 1993).

The bulk of the mineralization in most SEDEX deposits resides in the bedded ore facies. The ore minerals in this fa-

Table 1. Grade and tonnage of major global SEDEX deposits.

Deposit Name	Deposit Status	Location	Lat. (°)	Long. (°)	Age	Geological Resources (maximum size) Cu (%)	Zn (%)	Pb (%)	Ag (g/t)	Au (g/t)	Ore (Mt)	Zn+Pb (Mt)
HYC (McArthur River)	producer	Australia	-16.43	136.10	Late Paleoproterozoic	0.20	9.20	4.10	41.00		237	31.52
Talvivaara	deposit	Finland	63.98	-28.05	Paleoproterozoic	0.14	0.53		2.60		221	1.17
Mehdiabad	deposit	Iran	36.63	59.18	Cretaceous		7.20	2.30	51.00		218	20.71
Broken Hill	producer	Australia	-31.97	141.47	Paleoproterozoic	0.10	11.00	10.00	180.00	0.10	205	43.05
Ozernoe	deposit	Russia	52.50	112.50	Early Cambrian	1.20	6.20		37.00		180	11.16
Red Dog	producer	U.S.	68.07	-162.80	Mississippian		16.60	4.60	83.00		165	34.98
Sullivan	past producer	Canada	49.71	-116.01	Mesoproterozoic		5.86	6.08	67.36		162	19.33
Gamsberg	deposit	South Africa	-29.25	18.97	Mesoproterozoic		7.10	0.55			150	11.47
Mount Isa	producer	Australia	-20.73	139.48	Late Paleoproterozoic		6.80	5.90	148.00		124	15.75
Arditurri	deposit	Spain	43.17	-1.49	Late Carboniferous	1.00	8.00		50.00		120	9.60
Howards Pass (total)	deposit	Canada	62.56	-129.53	Early Silurian		5.00	2.00	17.00		120	8.40
Century	producer	Australia	-18.75	138.63	Mesoproterozoic		10.20	1.50	36.00		118	13.81
Saladipura	past producer	India	27.65	75.53	Paleoproterozoic		1.25				115	1.44
Big Syncline	deposit	South Africa	-29.20	18.83	Middle Paleo-proterozoic	0.09	2.45	1.01	12.90		101	3.49
Jiashengpan	deposit	China	41.00	109.32	Paleoproterozoic		3.80	1.30			100	100.0
Filizchai	producer	Azerbaijan	41.79	46.47	Early Jurassic	0.64	4.50	2.00		54.00	100	100.00
Broken Hill	producer	South Africa	-29.23	18.78	Middle Paleo-proterozoic	0.34	1.77	3.57	48.10		85	85.0
Black Mountain	deposit	South Africa	-29.23	18.73	Middle Paleo-proterozoic	0.75	0.59	2.67	30.00		82	85.0
Limonitovoye	deposit	Russia	58.24	93.19	Neoproterozoic	0.70	1.90				80	85.0
Navan	current producer	Ireland	53.62	6.82	Mississippian		8.04	2.68			78	8.34
Sindesar Kalan East	deposit	India	25.00	74.17	Paleoproterozoic		2.13	0.51			70	1.85
Changba-Lijiagou	producer	China	34.00	105.50	Middle Devonian		10.99	1.92			68	8.79
Rampura-Agucha	deposit	India	25.83	74.73	Paleoproterozoic		13.60	1.90	45.00		64	9.87
Howards Pass (Anniv)	deposit	Canada	62.47	-129.21	Early Silurian		5.40	2.10	25.00		61	4.58
Meggen	past producer	Germany	51.13	8.08	Middle Devonian	0.17	5.83	0.83			60	4.00
Howards Pass (XY)	deposit	Canada	62.56	-129.53	Early Silurian		5.40	2.10	9.00		59	4.43
Faro	past producer	Canada	62.36	-133.37	Late Cambrian		5.70	3.40	36.00		58	5.24
Rajpura-Dariba	producer	India	24.98	74.13	Paleoproterozoic	0.15	2.04	2.79	113.88	0.28	56	2.68
Tekeli	deposit	Kazakhstan	44.80	78.95	Neoproterozoic	1.00	6.00	5.00			50	5.50
Rosh Pinah	producer	Namibia	-27.95	16.77	Neoproterozoic	0.10	7.00	2.00			50	4.50
Hilton	producer	Australia	-20.57	139.47	Late Mesoproterozoic		9.30	6.50	151.00		49	7.74
Cannington	producer	Australia	-21.87	140.92	Paleoproterozoic		4.30	10.90	493.00		47	7.19
Dugald River	deposit	Australia	-20.25	140.15	Mesoproterozoic		13.28	2.09	42.00		43	6.59
Mokanpura North	deposit	India	25.00	74.13	Paleoproterozoic		2.40	0.60			40	1.20
Zinkgruvan	deposit	Sweden	58.82	15.10	Paleoproterozoic		10.00	1.50		45.00	40	4.60
Cirque	deposit	Canada	57.51	-125.15	Late Devonian		8.00	2.20	47.20		39	3.93
Su-Lik	deposit	U.S.	68.17	-163.20	Mississippian		8.00	2.00	30.00		34	3.40
Aguilar	producer	Argentina	-23.20	-65.70	Early Ordovician	0.05	8.50	6.50	150.00		32	4.83
Elura	past producer	Australia	-31.17	145.65	Devonian		8.62	5.58	108.98		32	4.57
Grum	past producer	Canada	62.27	-133.22	Late Cambrian		4.90	3.10	49.00		31	2.46
Rosh Pinah	producer	South Africa	-27.95	16.77	Neoproterozoic	0.10	7.25	2.10	11.00		30	2.76
Mochia	producer	India	24.36	73.72	Paleoproterozoic		3.79	1.69			27	1.47
Citronen Fjord	deposit	Denmark	83.08	-28.25	Ordovician		7.50				25	1.88
Rammelsberg	past producer	Germany	51.88	10.42	Middle Devonian	1.07	18.06	8.59			25	6.58
Hilton North (George Fisher)	deposit	Australia	-20.53	139.48	Late Mesoproterozoic		12.10	6.40	110.00		23	4.26
Lisheen	producer	Ireland	52.73	7.68	Mississippian		11.50	1.90	26.00		22	2.97
Balmat	producer	U.S.	44.25	-75.40	Mesoproterozoic		9.00	0.50			21	1.99
Franklin	past producer	U.S.	41.12	-74.57	Mesoproterozoic		19.60				20	4.00
Qingchengzi	deposit	China	40.73	123.59	Midfdle Proterozoic		2.00	3.00		75.00	20	1.00
Zhairem	deposit	Kazakhstan	48.33	70.50	Late Devonian	0.50	5.00	2.00			20	1.40

Notes: Data from Appendix 2 (DVD), Goodfellow and Lydon, 2007. Geological resources = production + economic reserves + sub-economic reserves; Mt = million tonnes; Zn+Pb Mt = Mt of combined Zn and Pb metal.

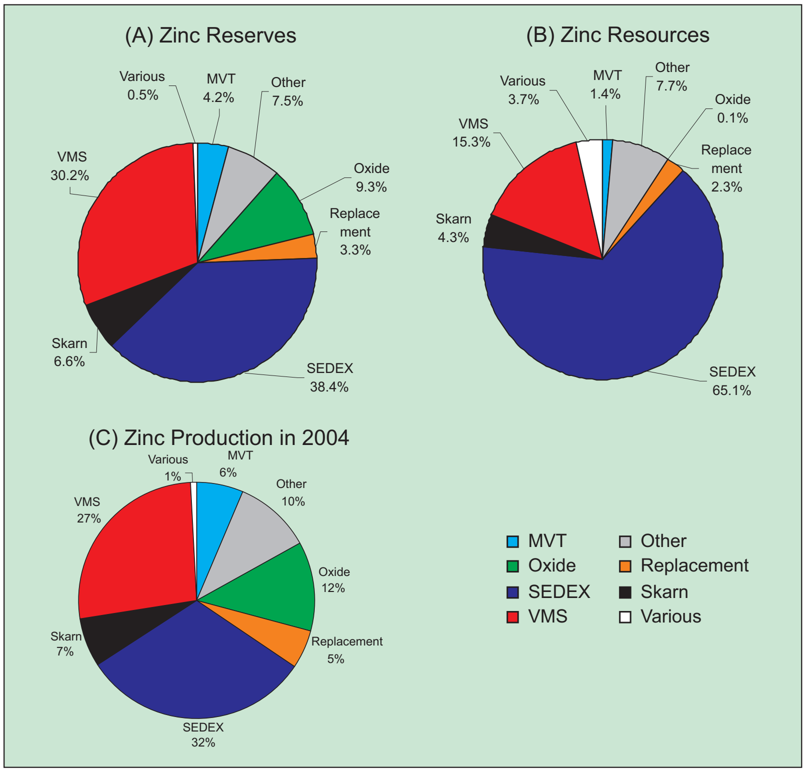

FIGURE 1. Zinc reserves **(A)**, resources **(B)**, and production **(C)** in 2004, broken down by deposit type. From Hunt, 2004.

cies are commonly fine-grained and intergrown, which leads to low metal recoveries during ore beneficiation. Although recrystallization of fine-grained sedimentary sulphides by metamorphism and/or by hydrothermal reworking in the vent complex produces coarser-grained ores from which higher recovery rates are obtained, these rates for SEDEX deposits are, on average, much lower than for VMS, MVT, and BHT deposits, the other major sources of Zn and Pb (Goodfellow et al., 1993).

Grade and Tonnage Characteristics

There are 132 SEDEX including Irish and BHT deposits world wide with grade and tonnage figures (Fig,. 2 and Appendix 2, DVD), and of these, 50 have geological resources greater than 20 Mt (Table 1). In Canada, there are 35 deposits with known geological resources (Appendix 1, DVD), of which seven contain more than 20 Mt, including the Sullivan deposit with 161 Mt and the Howards Pass deposits estimated at 120 Mt (Table 2 and Fig. 2). Of the 35 Canadian deposits, 12 are past producers, the largest of which is the Sullivan deposit that produced 149 Mt of 5.33% Zn and 5.64% Pb (Table 3). The Howards Pass deposit is currently not economic, although it is currently undergoing major exploration and evaluation. Most SEDEX deposits in Canada occur in the Anvil, MacMillan Pass, and Howards Pass districts, Selwyn Basin; the Gataga district, Kechika Trough; the Sullivan district, Belt-Purcell; and the Duncan district, southern British Columbia (Fig. 3).

In order of endowment of SEDEX deposits globally, the major basins are: Mt. Isa-McArthur Basin (seven deposits totaling 112 Mt of Zn + Pb metal), Curnamona Craton (one deposit of 75 Mt Zn+Pb), Selwyn Basin (17 deposits totaling 55 Mt Zn+Pb), Brooks Range (three deposits totaling 40 Mt Zn+Pb), Namaqualand (four deposits totaling 30 Mt Zn+Pb), Rajasthan (five deposits totaling 20 Mt Zn+Pb), Belt-Purcell Basin (one deposit totaling 19 Mt Zn+Pb), Irish Midlands (five deposits totaling 15 Mt Zn+Pb), and Rhenish Basin (two deposits totaling 11 Mt Zn+Pb; Sangster and Hillary, 2000).

Singer (1995) defined giant deposits as the top 10 percentile and super-giants as the top one percentile in terms of metal content. Using these criteria, giant deposits contain more than 8 Mt of Pb+Zn metal. If the criteria are extended to total geological size, giant and super-giant SEDEX deposits contain more than 100 and 300 Mt of ore, respectively. Some obvious conclusions from Table 1 and Figure 4 are:

- Broken Hill is a super-giant deposit based on both metal tonnes and grade; HYC and Mehdiabad are super-giant deposits based on geological resources.
- Nine of the 15 giant or super-giant deposits, based on total geological resources, are Meso-Palaeoproterozoic in age. Six of these - Red Dog, Ozernoe, Arditurri, Mehdiabad, Filizchai and Howards Pass - are Phanerozoic giant or super-giant deposits.
- The Broken Hill and Red Dog deposits stand out as producers in terms of both size and metal grade.

Metal grades are highly variable, with a mean of 0.97 wt. % Cu, 3.28 wt. % Pb, 6.76 wt. % Zn and 63 g/t Ag. Average geological resources are 34.78 Mt of sulphide and 3.165 Mt of Zn + Pb metal Fig. 5. Most of the production from SEDEX deposits in Canada came from the world-class Sullivan deposit in the Belt-Purcell basin, southeastern British Columbia, the Faro, Grum, and Vangorda deposits in the Selwyn Basin, Yukon, and the H.B. and Reeves-MacDonald deposits, southern British Columbia (Table 3).

Geological Attributes of SEDEX deposits

Deposit Morphology

The bulk of the ore is contained in a stratiform sulphide body that typically has a high aspect ratio (i.e., the ratio of the lateral extent of the body to its maximum stratigraphic thickness). Because most SEDEX deposits have an aspect ratio of 20 or more, the most common morphology is represented by sheets or tabular lenses of stratiform sulphides up to a few tens of metres in thickness and more than a km in length (Large, 1983). The Sullivan deposit in southern B.C.(Fig. 6), and the Tom and Jason deposits at MacMillan Pass, Yukon, are wedge-shaped and have a moderately high aspect ratio. The Howards Pass (Fig. 7) and Anniv deposits in the Howards Pass district, on the other hand, are saucer-shaped and taper gradually laterally for distances of several km. Unlike the

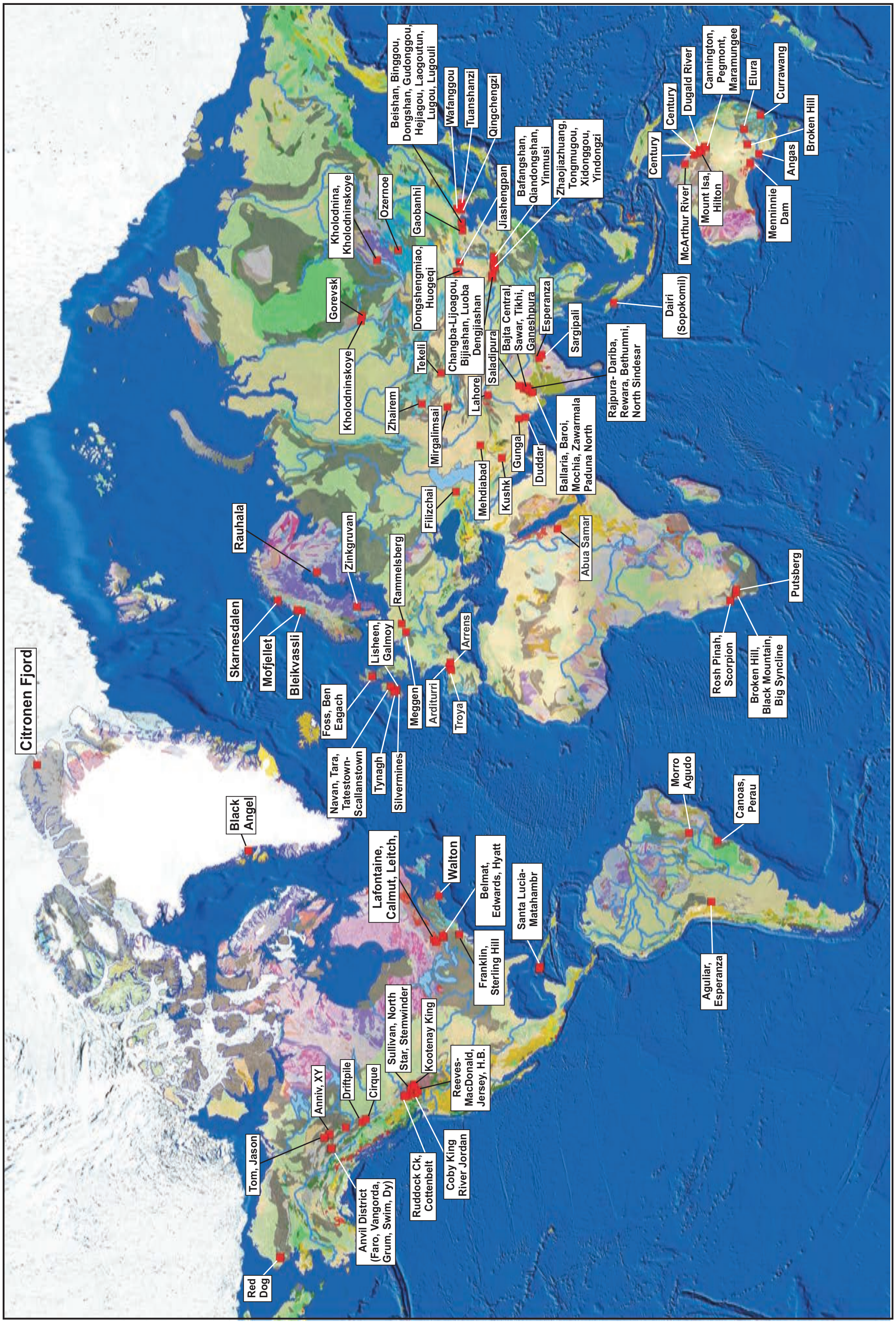

Figure 2. Global distribution of SEDEX deposits (includes Irish-type and BHP deposits) plotted on a simplified geological map of the world. Geology from Kirkham and Rafer (2003). Data on SEDEX deposits from Appendix 2 (DVD).

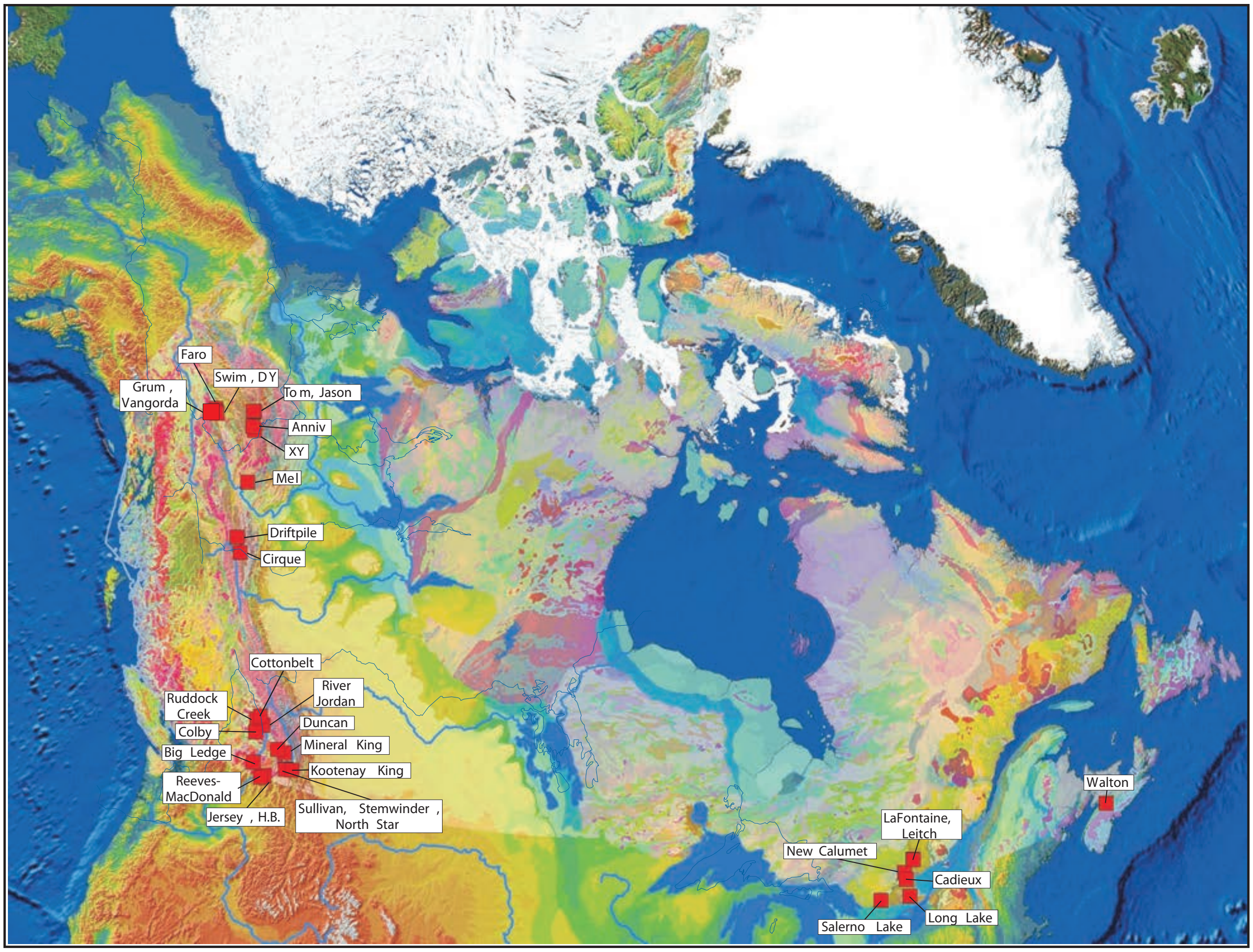

Figure 3. Canadian SEDEX deposits plotted on a 1:2 000 000 geological map of Canada by Wheeler et al. (1996). Data on SEDEX deposit from Appendix 1 (DVD).

vent-proximal Tom and Jason deposits (e.g.,Fig. 8A), the Howards Pass deposits (XY, Anniv, and OP) are probably not spatially associated with a hydrothermal seafloor vent (e.g., Fig. 8B). The geometry of distal deposits is controlled by the basin morphology within which hydrothermal metalliferous fluids formed brine pools similar to Atlantis II and Discovery deeps in the Red Sea (Zierenberg, 1990).

Deposit Architecture

Vent-proximal deposits are characterized by four distinct facies: 1. bedded sulphides, 2. vent complex, 3. sulphide stringer zone, and 4. distal hydrothermal sediments. Near the center of fluid up-flow represented by the stringer zone, the bedded sulphides are characteristically infilled, veined, and variable replaced by a higher-temperature mineral assemblage, producing the vent complex (Goodfellow et al., 1993). The distal hydrothermal sediments probably represent plume fallout that has been dispersed by bottom currents or alternatively clastic sulphides shed from sulphide mounds. Examples of deposits with zone-refined vent complexes include the Sullivan, Tom, Jason, and Rammelsberg deposits.

Vent-distal deposits, however, are typically weakly zoned, well bedded, and conform to the basin morphology (e.g., Fig. 8B). There is no evidence of the type of zone refining that accompanies veining, infilling, and replacement of bedded sulphides by a typically higher-temperature assemblage and that characterizes vent-proximal deposits.

Textures and Mineralogy

The bedded facies in both distal and proximal deposits is composed of sulphide minerals, other hydrothermal products such as carbonates, chert, barite, and apatite, and non-hydrothermal clastic, chemical, and biogenic sedimentary rocks. The dominant sulphide mineral in most deposits is pyrite, although in some deposits (e.g., Sullivan and Mt. Isa), pyrrhotite is predominant. The main economic minerals are sphalerite and galena (e.g., Fig. 9A, Howards Pass deposit), although chalcopyrite is an economically important mineral in a few deposits (e.g., Rammelsberg; Hannak, 1981). The ratio of iron sulphides to base metal sulphides ranges from less than 1:1 (e.g., Red Dog; Moore et al., 1986) to greater than 5:1 (e.g., Sullivan; Hamilton et al., 1982). The relative proportion of non-sulphide hydrothermal components is similarly variable. Barite, when present, occurs in major amounts (i.e., more than 25% of the hydrothermal product) and is present in about 25% of Proterozoic and about 75% of Phanerozoic SEDEX deposits (Goodfellow et al., 1993). Silica, usually as chert, is ubiquitous in most stratiform ores and is in part hydrother-

Table 2. Grade and tonnage of Canadian SEDEXdeposits.

Deposit Name	Province/ Territory	Lat. (°)	Long. (°)	Age	Age (Ma)	Deposit Status	Geological Resource (size of deposit)					
							Cu (%)	Zn (%)	Pb (%)	Ag (g/t)	Au (g/t)	Ore (Mt)
Sullivan	British Columbia	49.71	-116.01	Mesoproterozoic	1470	past producer		5.86	6.08	67.36		161.97
Howards Pass (total)	Yukon	62.56	-129.53	Early Silurian	435	deposit		5.40	2.10	17.00		120.00
Howards Pass (Anniv)	Yukon	62.47	-129.21	Early Silurian	435	deposit		5.40	2.10	25.00		61.00
Howards Pass (XY)	Yukon	62.56	-129.53	Early Silurian	435	deposit		5.40	2.10	9.00		59.00
Faro	Yukon	62.36	-133.37	Late Cambrian	514	past producer		5.70	3.40	36.00		57.60
Cirque	British Columbia	57.51	-125.15	Late Devonian	367	deposit		8.00	2.20	47.20		38.50
Grum	Yukon	62.27	-133.22	Late Cambrian	514	past producer		4.90	3.10	49.00		30.80
Dy	Yukon	62.23	-133.14	Late Cambrian	514	deposit	0.12	6.70	5.50	84.00	0.95	21.10
Tom	Yukon	63.17	-130.14	Late Devonian	367	deposit		7.00	4.61	49.10		15.72
South Cirque	British Columbia	57.51	-125.15	Late Devonian	367	deposit		6.90	1.40	32.00		15.50
Jason	Yukon	63.15	-130.26	Late Devonian	367	deposit		7.40	6.50	65.00		10.10
Jersey	British Columbia	49.10	-117.22	Early Cambrian	525	past producer		3.49	1.65	3.08		7.68
Vangorda	Yukon	62.25	-133.18	Late Cambrian	514	past producer		4.90	3.80	54.00	0.79	7.50
Mel	Yukon	60.35	-127.40	Cambrian	525	deposit		7.10	2.05			6.78
Big Ledge	British Columbia	49.50	-118.15	Neoproterozoic	700	deposit		4.00				6.50
H.B.	British Columbia	49.15	-117.20	Early Cambrian	525	past producer		4.10	3.30	4.80		6.45
Reeves-MacDonald	British Columbia	49.02	-117.37	Early Cambrian	525	past producer		3.42	0.98	3.40		5.80
Clear Lake	Yukon	62.78	-135.14	Mississippian	340	deposit		11.40	2.00	38.01		5.57
Ruddock Creek	British Columbia	51.27	-118.98	Late Proterozoic	650	deposit		7.50	2.50			5.00
Walton	Nova Scotia	45.21	-64.04	Mississipian	340	past producer	0.04	0.11	0.32	27.70		4.90
Swim	Yukon	62.21	-133.03	Late Cambrian	514	deposit		4.70	3.80	42.00		4.75
New Calumet	Quebec	45.70	-76.68	Mesoproterozoic	1300	past producer		5.95	1.66	121.33	0.64	3.65
Duncan	British Columbia	50.37	-116.95	Early Cambrian	525	deposit		3.10	3.30			2.76
River Jordan	British Columbia	51.13	-118.41	Late Proterozoic	650	deposit		5.60	5.10	35.00		2.60
Driftpile	British Columbia	58.05	-125.95	Late Devonian	367	deposit		11.90	2.00			2.40
Mineral King	British Columbia	50.35	-116.43	Neoproterozoic	370	past producer		4.12	1.76	27.50		2.10
Upton	Quebec	45.68	-72.67	Ordovician	472	past producer		2.21		15.00		1.00
Colby (Kingfisher)	British Columbia	50.73	-118.73	Proterozoic	1700	deposit		2.60	0.58			1.67
Cottonbelt	British Columbia	51.45	-118.82	Proterozoic	1700	deposit		2.00	6.00	50.00		1.00
Cadieux (Renfrew Zinc)	Ontario	45.41	-76.71	Mesoproterozoic	1300	deposit		10.00				1.00
Salerno Lake	Ontario	44.85	-78.47	Mesoproterozoic	1300	deposit		5.00				0.75
Long Lake	Ontario	44.69	-76.77	Mesoproterozoic	1300	past producer		10.00				0.10
Leitch	Quebec	46.13	-75.96	Mesoproterozoic	1300	deposit		8.00				0.08
North Star	British Columbia	49.68	-116.03	Mesoproterozoic	1470	past producer		6.12	35.50	673.00		0.06
Lafontaine	Quebec	46.12	-75.96	Mesoproterozoic	1300	deposit		12.03				0.03
Stemwinder	British Columbia	49.69	-116.02	Mesoproterozoic	1470	past producer		15.60	3.70	76.30		0.03
Kootenay King	British Columbia	49.74	-115.61	Mesoproterozoic	1468	past producer		15.60	5.35	66.50		0.01

Notes: Data from Appendix 1 (DVD), Goodfellow and Lydon, 2007

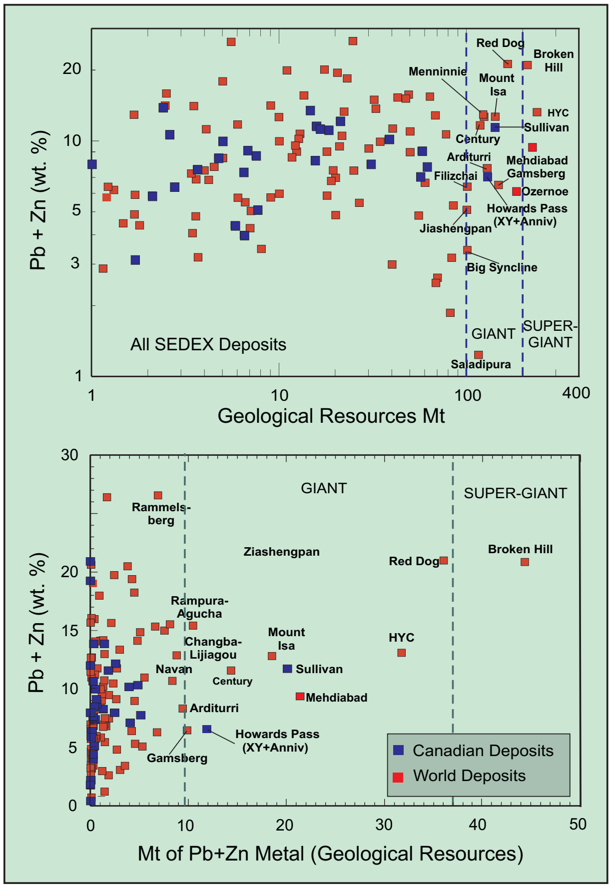

Figure 4. Grade vs. tonnage plots for SEDEX (including Irish and BHT) deposits world wide. Top: Pb + Zn (wt. %) vs. geological resources (Mt); Bottom: Pb + Zn (wt. %) vs. Pb + Zn metal (Mt).

mally derived.

The outer margins of the stratiform body, referred to as the distal facies, usually consist of bedded hydrothermal products that have no economic value, due to a decrease in the relative proportion of base metal sulphides with distance from the center of hydrothermal discharge (e.g., Sullivan horizon, Fig. 9C). The distal facies includes laminated pyrite and pyrrhotite, manganese, iron and calcium carbonates, iron oxides, barite, and phosphate. The contact between the bedded ore facies and the distal sedimentary facies is in most cases gradational and economically defined.

In contrast to the regularly layered appearance of the bedded ore facies, the vent complex is heterogeneous in nature and is typically composed of massive zones, replacement patches, irregular veins and/or disseminations of sulphides, carbonates, and silicates (mostly quartz; e.g., Fig. 9B, Tom vent complex). The mineral assemblage is dominated by pyrite, pyrrhotite, galena, sphalerite, ferroan carbonate, dolomite, quartz, tourmaline, and lesser muscovite, chlorite, chalcopyrite, arsenopyrite, and sulphosalt minerals. In deposits in which the vent complex has been well documented (e.g., Tom, Jason, and Sullivan), the contact between the stratabound vent complex and adjacent sedimentary-hydrothermal facies is a discordant replacement contact. The vent complex is formed by the reaction of upflowing hydrothermal fluids with hydrothermal and host sediment, which causes the replacement of the lower-temperature sedimentary minerals by higher-temperature vent assemblages (Turner, 1990; Kelley et al., 2004).

The feeder zone underlying vent complexes is discordant and composed of sulphide, carbonate, and silica veins, impregnations, and replacements that intersects the footwall sedimentary sequence (e.g., Fig. 9D, Sullivan deposit; Fig. 9E, Red Dog deposit). The feeder zone at many deposits appears to be rooted in a synsedimentary fault zone, and fault-scarp breccias, debris flows,

Table 3. Grade and tonnage of Canadian SEDEX deposits brought into production.

						Total Production					
Deposit Name	Province/ Territory	Lat. (°)	Long. (°)	Age	Date (Ma)	Cu (%)	Zn (%)	Pb (%)	Ag (g/t)	Au (g/t)	Mt
Sullivan	British Columbia	49.71	-116.01	Mesoproterozoic	1470	0.00	5.33	5.64	62.10	0.00	149.17
Faro	Yukon	62.36	-133.37	Cambrian	514		5.00	3.40	33.00	0.30	53.18
Vangorda	Yukon	62.25	-133.18	Cambrian	514		4.30	3.40	48.00	1.00	5.20
Grum	Yukon	62.27	-133.22	Cambrian	514		5.80	3.40	50.00	0.60	4.60
Jersey	British Columbia	49.10	-117.22	Early Cambrian	525		3.24	1.41	2.64		8.13
H.B.	British Columbia	49.15	-117.20	Early Cambrian	525		4.10	0.77	4.74	0.00	6.66
Reeves-MacDonald	British Columbia	49.02	-117.37	Early Cambrian	525	0.00	3.48	0.99	3.39		5.85
Walton	Nova Scotia	45.21	-64.04	Mississippian	340	0.56	1.44	4.33	374.00		0.36
New Calmut	Quebec	45.70	-76.68	Mesoproterozoic	1300		6.06	1.70	124.43	0.65	3.39
North Star	British Columbia	49.68	-116.03	Mesoproterozoic	1470		6.12	35.50	673.00		0.06
Mineral King	British Columbia	50.35	-116.43	Neoproterozoic	370	0.03	4.30	1.78	27.45		2.10
Kootenay King	British Columbia	49.74	-115.61	Mesoproterozoic	1468		15.60	5.35	66.50		0.01

Notes: Data from Appendix 1 (DVD), Goodfellow and Lydon, 2007.

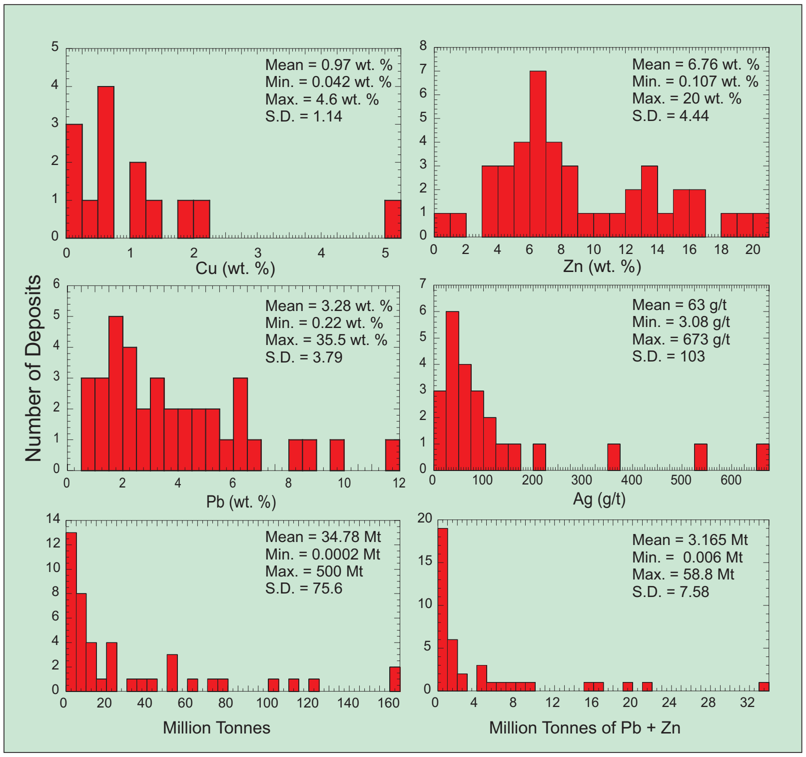

Figure 5. Histograms of metal grades and tonnage for global SEDEX deposits.

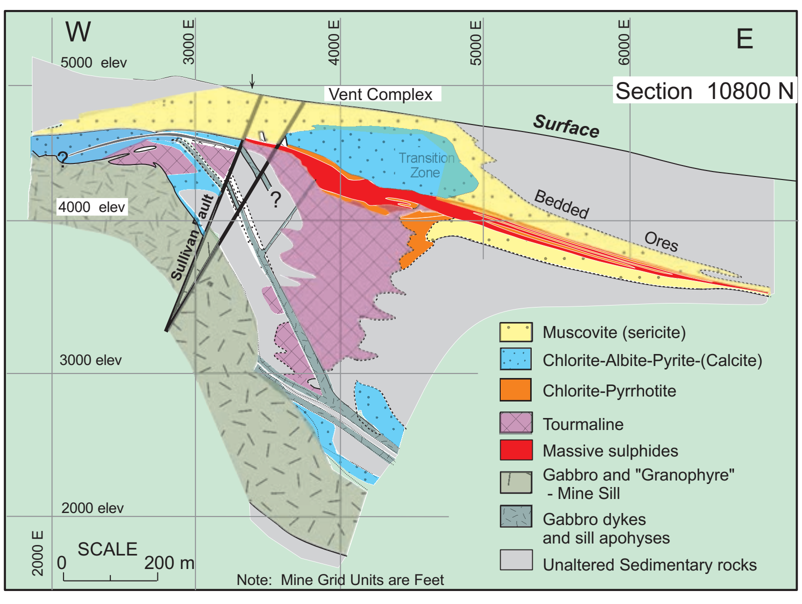

Figure 6. Cross section of the Sullivan deposit showing the local stratigraphy, major sulphide types, and core alteration facies (from Lydon et al., 2000a).

and abrupt facies changes associated with SEDEX deposits indicate that the fault was active before, during, and/or after sulphide formation (e.g., Jason and HYC deposits; Turner, 1990; Large and McGoldrick, 1998).

Host Rocks

Most SEDEX deposits are hosted by basinal marine, reduced facies, fine-grained sedimentary rocks that consist mostly of carbonaceous chert and shale. These sedimentary rocks generally represent pelagic and hemipelagic sediments. In some deposits (e.g., Sullivan), pelagic and/or hemipelagic sedimentary rocks are interbedded with basin-wide turbiditic siltstones and sandstones, and locally derived coarse-grained clastic sediments shed off uplifted blocks during extensional tectonism. In the case of the Irish-type deposits, the dominant lithologies are limestone and dolomite. BHT deposits are hosted by a bimodal volcanic and clastic sedimentary sequence that is commonly metamorphosed to amphibolite-granulite facies, as at Broken Hill, Australia.

Chemical Attributes of SEDEX Deposits

Ore Composition

The main economic constituents of SEDEX ores are Zn, Pb, and Ag that occur primarily in sphalerite and galena in both the bedded ores and vent complex. Grades of Pb + Zn are commonly highest near the transition between the zone-refined vent complex and the laterally extensive bedded ore facies (e.g., Tom and Sullivan, Goodfellow and Rhodes, 1990; Lydon et al., 2000a). This increase in base metals and ore-associated elements (e.g., Hg, As, Sb) is caused by the leaching of these elements from the vent complex and reprecipitation in bedded facies adjacent to the vent complex. In a few deposits, such as Rammelsberg in Germany and Mount Isa in Australia, Cu is an important economic resource and is concentrated in what has been interpreted as the vent facies (Goodfellow et al., 1993). Other economically recoverable elements include Sn in the Sullivan deposit (Hauser and Hutchinson, 1983) and Au in deposits of the Anvil district (Jennings and Jilson, 1986) and Sullivan (Conly et al., 2000), although the Au content of SEDEX deposits is typically low (Emsbo, 2000).

In addition to the ore-forming elements, SEDEX deposits are enriched in a large suite of ore-associate elements that may include Fe, Mn, P, Ba, Ca, Mg, Hg, Cd, As, Sb, Se, Sn, In, Ga, Bi, Co, Ni, and Tl (e.g., Goodfellow, 1984; Goodfellow and Rhodes, 1990; Slack et al., 2004).

Textural, Mineralogical, and Chemical Zonation

One of the most characteristic features of many SEDEX deposits is the radial zonation of hydrothermal textures, minerals, and elements about centers of hydrothermal fluid discharge. This lateral zonation away from the center of fluid discharge is controlled mostly by zone refining in the vent complex and is typically accompanied by a decrease in the

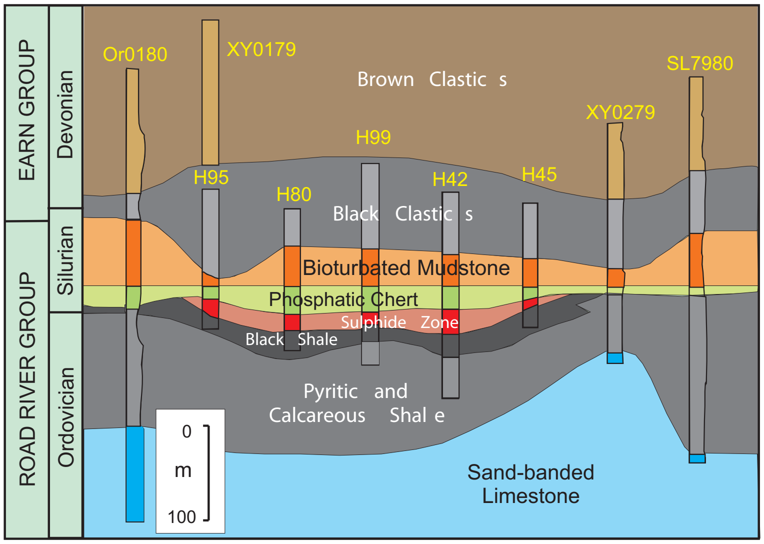

Figure. 7. Cross section of the Howards Pass (XY) deposit showing the local stratigraphy in the area of mineralization (from Goodfellow, 2004).

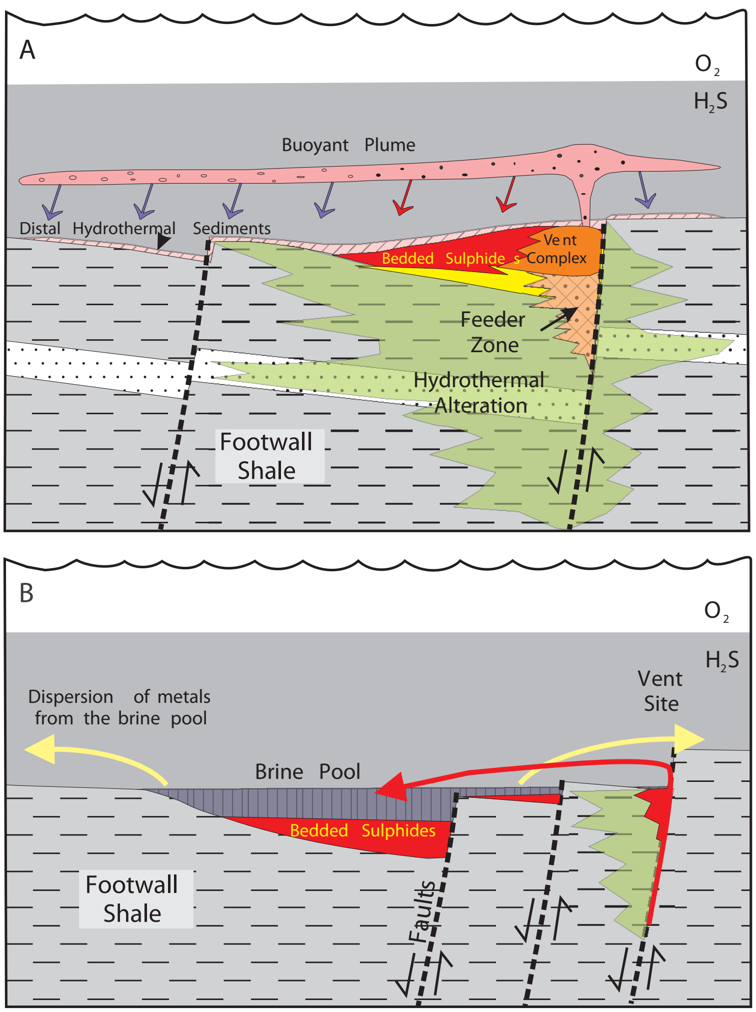

Figure. 8. Genetic models for SEDEX deposits. **(A)** Vent-proximal deposits formed from buoyant hydrothermal plume (e.g., Sullivan, B.C.; Tom and Jason, Yukon; Rammelsberg, Germany); **(B)** Vent-distal deposit formed from a bottom-hugging brine (e.g., Howards Pass and Anniv, Yukon; HYC deposit, Australia).

thickness of the stratiform body and the number and/or thickness of individual beds of hydrothermal minerals (Goodfellow et al., 1993).

An increase in the Zn:Pb ratio away from the vent complex is the most pronounced and consistent feature of SEDEX deposits, and has been well documented for the Tom (Goodfellow and Rhodes, 1990), Jason (Turner, 1990), Cirque (Jefferson et al., 1983), Sullivan (Hamilton et al., 1982), and Red Dog (Moore et al., 1986) deposits. Other chemical zonation patterns include increases in Pb:Ag, Cu:Zn+Pb, Fe:Zn, Ba:Zn, and SiO_2:Zn ratios away from the vent complex (e.g., Sullivan and Tom, Hamilton et al., 1982; Goodfellow, 2004).

The Tom deposit is a good example of a deposit that is highly zoned. The bedded ore facies sediments that overlie the fluid discharge conduit are brecciated, veined, and variably replaced by silica, ferroan carbonate, and sulphides. The subsurface replacement processes have produced a marked textural, mineralogical, and chemical zonation from the core of the vent complex to the distal fringes (Goodfellow and Rhodes, 1990). At the margins of the vent complex, fine-grained low-temperature phases of the bedded ore facies (i.e., Fe-poor, cream sphalerite, galena, framboidal pyrite, barite, and chert) are replaced by coarser-grained, higher-temperature assemblages (i.e., coarsely crystalline, Fe-rich black sphalerite, and Hg-rich pink sphalerite, galena, siderite, quartz, pyrrhotite, chalcopyrite, arsenopyrite, and tetrahedrite). These mineralogical changes are reflected by the systematic zonation of Zn, Pb, Cu, Cd, Hg, As, Sb, Ba, Fe, Mn, Ca, and CO_2 within and about the vent complex, and an increase in Pb/Pb+Zn ratios towards the center of hydrothermal fluid discharge (Goodfellow and Rhodes, 1990). Near the core of the vent complex, sedimentary barite has been completely replaced by ferroan carbonate minerals.

Alteration Textures, Mineralogy, and Chemistry

Although many SEDEX deposits are closely associated with an underlying hydrothermal feeder zone, hydrothermal alteration has not been well documented and mapped at most deposits. Alteration minerals that have been reported for SEDEX deposits include quartz, muscovite, chlorite, ankerite, siderite, tourmaline, and sulphides. The sulphide content of alteration zones is typically low, but pyrite, pyrrhotite, galena, sphalerite, chalcopyrite, tetrahedrite, and arsenopyrite may be present.

Hydrothermal alteration associated with SEDEX deposits is commonly widespread and extends for hundreds of metres into the pre- and post-ore sedimentary sequence and up to several kilometres laterally from the deposit. For example, sericite alteration at Sullivan extends more than 200 m below the ore, approximately 4 km in an east–west direction along the Kimberley Fault, and about 6 km south along the Sullivan-North Star corridor (Fig. 10 from

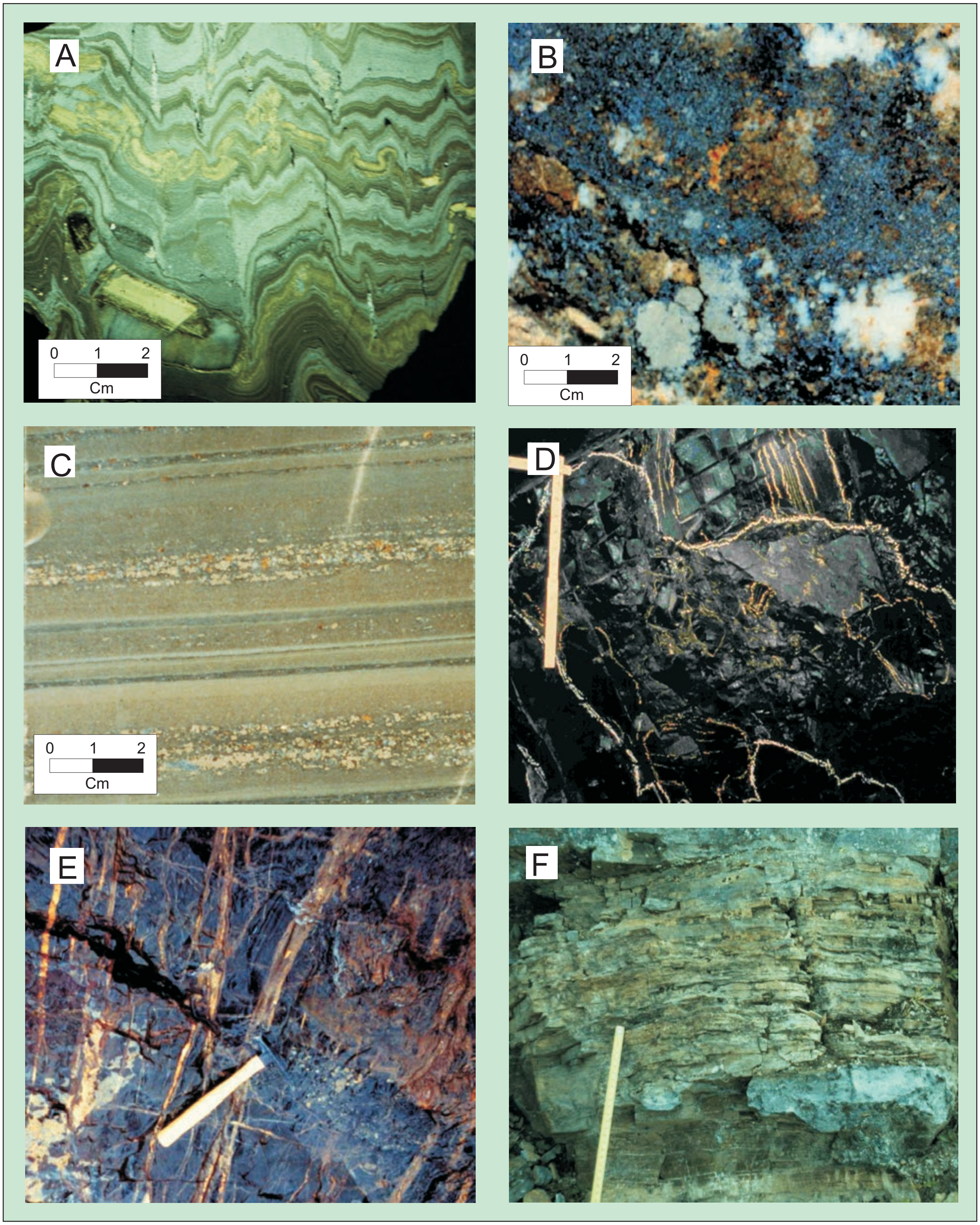

Figure. 9. Photographs of SEDEX and barite deposits. **(A)** Bedded facies: sphalerite and galena interlaminated with pyrite, hydrothermal carbonate, and carbonaceous chert, Howards Pass (XY) deposit, Yukon and Northwest Territories; **(B)** Vent complex: pyrite, sphalerite, galena, and ferroan carbonates replacing bedded sulphide facies, Tom Deposit, Selwyn Basin, Yukon; **(C)** Distal hydrothermal sediments: pyrrhotite and pyrite containing disseminated sphalerite interlaminated with fine-grained turbiditic sedimentary rocks, Concentrator Hill, Sullivan deposit, B.C.; **(D)** Vent complex: tourmalinized breccia infilled with pyrrhotite, sphalerite, and chalcopyrite, Sullivan Deposit, B.C.; **(E)** Sulphide stringer zone: black silicified shale cut by a network of brown sphalerite veins, Red Dog deposit, Alaska; **(F)** Well-bedded barren barite deposit, Gataga District, northeastern B.C.

Turner et al., 2000). Large et al. (2000) have described a widespread Zn, Pb, and Tl halo that extends laterally from the McArthur River deposit along the pyritic black shale facies of the Barney Creek Formation for at least 15 km to the west, and hundreds of metres above and below the mineralized zone.

Hydrothermal alteration of the hanging-wall sedimentary sequence has not been documented for most SEDEX deposits. Although post-ore hydrothermal sediments clearly show that hydrothermal fluids continued to vent well after SEDEX formation, the paucity of post-ore hydrothermal alteration described in the literature may indicate that it is too subtle in most cases to be readily recognized. Perhaps the best documented example of post-ore hydrothermal alteration is the albite-chlorite-pyrite alteration of turbiditic sedimentary rocks overlying the Sullivan deposit (Hamilton et al., 1982; Turner et al., 2000). The late albitization of the vent complex and feeder zone is clear evidence that post-ore hydrothermal fluids utilized the same conduits as the ore-forming fluids.

The nature and extent of the hydrothermal alteration and mineralization in the feeder zone depends to a large degree on the mineralogy and physical properties of footwall sediments, the temperature and chemical composition of the hydrothermal fluids, and hydrostatic pressure or water depth (Goodfellow et al., 1993). As a result, compared to VMS deposits, feeder pipes and associated alteration underlying SEDEX deposits are relatively inconspicuous due to low sulphide contents, less reactive siliciclastic sediments compared to glassy volcanic rocks, and limited seawater recharge through the low-permeability hemipelagic mud that hosts most deposits. Furthermore, subtle but diagnostic hydrothermal assemblages such as clay minerals are obscured by later metamorphism.

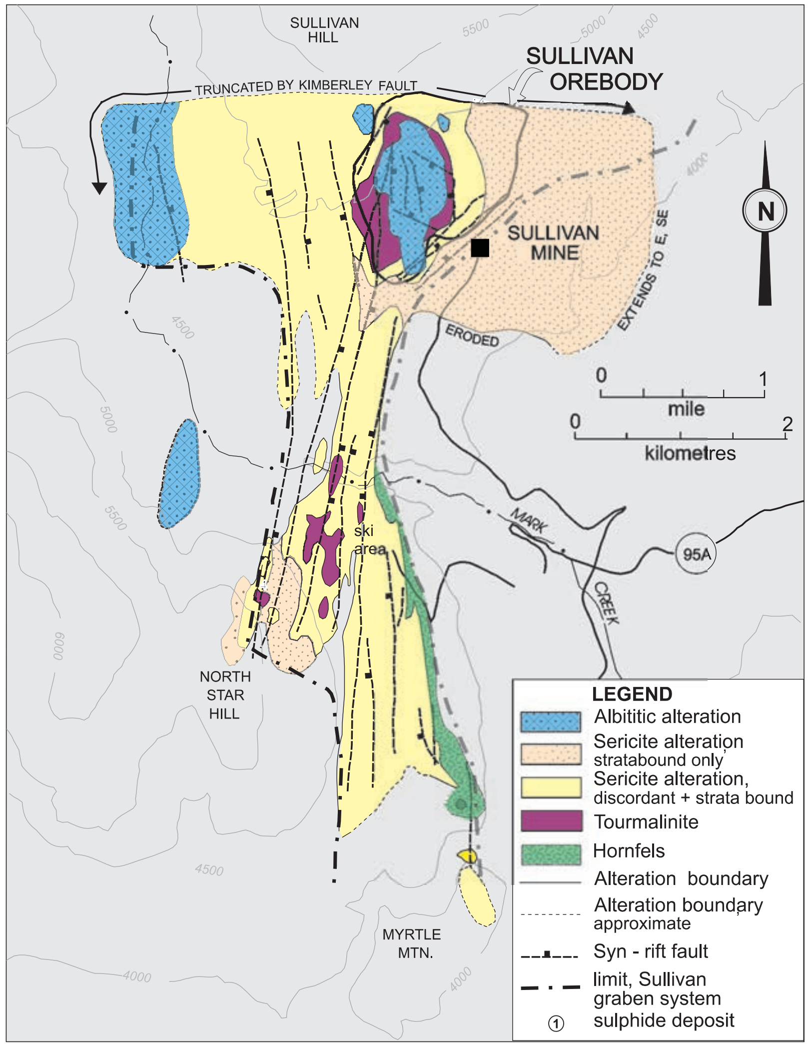

Figure 10. Map showing the distribution of major alteration facies within the Sullivan graben system (from Turner et al., 2000).

Distal and Post-ore Hydrothermal Sediments

Hydrothermal systems that form SEDEX deposits are typically long-lived and highly focused at discrete vent sites. Furthermore, hydrothermal activity commonly continues after sulphide formation, forming post-ore hydrothermal sediments and alteration that extend for hundreds of metres into the stratigraphic hanging-wall sequence. In most SEDEX deposits, the basal contact between the stratiform sulphides and underlying sedimentary rocks is sharp, whereas the top of the sulphide zone grades into an overlying sequence of host sedimentary pelagic and/or clastic sedimentary rocks.

Hydrothermal products that extend for hundreds of meters into the post-ore sequence and provide an important target for mineral exploration include:

1. Laminated and disseminated barite and pyrite (e.g., Tom, Jason, Rammelsberg, Meggen)
2. Manganese and iron carbonates (e.g., Meggen, Silvermines, McArthur River (HYC))
3. Phosphatic and pyritic chert (e.g., Howards Pass, Anniv)
4. Metal-rich laminated pyrite (e.g., HYC, Mt. Isa, Tom, Jason)
5. Albite-chlorite-pyrite alteration (e.g., Sullivan)

Most SEDEX deposits are also surrounded by hydrothermal sediments that extend for up to several km from the sulphide zone. In deposits containing barite (e.g., Tom and Meggen), these distal sediments typically consist of interlayered barite, chert, carbonate and host lithologies. In other deposits, this facies is represented by iron sulphides and/or chert interbedded with host lithologies (e.g., Sullivan, Hamilton et al., 1982). At Howards Pass in the Yukon, the distal fringe of the ore zone consists of a laminated phosphatic chert and pyritic shale (Goodfellow, 2004). A manganese-rich halo has been noted to surround several SEDEX deposits, including the Tom (Large, 1981a) and Meggen (Gwosdz and Krebs, 1977). Widespread lithogeochemical halos have also been documented at the Lady Loretta (Large and McGoldrick, 1998) and McArthur River (HYC; Large et al., 2000) deposits.

Geology—Continental and Global Scale

Tectonic Settings

SEDEX, Irish, and BHT deposits occur in intra-cratonic and epicratonic sedimentary basins (Large, 1980). The tectonic settings include intra-cratonic rifts driven by mantle plumes (e.g., Belt-Purcell basin; Anderson and Goodfellow, 2000), reactivated rifted margins (e.g., Howards Pass; Goodfellow et al., 1986), and far-field back-arc rifting (e.g., MacMillan Pass-Gataga (Fig. 11) and Mount Isa-McArthur districts; Nelson et al., 2002; Betts et al., 2003). Although there is considerable debate on BHT deposits, our interpretation is that the association of the Broken Hill deposit with coeval bimodal igneous rocks in a sedimentary basinal sequence suggests that this deposit type is similar to less-deformed and metamorphosed VSHMS (volcanic-sediment-hosted massive sulphide) deposits in sedimented back-arc continental rifts (e.g., Bathurst Mining Camp, Finlayson Lake, Iberian Pyrite Belt).

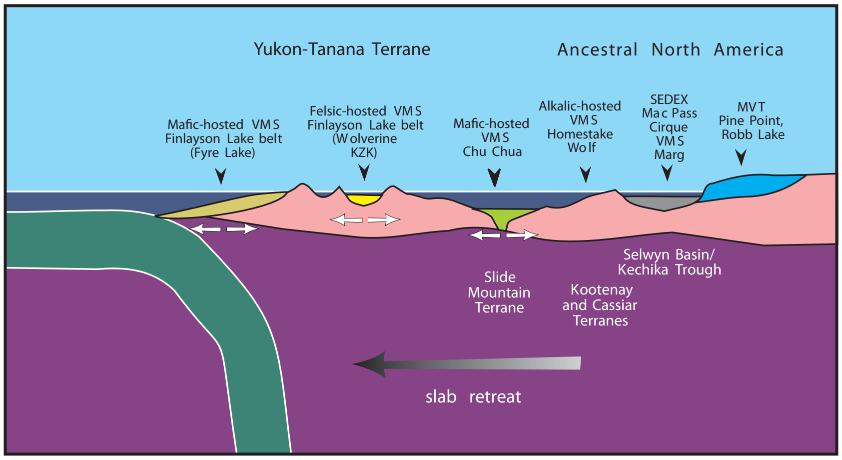

Figure 11. Tectonic model for the Devono-Mississipian margin of western North America, showing a complex history of ocean plate subduction and slab rollback, back-arc rifting and the formation of SEDEX and MVT deposits in the northern Canadian Cordillera (from Nelson et al., 2002).

Most SEDEX deposits formed during periods of tectonism which is typically manifested by fault reactivation, intrabasin clastic sedimentation, and in many cases magmatism represented by volcanism and/or sill emplacement. Most deposits occur in reduced marine basins that formed during the sag phase of basin history, adjacent to deeply penetrating faults.

Secular Variations and the Sulphur Cycle

SEDEX, Irish, and BHT deposits formed during several discrete episodes from Paleoproterozoic (about 2000 Ma) to Cretaceous (Fig. 12). The number and size of SEDEX per 50 million years are greatest in the Middle Paleoproterozoic and Paleoproterozoic, respectively. Lead and Ag grades are highest in the Early Mesoproterozoic, due to the influence of the giant Sullivan deposit, and Au grades reach a maximum in Paleoproterozoic and Early Mesoproterozoic deposits although the database of Au grades is very limited (see Table 1 and Appendix 1, DVD).

Most SEDEX deposits coincide with periods in Earth history when the oceans were episodically stratified with a lower anoxic and H_2S-rich water column (Fig. 13A). In the Paleozoic Selwyn Basin, for example, there is a close relationship between upward increasing $\delta^{34}S$ secular trends in sedimentary pyrite, anoxic laminated carbonaceous shales and cherts, and three major SEDEX forming events in the Late Cambrian, Early Silurian, and Late Devonian (Fig. 13B). In the Selwyn Basin, episodes of ocean stratification with reduced bottom waters coincide with global cycles of black shale deposition during the Paleozoic (Arthur and Sageman, 1994), indicating that the Selwyn Basin anoxic episodes reflect global processes. The secular variation of pyrite $\delta^{34}S$ values has been attributed to Rayleigh fractionation of S isotopes under closed or partly closed anoxic conditions, and accompanying increased rates of isotopically light S deposition as sedimentary sulphides causing an increase in $\delta^{34}S$ values for H_2S in the reduced water column (Goodfellow, 1987).

The transition from a ferrous Fe-dominated Archean ocean to a reduced S-dominated stratified Proterozoic and Phanerozoic oceans followed the oxidation and precipitation of Fe in Superior-type iron formations (Fig. 13A). This major change in ocean chemistry was accompanied by the build-up of sulphate, which was essential for bacterial sulphate reduction, and the establishment of H_2S-rich anoxic water columns. The absence of Archean and Early Paleoproterozoic SEDEX deposits is probably controlled, therefore, by the limiting effect of high contents of reduced Fe on the activity of H_2S in anoxic oceans. Under these conditions, metals in S-depleted saline hydrothermal fluids vented into seawater would be expected to be lost to the water column because of a lack of reduced S to precipitate them (Goodfellow et al., 1993).

Basin Architecture

The ideal basinal architecture for the formation of SEDEX deposits (Fig. 14) is a continental rift basin with at least 2 to 5 km of coarse-grained permeable clastics and related volcanics and/or volcaniclastics that form the syn-rift phase overlain by an impermeable cap or seal of basinal shales and/or carbonates (Lydon, 1983; Large, 1986). The source for Zn and Pb is syn-rift dominantly clastic sedimentary rocks (Lydon et al., 2000b). The ideal traps for the metals are reduced subbasins with an adequate supply of bacteriogenic H_2S in the ambient water column (Fig. 14). Although an association with magmatism is not indicated for all SEDEX deposits, mafic volcanic rocks and sills are spatially and temporally associated with many deposits (e.g., Selwyn Basin and Belt-Purcell basin) and bimodal volcanic rocks host most BHT deposits (e.g., Broken Hill; Parr and Plimer, 1993)

Two of the best understood continental basins hosting

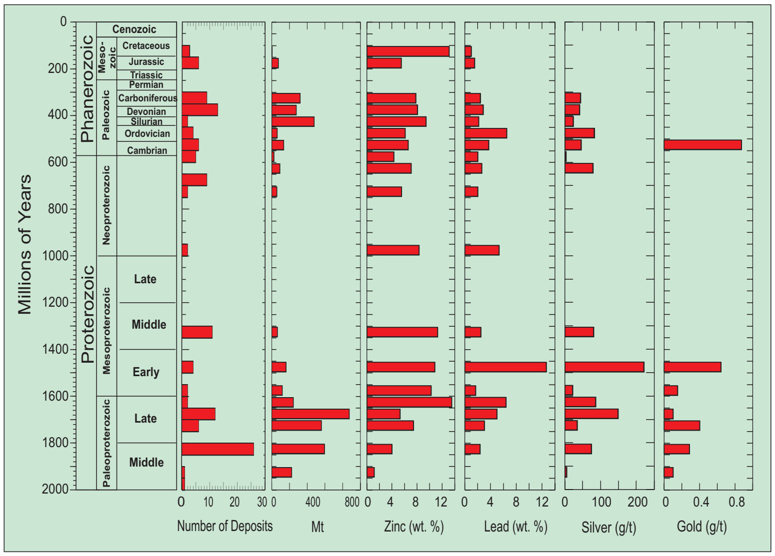

Figure 12. Secular variations of tonnage and metal grades for SEDEX deposits world wide. Plotted from data in Appendix 2 (DVD).

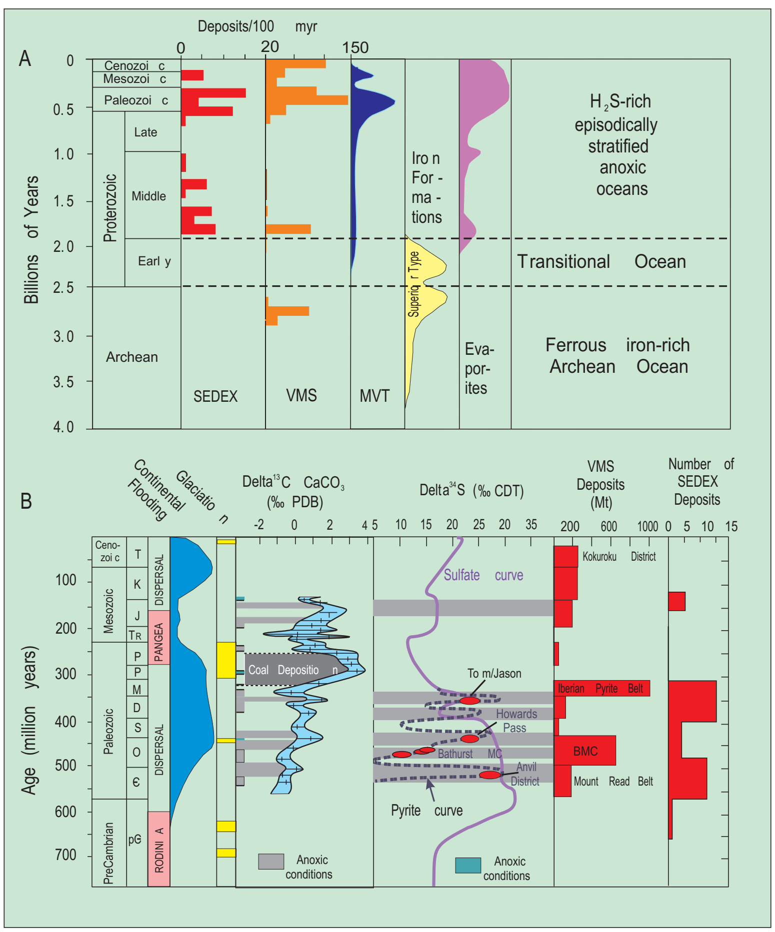

Figure 13. **(A)** Secular distribution of SEDEX, VMS, and MVT deposits, iron formation, evaporites, and H_2S-rich anoxic periods (Goodfellow, 2004). **(B)** Late Proterozoic and Phanerozoic tectonic (continent accretion and dispersion; Fischer, 1984) and glacial (Baker, 1997) events, continental flooding (Vail et al., 1977), and sulfur isotope secular curves for evaporites (Claypool et al., 1980), carbonates (Arthur and Sageman, 1994), and pyrite (Goodfellow, 1987). Also shown are global (Arthur and Sageman, 1994) and Selwyn Basin (Goodfellow, 1987) anoxic periods, and the temporal distribution of volcanic-associated massive sulphide (Mosier et al., 1983) and SEDEX (Goodfellow et al., 1993) deposits. BMC = Bathurst Mining Camp.

SEDEX deposits in Canada are the Paleozoic Selwyn Basin that extends from Alaska border through Canada into the U.S. south of the British Columbia (Fig. 15 from Goodfellow et al., 1995), and the Middle Proterozoic Belt-Purcell basin that extends from southeastern British Columbia to Montana and Idaho in the U.S. The Bathurst Mining Camp in northern New Brunswick (Goodfellow and McCutcheon, 2003) and the Finlayson district in the Yukon are two possible examples of BHT deposits (Piercey et al., 2001; Peter et al., 2007).

District Scale (Canada)

At the district scale, SEDEX deposits commonly occur in clusters and formed during several hydrothermal events within local second-order basins adjacent to extensional structures (e.g., Fig. 16, Sullivan deposit) separating basinal facies fine-grained sediments from platformal carbonates sequences. Some deposits are spatially and temporally associated with volcanic and intrusive rocks. Most deposits are hosted by marine basinal sedimentary rocks that include black shales and cherts, carbonates, and intrabasinal clastic sedimentary rocks.

Deposit Scale

SEDEX, Irish, and BHT deposits typically occur in local third-order sedimentary basins. Vent-proximal deposits are associated with active faults that commonly define the margins of local basins (Fig. 8A), whereas vent-distal deposits occupy bathymetric depressions on the seafloor (Fig. 8B). The most recognized control on the siting of vents and associated ores is cross-stratal faults that served as conduits for transporting metalliferous fluids from the hydrothermal reaction zone to the seafloor. Other factors that influenced the location of vents are: 1. basement highs where the thickness of soft sediment is at a minimum, 2. the hydrology of the reaction zone which is partly controlled by the thermal structure, 3. the basement geometry, and 4. the position of recharge zones. In the case of vent-distal deposits, the predominant control other than proximity to vents on the location of deposits is fluid density and local seafloor bathymetry.

Distribution of Canadian Metallogenetic Districts

Major metallogenetic districts that host SEDEX deposits (Fig. 3) are:

- Mississippian Walton District, Carboniferous basin, Nova Scotia
- Late Devonian MacMillan Pass District, Selwyn Basin, northeastern Yukon
- Late Devonian Gataga District, Kechika Trough, northeastern British Columbia

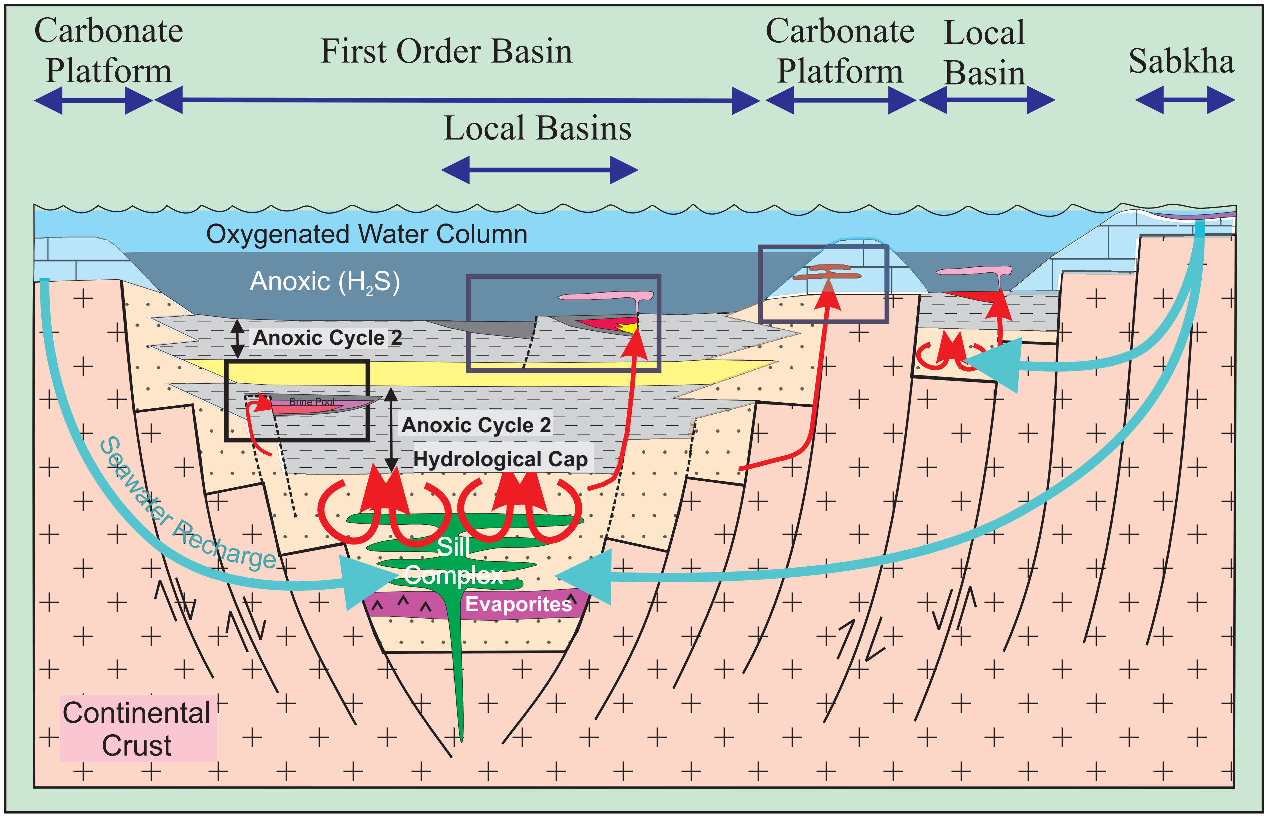

Figure 14. Model of the sedimentary basin architecture of productive basins hosting SEDEX deposits.

- Early Silurian Howards Pass District, Selwyn Basin, northeastern Yukon
- Late Cambrian Anvil District, Selwyn Basin, Yukon
- Late Cambrian Duncan District, southern British Columbia
- Neoproterozoic Shuswap District, southern British Columbia
- Mesoproterozoic Sullivan District, Belt-Purcell basin, southeastern British Columbia
- Mesoproterozoic Maniwaki-Gracefield District, Grenville Province, Quebec

The Selwyn Basin occupies the Paleozoic margin of western North America and has been subdivided into five spatially distinct mining districts representing three ages of mineralization: 1. Late Cambrian Anvil, 2. Late Cambrian Duncan, 3. Early Silurian Howards Pass, 4. Late Devonian MacMillan Pass, and 5. Late Devonian Gataga districts. The Middle Proterozoic Belt-Purcell is an intracratonic basin (Price and Sears, 2000) that hosts the Sullivan district (Höy et al., 2000). Other SEDEX districts include the highly metamorphosed Neoproterozoic Shuswap district in southern British Columbia, and the Mesoproterozoic Maniwaki-Gracefield district in the Grenville Province of Quebec. In the Appalachian orogen, the Carboniferous Walton district of Nova Scotia hosts the past-producing Walton deposit.

Genetic and Exploration Models

Conventional Models

SEDEX deposits most likely formed from oxidized and therefore H_2S-poor fluids generated in geopressured hydrothermal reservoirs within syn-rift clastic (and evaporitic) sediments sealed by fine-grained marine sediment or carbonates (Goodfellow et al., 1993; Cooke et al., 2000). During the post-rift or sag phase of basin formation, which is typically long-lived and spans over 200 million years in the case of the Selwyn Basin, Zn and Pb were probably leached from iron oxides coating detrital minerals and homogenized by convecting fluids in the hydrothermal reservoir. The large variability in the temperature, salinity, metal content, and redox conditions of SEDEX fluids was controlled by a number of parameters including the local thermal regime, the redox state of the reservoir sediments, and the presence or absence of evaporates. Ancient SEDEX fluids are similar to metalliferous fluids in modern sedimentary basins, which are characterized by temperatures up to 305°C (e.g., Salton Sea brines; McKibben et al., 1988), high salinities, and very low total S(reduced):total metal ratios.

A mineralizing episode is triggered by tectonic events that re-activate major rift faults that generate rapidly subsiding grabens or half-grabens. The reactivated rift faults can breach the sediment cap, causing the discharge of metal-rich saline fluids (enriched in Fe, Zn, Pb as chloride complexes, and variable SO_4^{2-}) along the faults to the basin floor. For most SEDEX deposits, metal sulphides are precipitated at or

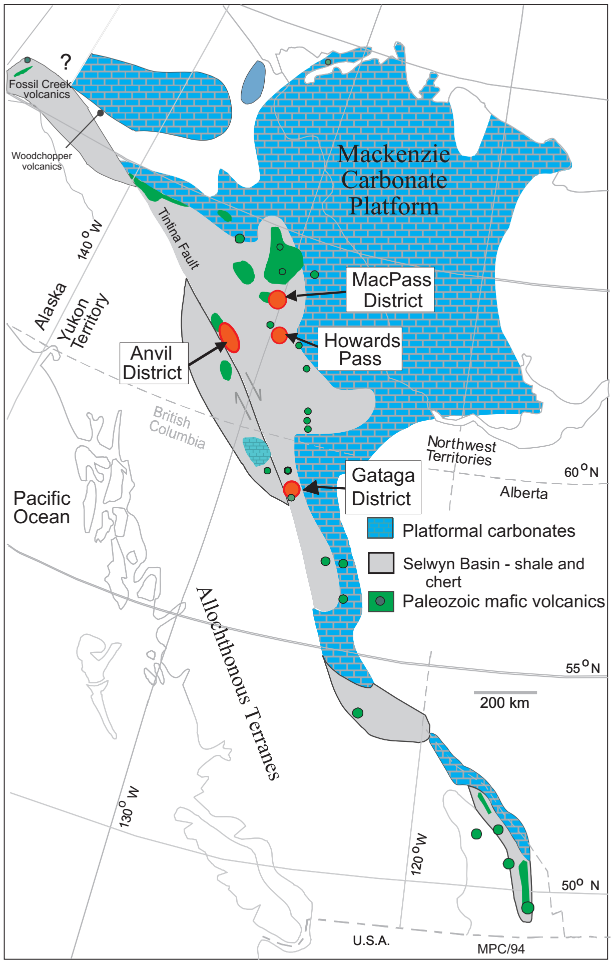

FIGURE 15. Paleofacies distribution and SEDEX deposits of the Selwyn Basin, Yukon and British Columbia (modified from Goodfellow et al., 1995; Cecile et al., 1997).

above the seafloor by reaction with H_2S in the overlying reduced water column (Goodfellow, 1987). Continued fluid discharge from the reservoir is driven by free convection, as cold seawater descends into the basin sedimentary sequence along recharge faults (Yang et al., 2004), where it is heated and leaches Zn and Pb from the reservoir sediments.

Because most fluids that formed SEDEX deposits were probably depleted in reduced S, an important requirement for this deposit-type to form is a sufficient supply of reduced S at the site of deposition (Goodfellow, 1987; Cooke et al., 1998). In the case of well-bedded deposits that formed at the seafloor, the most likely S source is biogenic H_2S that is typically enriched in anoxic water columns (Goodfellow, 2000). The presence or absence of barite is controlled by two major factors: 1. the activity of sulphate in the ore-forming fluids, which limits barium solubility, and 2. the activity of sulphate in the water column, which controls the precipitation of barite. In extreme anoxic basins where all the sulphate has been reduced to sulphide, barium carried by hydrothermal fluids will be lost to the water column because of a lack of sulphate to precipitate barite.

Recent Advances in Genetic/Exploration Models

Major advances in the genetic and exploration models are listed and discussed briefly below:

- The tectonic settings for sedimentary basins that host SEDEX deposits, particularly far-field back-arc extensional environments and intracratonic rifts driven by mantle plumes are better understood.
- The architecture of productive sedimentary basins, particularly as it relates to syn-rift clastic sedimentation, the development of hydrothermal reservoirs, and the onset of subsequent sagging related to conductive cooling of the lithosphere has been documented in detail for several basins.
- The temporal distribution of SEDEX deposits (post-1.8 billion years) is probably controlled by the oxidation of Archean oceans, the buildup of sulphate and associated bacterial sulphate reduction, the development of Proterozoic and Phanerozoic oceans episodically stratified with lower anoxic water columns, and the precipitation of sulphides by the mixing of S-poor metalliferous fluids with ambient H_2S-rich anoxic oceans.
- Detailed documentation of different aspects of SEDEX deposits:
    - Geology and sedimentology of local third-order basins hosting deposits.

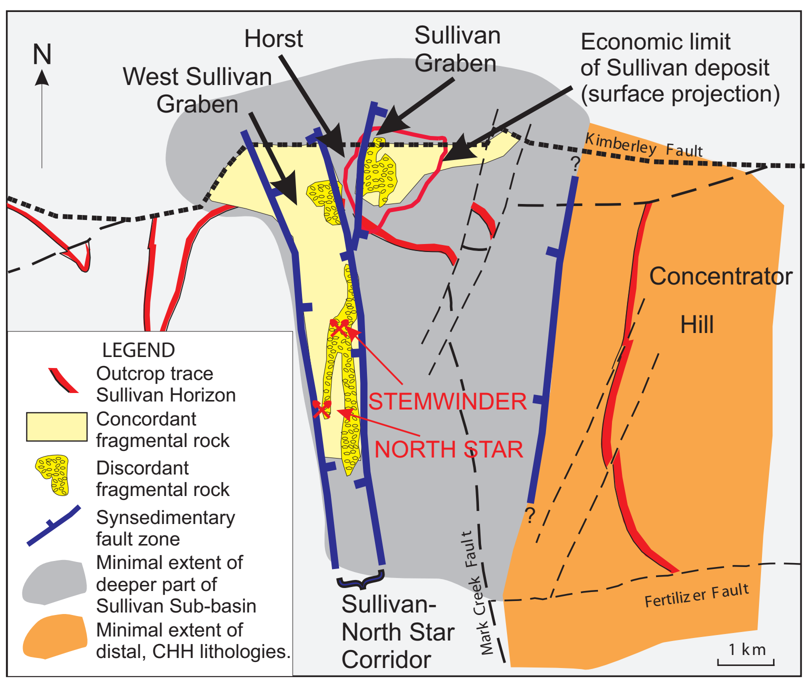

FIGURE 16. Surface map of the Sullivan deposits showing the Sullivan and West Sullivan grabens or third-order basins, and basin bounding faults (from Lydon et al., 2000a).

- Morphology and architecture of mineralized zones.
- Mineralogy and chemical composition of hydrothermal sediments and the development of exploration vectors.
- Mapping of hydrothermal alteration surrounding SEDEX deposits.

- New thermal chemical models which indicate that SEDEX deposits formed from high f_{O2} and therefore H_2S-depleted basinal metalliferous fluids (Cooke et al., 2000).
- The recognition that SEDEX deposits in the Selwyn Basin are genetically related to coeval MVT deposits on the adjacent Mackenzie Carbonate Platform (Goodfellow, 1987).

Key Exploration Criteria for Canadian SEDEX Deposits

Continental Scale

At the continental or basin-wide scale, criteria indicating a high potential for SEDEX and BHT Zn-Pb deposits include:

- Age: post-1800 Ma because of the S cycle.
- Tectonic setting: sedimented intra-cratonic and epicontinental rifts.
- Sedimentary basin architecture: syn-rift clastic sequence overlain by post-rift impervious marine basinal sediments; the recharge of saline brines on adjacent carbonate platforms may be an important source of chloride to complex metals in basinal hydrothermal fluids.
- Anoxic episodes: interglacial, warm oceanic conditions represented by global episodes of anoxic sedimentation (e.g., carbonaceous non-bioturbated shales, laminated pyrite, the absence of benthic fauna) and evaporate formation.
- Magmatic events: syn- and/or post-rift mafic alkali volcanic rocks, and tholeiitic sills and dykes.
- Coeval MVT deposits in adjacent carbonate platforms.
- Geochemical stream anomalies: sediment and water samples that are anomalous in ore-forming and ore-associated elements over a large area of the basin. An example is widespread Zn anomalies that extend for hundreds of kilometres in the Selwyn Basin (e.g., Fig. 17, Selwyn Basin).

District and Deposit Scale

At the district scale, the criteria for evaluating the potential to host SEDEX and BHT Zn-Pb deposits are:

- Second- and third-order basins within sedimented continental rifts.
- Local tectonism: reactivation of extensional faults as evidenced by sedimentary facies and thickness changes, fault scarp breccias, local unconformities, major fault offsets and fault intersections.
- Magmatic centres (e.g., volcanic and sill complexes).
- Reduced seafloor environments: anoxic cycles in the evolution of a given basin.
- Paleoclimate: evaporites in the hydrothermal reaction zone and/or saline recharge fluids on the adjacent platforms that provide a source of chloride to complex base metals.
- Distal hydrothermal sediments: e.g., barite, apatite, pyrite, and Mn-Fe-Ca-Mg carbonates.
- Hydrothermal alteration: pre- and post-ore quartz, muscovite, chlorite, ankerite, siderite, and tourmaline alteration with associated disseminated and vein sulphides of ore-forming and ore-associated elements.
- Geochemically anomalous shales: enriched in base metals and ore-associated elements (e.g., As, Sb, Cd, Mn, P, Ba, Hg, Tl).

Surficial geochemical anomalies: sediment and water samples that are locally anomalous in deposit-forming and ore-associated elements.

Knowledge Gaps

Key knowledge gaps are summarized below.

1. Radiometric and paleontological ages of ore-forming events is required to relate the causes of ore formation to other geological events such as tectonism, magmatism, and ocean stratification. This can be carried out by direct dating of the various ore components (e.g., Nd/Sm in carbonate, sulphides; Rb/Sr in carbonates; U/Pb in xenotime); detailed micropaleontology of Phanerozoic rocks; or by bracketing the age of the ore horizon by U/Pb dating of intercalated volcanic ash horizons.
2. Development of exploration criteria for discovering SEDEX in sedimentary basins. This would involve comparative studies of the geological and hydrothermal evolution of productive and non-productive basins. Essential information would include:
    - History of tectonic and magmatic events within basins.

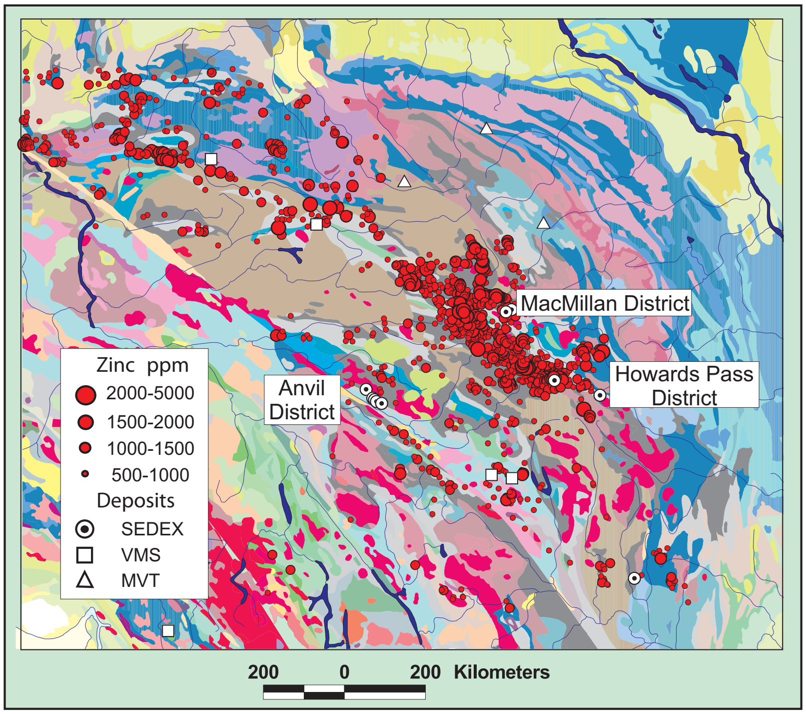

FIGURE 17. Proportional circle map for stream sediments that are highly anomalous (>1,000 ppm) in Zn, Selwyn Basin, Yukon.

- Sediment accumulation rates (needs radiometric dating control).

- Evolutionary pathways of mineralogical and lithogeochemical changes during diagenesis and burial metamorphism. This requires transects of the basin supported by careful stratigraphy, sedimentology, lithogeochemistry and radiometric dating of diagenetic and burial metamorphic minerals.

- Evolutionary paths of pore fluids in the basin (would have to rely on studies of fluid inclusions in cements and diagenetic minerals), with emphasis on determining the stage or circumstances under which pore fluids become metalliferous.

- Paleoclimatology and the history of ocean stratification. This would require geochemical and isotopic (e.g., S, C, Sr) profiles of basinal stratigraphy and the systematic documentation of lithological and sedimentological indicators.

3. Development of prognostic criteria for stratigraphic interval(s) with a high mineral potential and the most favorable spatial position(s) for SEDEX deposits in a sedimentary basin. This requires a fundamental understanding of all the key processes controlling focused expulsion of metalliferous hydrothermal fluids in a sedimentary basin. This could be accomplished by compilation of key data (especially data generated by the oil industry), mathematical modeling of fluid flow using constrained rock property parameters, and targeted research on key basins where the critical components are well preserved.

4. Refine models of SEDEX formation. There is still much debate as to the ore-forming environment required for the deposition and preservation of sedimentary Zn-Pb deposits. It is still not decided whether SEDEX deposits require a brine pool, whether they can form as a sulphide mound, or whether they are predominantly subsurface replacements of fine-grained sediments. These and other unresolved questions on the genesis of SEDEX deposits require further studies of more pristine examples of SEDEX deposits such as those of the Tethyan Belt and Cuba.

5. Determine the impact of ocean evolution on the temporal distribution of SEDEX deposits. The empirical observation that there are no SEDEX deposits older than about 1.8 billion years and the proposed ocean chemical evolution model as it relates to reduced biogenic S supply needs to be tested in sedimentary basins that span the geological time scale. This question is of particular interest to Canada because of the large number of Early Proterozoic sedimentary basins especially in Northern Canada (e.g., Labrador Trough, Labrador; Foxe-Rinkian Basin, western Nunavut; Wopmay Orogen, northern NWT; Athapuscow Aulacogen, NWT; Kilohigok Basin, Bathurst Inlet-Victoria Island, NWT).

Areas of High Mineral Potential in Canada

Using the criteria outlined above for identifying productive basins, major sedimentary basins in Canada are rated for their potential to host SEDEX, Irish-type and BHT sulphide deposits. It should be noted that the confidence level varies with the quality and comprehensiveness of geoscientific data, and the level of exploration by the mining industry.

Basins Hosting SEDEX Deposits

The following basins host SEDEX and VSHMS deposits and are therefore highly prospective for additional new deposits within existing districts and new districts.

- Selwyn Basin, Yukon, Northwest Territories, and British Columbia (Cambrian to Mississippian). Although most deposits are located in the Yukon and British Columbia, the potential for SEDEX deposits is considered high in Selwyn Basin facies that extends the full length of the Canadian Cordillera.

- The Mesoproterozoic Belt-Purcell basin, southeastern British Columbia and northwestern U.S. This continental rift hosts several SEDEX deposits including the world-class Sullivan deposit.

- Finlayson Lake district, Yukon (Middle-Late Devonian).

This sedimented back-arc continental rift is host to several major deposits.

- Bathurst Mining Camp, northern New Brunswick (Middle Ordovician). This back-arc sediment-covered continental rift hosts over 20 deposits greater than 1 Mt, and several past and current producers including the world-class Brunswick No. 12 deposit.

Highly Prospective Sedimentary Basins

The following basins do not contain SEDEX deposits but exhibit all or most of the key attributes of productive basins.

- Borden Basin, Nunavut (Middle Proterozoic)
- Franklinian Basin, northern Nunavut (Paleozoic)
- Wernecke Supergroup, central Yukon (Mesoproterozoic)

Moderately Prospective Sedimentary Basins

The following basins do not contain SEDEX deposits and exhibit most of the key attributes of productive basins but are deficient in at least one fundamental attribute. The Richardson Trough in not underlain by a syn-rift clastic sequence and therefore does not exhibit the classic architecture of productive sedimentary basins. All the remaining sedimentary basins listed below are older than the oldest SEDEX deposits and may be deficient in bacteriogenic S that is considered essential for precipitating base metals vented by H_2S-poor hydrothermal fluids into ambient seawater.

- Richardson Trough, northern Yukon and NWT (Paleozoic)
- Labrador Trough, Labrador (Paleoproterozoic)
- Foxe-Rinkian Basin, western Nunavut (Paleoproterozoic)
- Wopmay Orogen, northern Nunavut (Paleoproterozoic)

Acknowledgements

This synthesis is based largely on previous reviews of SEDEX deposits and research emanating from Geological Survey of Canada research projects on SEDEX deposits of the Selwyn Basin, Yukon, and Sullivan mining district, southern British Columbia. It is intended to have a global perspective but a national focus on SEDEX deposits and sedimentary basins considered to have SEDEX potential. We thank C. Allen and S. Paradis for reviewing the manuscript and offering many excellent suggestions, and I. Kjarsgaard for checking and editing an earlier version of the manuscript and accompanying Canadian and global SEDEX databases. P. Smith of Brook Hunt is thanked for making recent data on global Zn and Pb production, reserves and resources available for plotting in Figure 1.

References

Anderson, H.E., and Goodfellow, W.D., 2000, Geochemistry and isotope chemistry of the Moyie sills: Implications for the early tectonic setting of the Mesoproterozoic Purcell basin, in Lydon, J.W., Höy, T., Knapp, M., and Slack, J., eds., The geological environment of the Sullivan deposit, British Columbia: Geological Association of Canada, Mineral Deposits Division, Special Publication 1, p. 302–321.

Arthur, M., and Sageman, B.B., 1994, Marine shales: Depositional mechanisms and environments of ancient deposits: Annual Review of Earth and Planetary Sciences, v. 22, p. 499–551.

Baker, V.R., 1997, Megafloods and glaciation, in Martini, I.P., ed., Late glacial and postglacial environmental changes; Quaternary, Carboniferous-Permian, and Proterozoic: New York, Oxford University Press, p. 98–108.

Beeson, R., 1991, Broken Hill-type lead-zinc deposits—An overview of their occurrence and geological setting: Institution of Mining and Metallurgy, Transactions, Section B: Applied Earth Science, v. 99, p. 163–175.

Betts, P.G., Giles, D., and Lister, G.S., 2003, Tectonic environment of shale-hosted massive sulfide Pb-Zn-Ag deposits of Proterozoic northeastern Australia: Economic Geology, v. 98, p. 557–576.

Bull, S.W., and Rawlings, D.J., 1999, A tectono-stratigraphic review of the northern Australian Proterozoic zinc belt: Centre for Ore Deposit and Exploration Studies (CODES), Special Publication, v. 2, p. 1–13.

Cecile, M.P., Morrow, D.W., and Williams, G.K., 1997, Early Paleozoic (Cambrian to Early Devonian) tectonic framework, Canadian Cordillera: Bulletin of Canadian Petroleum Geology, v. 45, p. 54–74.

Claypool, G.E., Holser, W.T., Kaplan, I.R., Sakai, H., and Zak, I., 1980, The age curves of sulfur and oxygen isotopes in marine sulfate and their mutual interpretation: Chemical Geology, v. 28, p. 3–4.

Conly, A.G., Goodfellow, W.D., Taylor, R.P., and Lydon, J.W., 2000, Geology, geochemistry, and sulphur isotope geochemistry of the hanging wall sulphide zones and their related hydrothermal alteration, Sullivan Zn-Pb-Ag deposit, in Lydon, J.W., Höy, T., Knapp, M., and Slack, J., eds., The geological environment of the Sullivan deposit, British Columbia: Geological Association of Canada, Mineral Deposits Division, Special Publication 1, p. 541–573.

Cooke, D.R., Bull, S.W., Large, R.R., and McGoldrick, P.J., 1998, Oxidised (sulfate-bearing) brines; their importance for the formation of Australian Proterozoic Pb-Zn (SEDEX) deposits [abs.]: Geoscience for the new Millennium, 14th Australian Geological Convention, Townsville, Queensland, Geological Society of Australia, Abstracts, p. 91.

Cooke, D.R., Bull, S.W., Large, R.R., and McGoldrick, P.J., 2000, The importance of oxidized brines for the formation of Australian Proterozoic stratiform sediment-hosted Pb-Zn (SEDEX) deposits: Economic Geology, v. 95, p. 1–18.

Emsbo, P., 2000, Gold in SEDEX deposits: Reviews in Economic Geology, v. 13, p. 427–437.

Fischer, A.G., 1984, Biological innovations and the sedimentary record, in Holland, H.D., and Trendall, A.F., eds., Patterns of change in Earth evolution: Berlin, Springer-Verlag, p. 145–157.

Goodfellow, W.D., 1984, Geochemistry of rocks hosting the Howards Pass (XY) strata-bound Zn-Pb deposit, Selwyn Basin, Yukon Territory, Canada: Proceeding of the Sixth Quadrennial IAGOD Symposium: Stuttgart, Germany, E. Schweizerbart'sche Verlagsbuchhandlung (Nägele u. Obermiller), p. 91–112.

—— 1987, Anoxic stratified oceans as a source of sulphur in sediment-hosted stratiform Zn-Pb deposits (Selwyn Basin, Yukon, Canada): Chemical Geology, v. 65, p. 359–382.

—— 2000, Anoxic conditions in the Aldridge Basin during formation of the Sullivan Zn-Pb deposit: Implications for the genesis of massive sulphides and distal hydrothermal sediments, in Lydon, J.W., Höy, T., Knapp, and M., Slack, J., eds., The geological environment of the Sullivan deposit, British Columbia: Geological Association of Canada, Mineral Deposits Division, Special Publication 1, p. 218–250.

—— 2004, Geology, genesis, and exploration of SEDEX deposits, with emphasis on the Selwyn Basin, Canada, in Deb, M., and Goodfellow, W.D., eds., Sediment-hosted lead-zinc sulphide deposits: Attributes and models of some major deposits of India, Australia, and Canada: Delhi, India, Narosa Publishing House, p. 24–99.

—— 2007, Base metal metallogeny of the Selwyn Basin, Canada, *in* Goodfellow, W.D., ed., Mineral deposits of Canada: A synthesis of major deposit types, district metallogeny, the evolution of geological provinces, and exploration methods: Geological Association of Canada, Mineral Deposits Division, Special Publication 5, p. 553–579.

Goodfellow, W.D., and McCutcheon, S.R., 2003, Geological and genetic attributes of volcanic-associated massive sulfide deposits of the Bathurst Mining Camp, northern New Brunswick—A synthesis: Economic Geology Monograph 11, p. 245–301.

Goodfellow, W.D., and Rhodes, D., 1990, Geological setting, geochemistry and origin of the Tom stratiform Zn-Pb-Ag-barite deposits, in Abbott, J.G., and Turner, R.J.W., eds., Mineral deposits of the northern Canadian Cordillera: Ottawa, International Association on the Genesis of Ore Deposits, Eighth Symposium, Field Trip 14 Guidebook, p. 177–244.

Goodfellow, W.D., Jonasson, I.R., and Morin, J.A., 1986, Environment of formation of the Howards Pass (XY) Zn-Pb deposit, Selwyn Basin, Yukon: Canadian Institute of Mining and Metallurgy, Special Volume, v. 37, p. 19–50.

Goodfellow, W.D., Lydon, J.W., and Turner, R.W., 1993, Geology and genesis of stratiform sediment-hosted (SEDEX) Zn-Pb-Ag sulphide deposits: Geological Association of Canada, Special Paper 40, p. 201–251.

Goodfellow, W.D., Cecile, M.P., and Leybourne, M.I., 1995, Geochemistry, petrogenesis and tectonic setting of lower Paleozoic alkalic and potassic volcanic rocks, northern Canadian Cordilleran Miogeocline: Canadian Journal of Earth Sciences, v. 32, p. 1236–1254.

Gwosdz, W., and Krebs, W., 1977, Manganese halo surrounding Meggen ore deposit, Germany: Institution of Mining and Metallurgy, Transactions, Section B: Applied Earth Science, v. 86, p. 73–77.

Hamilton, J.M., Bishop, D.T., Morris, H.C., and Owens, O.E., 1982, Geology of the Sullivan orebody, Kimberley, B.C., Canada: Geological Association of Canada, Special Paper 25, p. 597–665.

Hannak, W.W., 1981, Genesis of the Rammelsberg ore deposit near Goslar/Upper Hartz, Federal Republic of Germany, in Wolfe, K.H., ed., Handbook of strata-bound and stratiform ore deposits, 9: Amsterdam, Elsevier, p. 551–642.

Hauser, R.L., and Hutchinson, R.W., 1983, Tin in the Sullivan deposit, Kimberley, B.C.: Geological Association of Canada; Mineralogical Association of Canada, Canadian Geophysical Union; Joint Annual Meeting, Program with Abstracts, v. 8, p. A31.

Hitzman, M.W., and Beaty, D.W., 1997, The Irish Zn-Pb-(Ba) orefield: Society of Economic Geologists, Special Publication 4, p. 112–143.

Höy, T., Anderson, D., Turner, R.J.W., and Leitch, C.H.B., 2000, Tectonic, magmatic and metallogenic evolution of the early synrift phase of the Purcell basin, southeastern British Columbia, in Lydon, J.W., Höy, T., Knapp, M., and Slack, J., eds., The geological environment of the Sullivan deposit, British Columbia: Geological Association of Canada, Mineral Deposits Division, Special Publication 1, p. 32–60.

Hunt, B., 2006, Lead and zinc costs: Mines and projects, 2006 Edition: Surrey, England, Brook Hunt and Associates Ltd.

Jefferson, C.W., Kilby, D.B., Pigage, L.C., and Roberts, W.J., 1983, The Cirque barite-zinc-lead deposits, northeastern British Columbia, in Sangster, D.F., ed., Short course in sediment-hosted stratiform lead-zinc deposits: Mineralogical Association of Canada, Short Course Handbook, v. 8, p. 121–139.

Jenkins, C.L., and Lydon, J.W., 2002, A mineral deposit data base structure and a data base of VMS and SEDEX deposits: Geological Survey of Canada, Open File 4165, (CD-ROM).

Jennings, D.S., and Jilson, G.A., 1986, Geology and sulphide deposits of the Anvil Range, Yukon: Canadian Institute Mining and Metallurgy, Special Volume 37, p. 339–361.

Kelley, K.D., and Jennings, S., 2004, Barite and Zn-Pb-Ag deposits in the Red Dog District, western Brooks Range, Northern Alaska; preface: Economic Geology, v. 99, p. 1267–1280.

Kelley, K.D., Dumoulin, J.A., and Jennings, S., 2004, The Anarraaq Zn-Pb-Ag and barite deposit, Northern Alaska; Evidence for replacement of carbonate by barite and sulfides: Economic Geology, v. 99, p. 1577–1591.

Kirkham, R.V., and Rafer, A.B., 2003, Selected world mineral deposits database. Geological Survey of Canada, Open File 1801 (CD-ROM).

Large, D.E., 1980, Geological parameters associated with sediment-hosted, submarine exhalative Pb-Zn deposits: An empirical model for mineral exploration: Geologisches Jahrbuch, v. D40, p. 59–129.

—— 1981a, Geochemistry of sedimentary rocks in the vicinity of the Tom Pb-Zn-Ag deposit, Yukon Territory, Canada: 8th International Geochemical Exploration Symposium, Hanover, April 10-15, 1980, Transactions, p. 203–217.

—— 1981b, Sediment-hosted submarine exhalative lead-zinc deposits—A review of their geological characteristics and genesis, in Wolf, K.H., ed., Handbook of strata-bound and stratiform ore deposits, 9: New York, Elsevier, p. 469–507.

—— 1983, Sediment-hosted massive sulphide lead-zinc deposits: An em pirical model, in Sangster, D.F., ed., Sediment-hosted stratiform lead-zinc deposits: Mineralogical Association of Canada, Short Course Handbook 8, p. 1–29.

—— 1986, The paleotectonic setting of Rammelsberg and Meggen, Germany—A basin analysis study, in Turner, R.J.W., and Einaudi, M.T., eds., The genesis of stratiform sediment-hosted lead and zinc deposits: Stanford University Publications, Geological Sciences, Conference proceedings, 20, p. 109–112.

Large, R.R., and McGoldrick, P.J., 1998, Lithogeochemical halos and geochemical vectors to stratiform sediment hosted Zn-Pb-Ag deposits; 1, Lady Loretta deposit, Queensland: Journal of Geochemical Exploration, v. 63, p. 37–56.

Large, R.R., Bull, S.W., Cooke, D.R., McGoldrick, P.J., and Williams, P.J., 1998, A genetic model for the H.Y.C. Deposit, Australia; Based on regional sedimentology, geochemistry, and sulfide-sediment relationships: Economic Geology, v. 93, p. 1345–1368.

Large, R.R., Bull, S.W., and McGoldrick, P.J., 2000, Lithogeochemical halos and geochemical vectors to stratiform sediment hosted Zn-Pb-Ag deposits; Part 2, HYC Deposit, McArthur River, Northern Territory: Journal of Geochemical Exploration, v. 68, p. 105–126.

Leach, D.L., Bradley, D., Lewchuk, M.T., Symons, D.T.A., de, M.G., and Brannon, J., 2001, Mississippi Valley-type lead-zinc deposits through geological time; Implications from recent age-dating research: Mineralium Deposita, v. 36, p. 711–740.

Leach, D.L., Sangster, D.L., Kelly, K.D., Large, R.R., Garven, G., Allen, C.R., Gutzmer, J., and Walter, S., 2005, Sediment-hosted lead-zinc deposits: A global perspective: Society of Economic Geologists, One Hundredth Anniversary Volume 1905–2005, p. 561–607.

Lydon, J.W., 1983, Chemical parameters controlling the origin and deposition of sediment-hosted stratiform lead-zinc deposits, in Sangster, D.F., ed., Sediment-hosted stratiform lead-zinc deposits: Mineralogical Association of Canada, Short Course Handbook, v. 8, p. 175–250.

Lydon, J.W., Paakki, J.J., Anderson, H.E., and Reardon, N.C., 2000a, An overview of the geology and geochemistry of the Sullivan Deposit, in Lydon, J.W., Höy, T., Knapp, M., and Slack, J., eds., The geological environment of the Sullivan deposit, British Columbia: Geological Association of Canada, Mineral Deposits Division, Special Publication 1, p. 505–522.

Lydon, J.W., Walker, R., and Anderson, E.H., 2000b, Lithogeochemistry of the Aldridge formation and the chemical effects of burial diagenesis, in Lydon, J.W., Höy, T., Knapp, M., and Slack, J., eds., The geological environment of the Sullivan deposit, British Columbia: Geological Association of Canada, Mineral Deposits Division, Special Publication 1, p. 137–179.

Lydon, J.W., 2007, An overview of the economic and geological contexts of Canada's major mineral deposit types, in Goodfellow, W. D., ed., Mineral Deposits of Canada: A Synthesis of Major Deposit-types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods, Special Publication 5, Mineral Deposits Division, Geological Association of Canada, p. 3–48.

McKibben, M.A., Eldridge, C.S., and Williams, A.E., 1988, Sulfur and base metal transport in the Salton Sea geothermal system, in Tucker, R., ed., New horizons, 12. Davis, CA, United States, Geothermal Resources Council, Transactions, p. 121–125.

Mosier, D.L., Singer, D.A., and Salem, B.B., 1983, Geologic and grade-tonnage information on volcanic-hosted copper-zinc-lead massive sulphide deposits: USGS Open File Report, 83-89, 77p.

Moore, D.W., Young, L.E., Modene, J.S., and Plahuta, J.T., 1986, Geological setting and genesis of the Red Dog zinc-lead-silver deposit, Western Brooks Range, Alaska: Economic Geology, v. 81, p. 1696–1727.

Nelson, J., Paradis, S., Christensen, J., and Gabites, J., 2002, Canadian Cordilleran mississippi valley-type deposits; A case for Devonian-Mississippi back-arc hydrothermal origin: Economic Geology, v. 97, p. 1013–1036.

Paradis, S., Hannigan, P., and Dewing, K., 2007, Mississippi Valley-type lead-zinc deposits, *in* Goodfellow, W.D., ed., Mineral deposits of Canada: A synthesis of major deposit types, district metallogeny, the evolution of geological provinces, and exploration methods: Geological Association of Canada, Mineral Deposits Division, Special Publication 5, p. 185-203.

Parr, J.M., and Plimer, I.R., 1993, Models for Broken Hill-type lead-zinc-silver deposits: Geological Association of Canada, Special Paper 40, p. 253–288.

Peter, J.M., Layton-Matthews, D., Piercey, S., Bradshaw, G., Paradis, S., and Boulton, A., 2007, Volcanic-hosted massive sulphide deposits of the Finlayson Lake District, Yukon in Goodfellow, W. D., ed., Mineral Deposits of Canada: A Synthesis of Major Deposit-types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods, Special Publication 5, Mineral Deposits Division, Geological Association of Canada, p. 471–508.

Piercey, S.J., Paradis, S., Murphy, D.C., and Mortensen, J.K., 2001, Geochemistry and paleotectonic setting of felsic volcanic rocks in the Finlayson Lake volcanic-hosted massive sulfide district, Yukon, Canada: Economic Geology, v. 96, p. 1877–1905.

Price, R.A., and Sears, J.W., 2000, A preliminary palinspastic map of the Mesoproterozoic Belt-Purcell Supergroup, Canada and USA; Implications for the tectonic setting and structural evolution of the Purcell anticlinorium and the Sullivan deposit, in Lydon, J.W., Höy, T., Knapp, M., and Slack, J., eds., The geological environment of the Sullivan deposit, British Columbia: Geological Association of Canada, Mineral Deposits Division, Special Publication 1, p. 61–81.

Sangster, D.F., 1990, Mississippi Valley-type and SEDEX lead-zinc deposits: A comparative examination: Institution of Mining and Metallurgy, Transactions, Section B: Applied Earth Science, v. 99, p. 21–42.

Sangster, D.F., and Hillary, E.M., 2000, SEDEX lead-zinc deposits—Proposed subtypes and their characteristics: Exploration and Mining Geology, v. 7, p. 341–357.

Singer, D.A., 1995, World class base and precious metal deposits—A quantitative analysis: Economic Geology, v. 90, p. 88–104.

Slack, J.F., Kelley, K.D., Anderson, V.M., Clark, J.L., and Ayuso, R.A., 2004, Multistage hydrothermal silicification and Fe-Tl-As-Sb-Ge-REE enrichment in the Red Dog Zn-Pb-Ag district, Northern Alaska: Geochemistry, origin, and exploration applications: Economic Geology, v. 99, p. 1481–1508.

Turner, R.J.W., 1990, Jason stratiform Zn-Pb-barite deposit, Selwyn Basin, Canada (NTS 105-O-1): Geological setting, hydrothermal facies and genesis, in Abbott, J.G., and Turner, R.J.W., eds., Mineral deposits of the northern Canadian Cordillera: International Association on the Genesis of Ore Deposits, Field Trip 14: Guidebook, p. 137–175.

Turner, R.J.W., Leitch, C.H.B., and Ross, K.V., 2000, District-scale alteration associated with the Sullivan deposit, British Columbia, Canada, in Lydon, J.W., Höy, T., Knapp, M., and Slack, J., eds., The geological environment of the Sullivan deposit, British Columbia: Geological Association of Canada, Mineral Deposits Division, Special Publication 1, p. 408–439.

Vail, P.R., Mitchum, R.M., Jr., and Thompson, S., III, 1977, Seismic stratigraphy and global changes of sea level; Part 4: Global cycles of relative changes of sea level: American Association of Petroleum Geologists, Memoir 26, p. 83–97.

Walters, S.G., 1998, Broken hill-type deposits: AGSO Journal of Australian Geology and Geophysics, v. 17, p. 229–237.

Wheeler, J.O., Hoffman, P.F., Card, K.D., Davidson, A., Sanford, B.V., Okulitch, A.V., and Roest, W.R., 1996, Geological map of Canada, Map 1860A, Geological Survey of Canada, CD-ROM.

Yang, J., Large, R.R., and Bull, W., 2004, Factors controlling free thermal convection in faults in sedimentary basins: Implications for the formation of zinc-lead mineral deposits: Geofluids, v. 4, p. 237–247.

Young, L.E., 2004, A geologic framework for mineralization in the western Brooks Range, Alaska: Economic Geology, v. 99, p. 1281–1306.

Zierenberg, R.A., 1990, Deposition of metalliferous sediment beneath a brine pool in the Atlantis II deep, Red Sea, in McMurray, G.R., ed., Gorda Ridge: A seafloor spreading center in the United States exclusive economic zone: New York, Springer-Verlag, p. 131–142.