

MISSISSIPPI VALLEY-TYPE LEAD-ZINC DEPOSITS

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Abstract

Mississippi Valley-type (MVT) deposits are epigenetic, stratabound, carbonate-hosted sulphide bodies composed predominantly of sphalerite, galena, iron oxides (pyrite, marcasite), and carbonates (calcite, dolomite). MVT deposits are important Zn and Pb reserves and resources in the world. Silver, barite, gypsum, and fluorite may also be economically recovered from these deposits. Major world MVT deposits are found in Canada (Pine Point, Polaris, Nanisivik, Gays River, and Daniel's Harbour), mid-United States districts (Upper Mississippi Valley, Missouri, Tri-State, and Tennessee), Australia (Lennard Shelf and Coxco), and Europe (Silesia, Alpine, Reocin and Cévennes).

The mineralization occurs as open-space fillings of breccias and fractures, and/or as replacement of the host dolomite. Less commonly, sulphide and gangue minerals occupy primary carbonate porosity.

Most MVT deposits are found in carbonate platforms adjacent to cratonic sedimentary basins; they occur in limestone less frequently. They are also restricted to rocks younger than two billion years and formed during short time intervals, primarily within the Phanerozoic. MVT mineral districts are the product of regional- or subcontinental-scale fluid migration. Deposits are formed by the migration of warm saline aqueous solutions, similar to oilfield brines, through aquifers within platform-carbonate sequences toward the basin periphery. One of the most popular models relates ore-fluid migration to compressive tectonic regimes associated with continental accretion. This model is not universally applicable, however, as some of the MVT deposits most likely formed under an extensional tectonic regime.

Résumé

Les gisements du type Mississippi Valley consistent en des corps sulfurés stratoïdes épigénétiques encaissés dans des carbonates et se composent principalement de sphalérite, de galène, d'oxydes de fer (pyrite et marcassite) et de carbonates (calcite et dolomite). Ils constituent d'importantes réserves et ressources mondiales de Zn et Pb, et il est parfois possible d'extraire de manière rentable de l'argent, de la baryte, du gypse et de la fluorine de ces gisements. Les plus importants gisements de ce genre reposent au Canada (Pine Point, Polaris, Nanisivik, Gays River et Daniel's Harbour), dans les districts du milieu des É.-U. (Upper Mississippi Valley, Missouri, Tri-State, et Tennessee), en Australie (plate-forme de Lennard et Coxco) et en Europe (Silésie, Alpes, Reocin, et Cévennes).

Les minéralisations se présentent comme des remplissages dans des brèches et des fractures ou comme un remplacement de la dolomie encaissante. Moins fréquemment, les minéraux sulfurés et de gangue occupent les pores primaires des carbonates.

La plupart des gisements du type Mississippi Valley reposent dans des plates-formes carbonatées contiguës à des bassins sédimentaires cratoniques, mais parfois, ils sont logés dans du calcaire. Par ailleurs, ils sont encaissés dans des roches de moins de 2 Ga qui se sont formées rapidement, principalement pendant le Phanérozoïque. Les districts minéraux du type Mississippi Valley résultent d'une migration de fluides régionale ou sous continentale. Les gisements sont issus de solutions aqueuses salines chaudes qui sont similaires à des saumures de champ de pétrole qui ont circulé par des aquifères, dans des séquences de roches carbonatées néritiques, jusqu'aux environs d'un bassin. L'un des modèles les plus populaires établit un lien entre la migration du minerai et les régimes tectoniques compressifs rattachés à une accretion continentale. Ce modèle n'est pas toujours applicable, car certains gisements du type Mississippi Valley se sont fort probablement formés dans un régime tectonique de distension.

Definition

Mississippi Valley-type (MVT) deposits are epigenetic, stratabound, carbonate-hosted bodies composed predominantly of sphalerite, galena, iron sulphides, and carbonates. The deposits account for approximately 27 percent of the world's current lead and zinc resources¹ (Tikkanen, 1986). They are so-named because several classic MVT deposits are located in carbonate rocks within the drainage basin of the Mississippi River in the central United States (US). Important Canadian deposits include Pine Point, Polaris, Nanisivik, Daniel's Harbour, Gays River, Monarch-Kicking Horse, and Robb Lake.

The deposits occur mainly in dolomite as open-space fillings, collapse breccias, and/or as replacement of the carbonate host rock. Less commonly, sulphide and gangue minerals occupy primary carbonate porosity. The deposits are epigenetic, having been emplaced after lithification of the host rocks.

MVT deposits originate from saline basinal metalliferous fluids at temperatures in the range of 75 to 200°C (Leach and Sangster, 1993). They are located in carbonate platform settings, typically in relatively undeformed orogenic foreland rocks, commonly in foreland thrust belts, and rarely in rift zones (Leach and Sangster, 1993).

Individual deposits are generally less than 2 million tonnes, are zinc-dominant, and possess grades that rarely exceed 10% (Pb+Zn). The deposits do, however, characteristically occur in clusters, referred to as "districts". A metallogenic district is defined as a continuous area that contains the expressions of the geological environment and tectonic events that controlled the formation of MVT deposits. For example, the Cornwallis district in Nunavut hosts one deposit², the Polaris mine, and approximately 80 showings³ (Dewing et al., 2007). Another example is the Pine Point district in the Northwest Territories, which hosts the Pine Point

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 No. 5, p. 185-203.

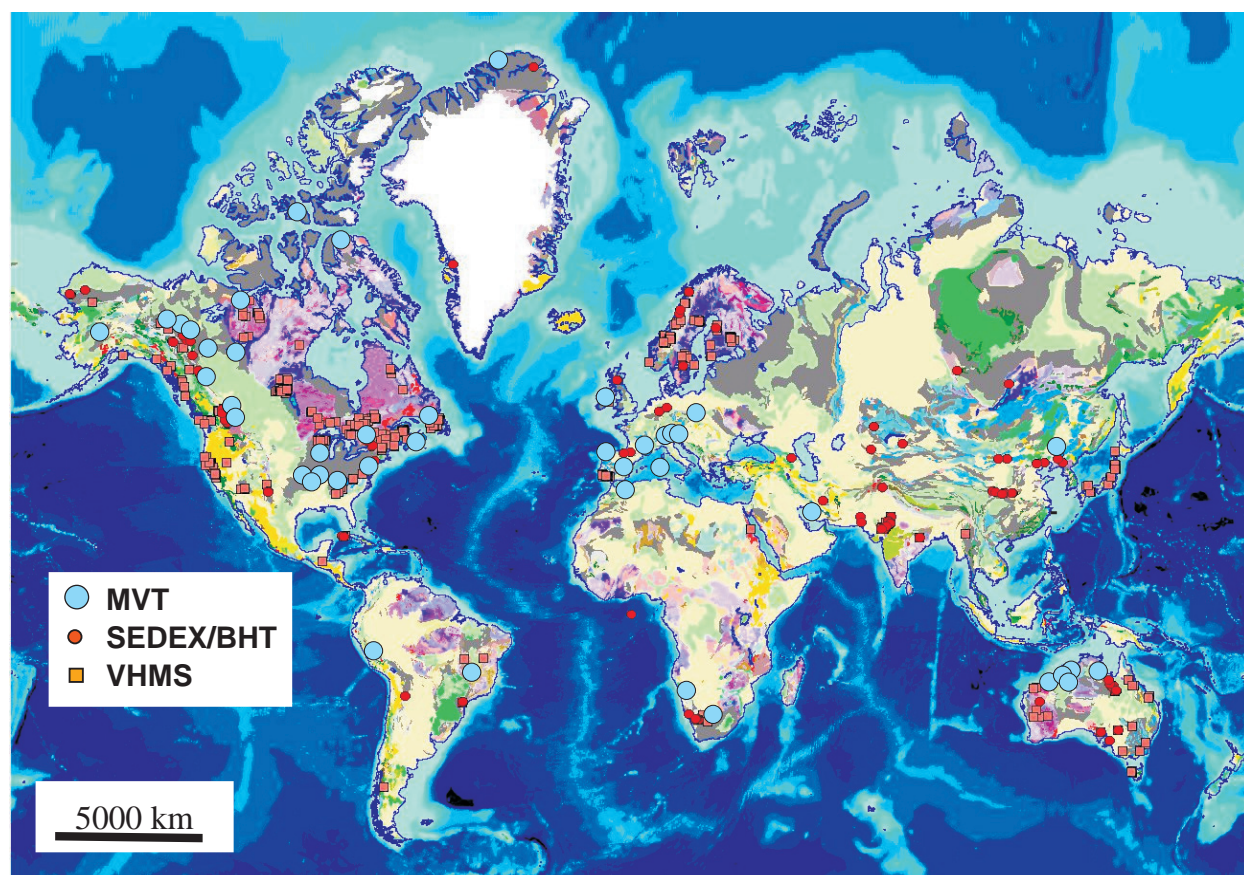


FIGURE 1. Distribution of Mississippi Valley-type deposits and districts worldwide. BHT = Broken Hill-type, MVT = Mississippi Valley-type, SEDEX = sedimentary exhalative, and VHMS = volcanic-hosted massive sulphides.

deposit containing approximately 100 orebodies⁴ (Hannigan, 2007). Other districts may have a half-dozen to more than 300 orebodies, which can contain up to several hundred million tonnes of ore scattered over hundreds to thousands of square kilometres (Sangster, 2002).

Mineral Deposit Subtypes

MVT deposits are part of a larger family of carbonate-hosted deposits, all of which are epigenetic and contain zinc. Sub-types of MVT deposits include the carbonate-hosted F (\pm Ba, \pm Zn, \pm Pb) deposits (Dunham, 1983; Rowan et al., 1996) and some “Irish-type” deposits (Hitzman and Beaty, 1996). The “Irish-type” deposits are stratabound, structurally controlled, carbonate-hosted, Pb-Zn deposits that have sedimentary exhalative (SEDEX) and/or MVT characteristics. Those that show epigenetic features are considered subtypes of MVT deposits.

Associated Mineral Deposit Types

MVT-associated deposits include a variety of deposits that belong to the spectrum of sediment-hosted base-metal deposits. These include SEDEX deposits, Broken Hill-type

Pb-Zn deposits, sandstone-hosted Pb deposits, carbonate-hosted Cu-Pb-Zn deposits (or Kipushi type), fracture-controlled carbonate-hosted F (\pm Ba) deposits, carbonate-hosted manto-type Ag-Pb-Zn deposits, high-temperature carbonate replacement Pb-Zn (\pm Fe, \pm Cu, \pm Ag, \pm Au) deposits (Megaw et al., 1996; Smith, 1996; Titley, 1996), and the diapir-related Zn-Pb (\pm Ag, \pm Cd, \pm Cu, \pm Hg) deposits (Sheppard et al., 1996).

Economic Characteristics

Summary of Economic Characteristics

MVT deposits account for approximately 27% of the world's lead and zinc resources, and they are dispersed throughout the world (Fig. 1). The proportion of the world's primary production of Zn and Pb from MVT deposits is 25% and 26%, respectively (Tikkanen, 1986). A large proportion of Pb and Zn production comes from several classic MVT districts located in the drainage basin of the Mississippi River in the central US and in the East Tennessee district in the eastern United States. MVT deposits also occur in Canada, Australia, Europe (Belgium, Poland, France, Ireland, Spain, Austria, Italy, Bulgaria, Macedonia, and

¹ Resources: Maximum estimate of geological resources from a systematic evaluation of a deposit that has been mined (i.e. production + proven reserves + probable reserves) or that hasn't been mined (i.e. measured resources + indicated resources).

² Deposit: A mineral deposit is any natural, but locally restricted, concentration of minerals in the Earth's crust. It carries no necessary profitability implications.

³ Showing: Occurrences hosting minor in situ mineralization.

⁴ Orebody: Concentration of metallic and non-metallic minerals of sufficient ore content to make extraction economically feasible.

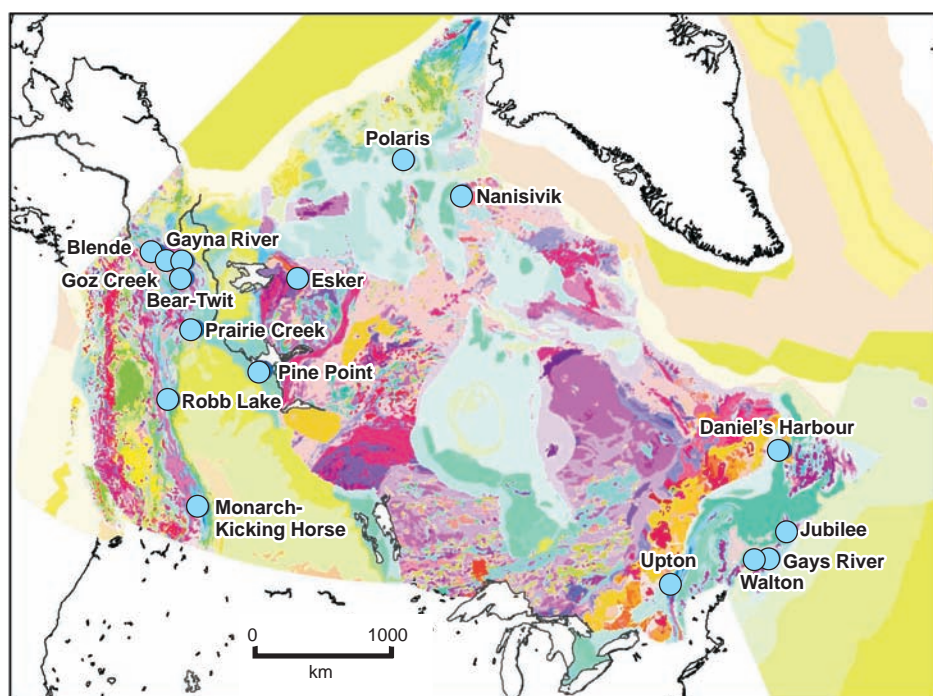


FIGURE 2. Distribution of Mississippi Valley-type deposits plotted on a simplified geological map of Canada (Map D1860A). Major attributes of these deposits are listed in Appendix 1.

Serbia), Africa (Egypt, Tunisia, Algeria, Morocco, and South Africa), Asia (Russia, China, India, Iran, Saudi Arabia, and Turkey), and South America (Brazil and Peru). In Canada, there are 16 major deposits (Fig. 2) that in themselves form districts. Each district contains one to more than 100 sulphide bodies. The Pine Point district, for example, contains 100 orebodies distributed over 1,600 square kilometres.

MVT deposits contributed only negligibly to Canadian Zn and Pb production prior to the opening of the Pine Point mine in 1964. Between 1964 and 2002, about 30% of the annual lead and zinc production in Canada was derived from MVT deposits (Sangster, 2002). With the closure of Polaris and Nanisivik in 2002, however, the proportion of Zn and Pb derived from MVT deposits in Canada dropped to nil.

Grade and Tonnage Characteristics

The size, grade, and metal ratio parameters of individual MVT deposits are difficult to compare. As mentioned by Sangster (1990, 1995) and Leach and Sangster (1993), several deposits were mined before accurate data were recorded. Furthermore, the production and reserve data are usually published as district totals rather than for each individual deposit or orebody. An exception to this is Pine Point, where grade and tonnage are recorded for individual orebodies that range in size from less than 100,000 tonnes to 17.5 million tonnes with average grades of 2% Pb and 6.2% Zn (Hannigan, 2007). Orebodies average 1.32 Mt of Zn-Pb ore grading near 7% Zn and 3% Pb. The total geological resource (produced resource and remaining proven reserves) for the Pine Point district is estimated to be around 80 Mt (Appendix 1).

There are over 80 MVT deposits (with grade and tonnage data) worldwide (Fig. 1), 16 of them in Canada (Fig. 2; Appendix 1). Seven out of 16 Canadian MVT deposits have

been mined for a total of 112.5 Mt of ore. Pine Point was the largest deposit with a production of approximately 64,300,000 tonnes of 6.95% Zn and 3.0% Pb (Appendix 1). There are currently no MVT deposits in production in Canada.

Geological resource estimates for Canadian deposits range approximately from 800,000 to 79.3 million tonnes (average 16 Mt) with 0.4 to 17.6% combined Pb and Zn (average 7.69%; Fig. 3). Geological resources tabulated in Appendix 1 for Canadian deposits that have not been in production are generally not in compliance with the National Instrument 43-101 standards. Most non-Canadian individual deposits yield less than 10 million tonnes of Pb+Zn metals, with combined Pb+Zn grades seldom exceeding 15%. These figures are similar to Canadian deposits (Fig. 3). The size (in tonnes of Pb+Zn metals) of non-Canadian

MVT districts (e.g. Tri-States, United States; Silesia, Poland) is approximately an order of magnitude greater than the size of individual deposits with combined Pb+Zn grades of between 2 and 5% (Fig. 3).

The metal ratios in Canadian deposits, expressed as Zn/(Zn+Pb) values (Fig. 4), show a bimodal distribution with the majority of deposits having values between 0.6 and 0.8 (median = 0.74), and a smaller group between 0.9 and 1.0 (median = 0.97). The majority of Canadian deposits are Zn-rich relative to Pb, with Zn grades between 4 and 6 wt.% (median = 5.42) and Pb grades between 0 and 2 wt.% (median = 1.4) (Fig. 5). Daniel's Harbour and many deposits in the East Tennessee district (US) are essentially free of lead and have Zn/(Zn+Pb) ratios close to 1.0. Silver and copper content in MVT deposits is low and often not reported. When reported, silver grades vary from 10 to 161 g/t Ag. The

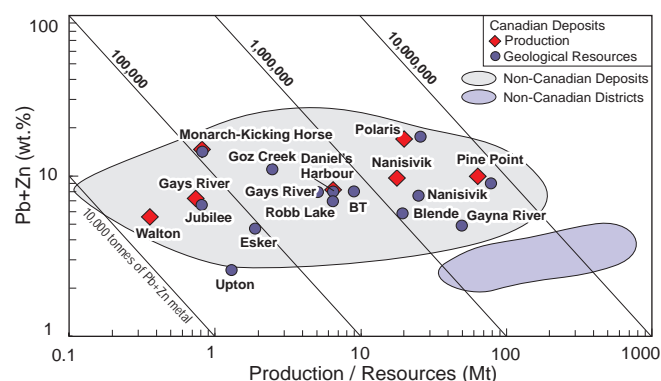


FIGURE 3. Grade-tonnage for Canadian Mississippi Valley-type deposits with geological and production resources. Diagonal lines represent total tonnage of contained lead and zinc metal. The fields for non-Canadian deposits and districts are approximate and include geological resource and grade data from the World's Minerals Project. BT = Bear-Twit.

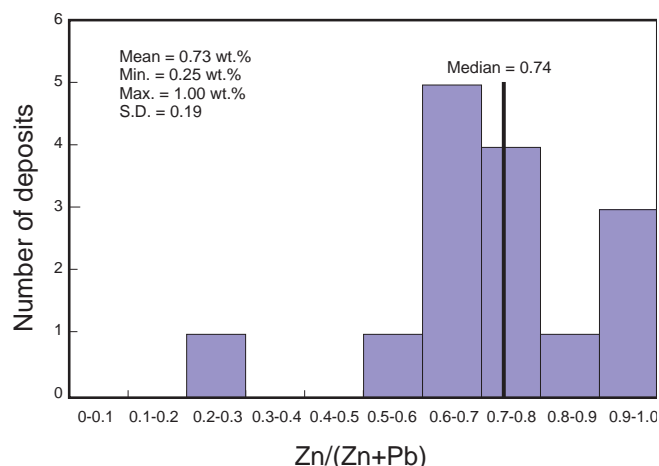


FIGURE 4. Zn/(Zn+Pb) ratios in Canadian MVT deposits.

Walton deposit, with an average value of 350 g/t Ag, has the highest silver grades of any MVT deposit in Canada (Patterson, 1988a,b, 1989). It is also the only Canadian deposit where production reported Cu grade values (Appendix 1).

Geological Attributes of MVT Deposits

Nature of Sulphide Bodies

MVT deposits occur in clusters of a few to hundreds of individual sulphide bodies that vary in character and shape and are often interconnected (Fig. 6). Deposits range from massive replacement zones to open-space fillings of breccias and fractures, to disseminated clusters of crystals that occupy intergranular pore spaces (Leach and Sangster, 1993). Sulphide-hosting structures are most commonly zones of highly brecciated dolomite; in some instances (e.g. Pine Point, Robb Lake, Daniel's Harbour, Nanisivik) these zones are arranged in linear patterns that suggest a tectonic control (Figs. 6, 7, 8). These breccia zones may range from more or less concordant tabular structures, controlled by individual strata, to discordant cylindrical structures within tens of metres of sedimentary sequences. At Pine Point, the orebodies are either tabular or prismatic structures in interconnected paleokarst networks (Fig. 8). The karst networks are directly related to distinct facies and lithofacies features in the Presqu'île barrier complex. The MVT sulphide bodies are, therefore, discordant on the deposit scale, but stratabound on a district scale.

Dimensions

The dimensions of sulphide bodies can be difficult to measure because of their irregular and variable shape. At Pine Point, the L-36 orebody has dimensions of 1450 m in length, 50 to 400 m in width, and 2.5 to 10 m in thickness and the X-15 orebody is 800 m in length, 400 m in width, and 20 to 30 m in thickness (Hannigan, 2007). At Robb Lake, several bodies extend for more than 300 m along bedding and crosscut more than 50 m of stratigraphic section; others are thin and narrow bodies and pods parallel to bedding (Paradis et al., 1999). At Polaris, the main orebody had dimensions of 800 m in length, 300 m in width, and 150 m in thickness (Dewing et al., 2007).

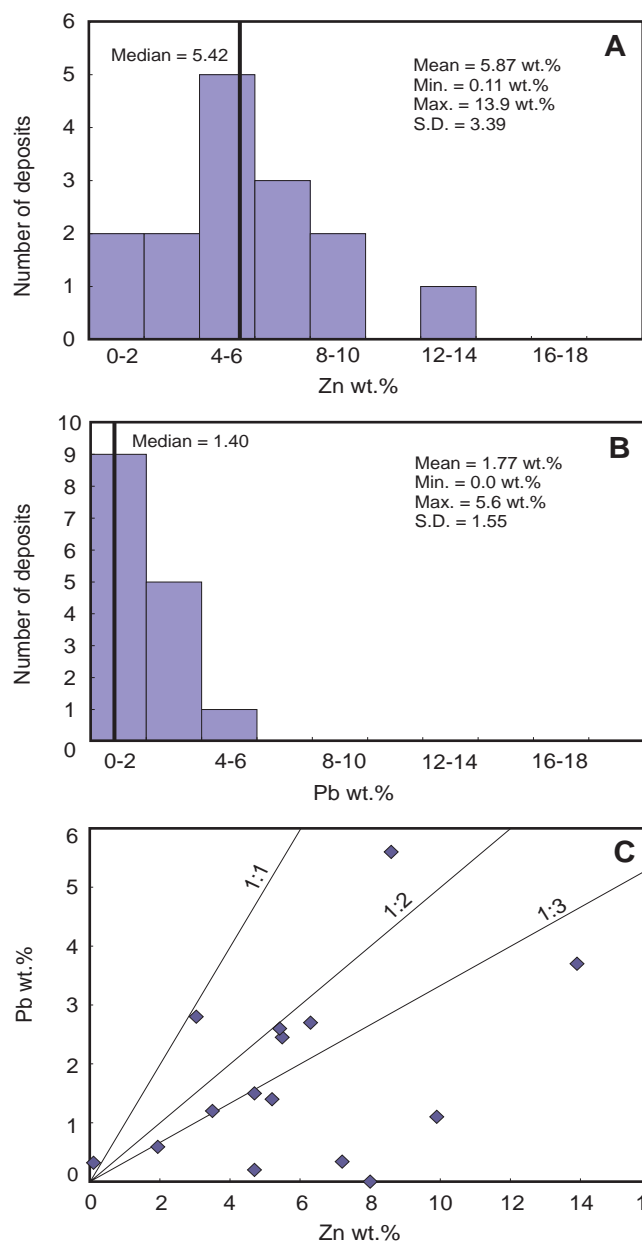


FIGURE 5. (A) and (B) Histograms of the lead and zinc grades of Canadian deposits. (C) Pb wt.% versus Zn wt.% for Canadian MVT deposits.

Host Rocks

The deposits are hosted in carbonate rocks, usually dolostone and less frequently limestone. The dolostone consists of medium- to coarse-grained white sparry dolomite that has replaced a fine-grained dolostone host, which itself has replaced a limestone host. The Pine Point orebodies, for example, are enclosed in large, discordant zones of secondary coarse-grained vuggy dolostone with white saddle dolomite and calcite gangue. The deposit host rocks are mostly fine-grained crystalline dolostone and local limestone (Rhodes et al., 1984). Gays River is an example of a deposit in early diagenetic dolostone without secondary sparry or saddle dolomite (Ravenhurst et al., 1989). In the East Tennessee (US) and Alpine (Europe) districts, the secondary dolomite is only locally developed (Sangster, 1990), whereas at the Jubilee deposit in Nova Scotia, the deposit is

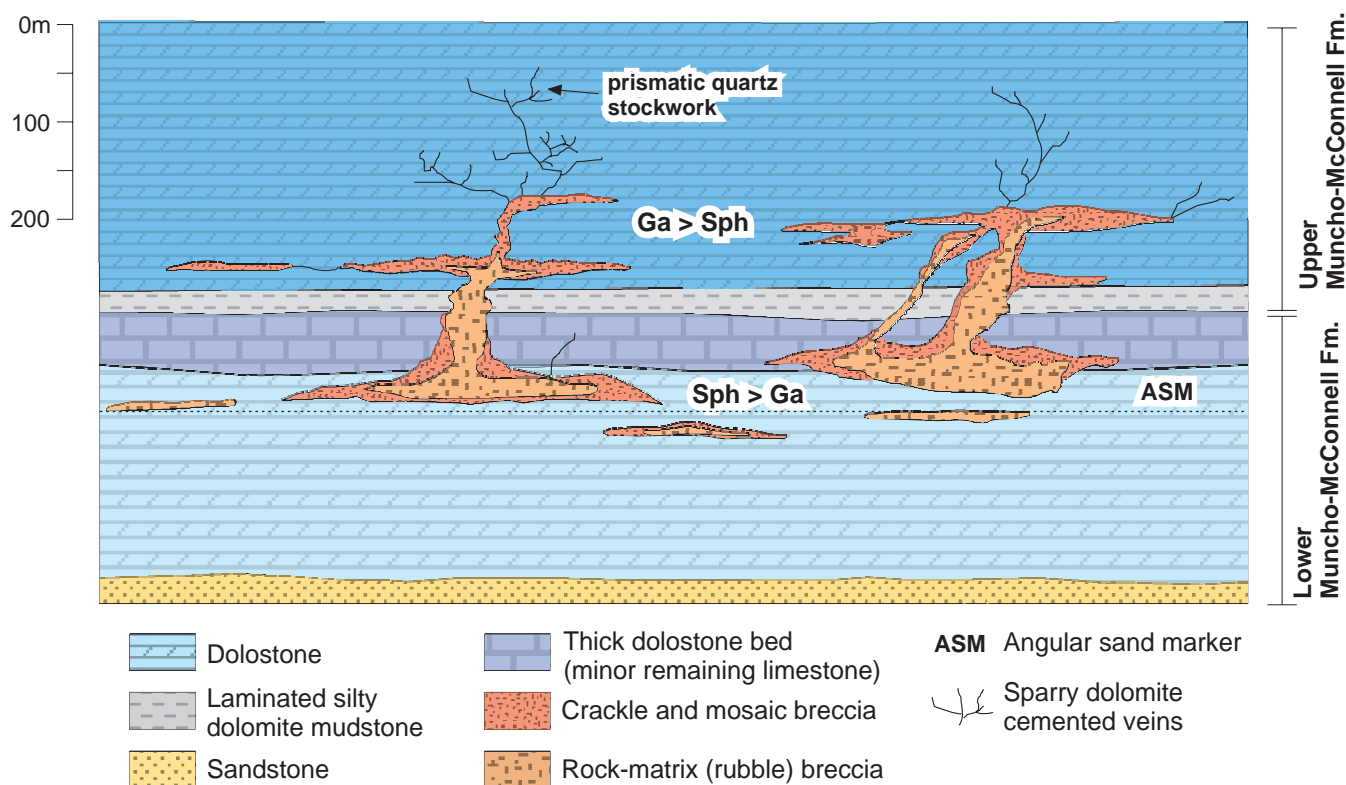


FIGURE 6. Schematic representation of the Robb Lake breccia-hosted Zn-Pb sulphide bodies, showing textural and mineralogical zoning and stratigraphic controls (from Nelson et al., 1999; from Paradis et al., 1999; Paradis and Nelson, 2007).

exclusively hosted in limestone (Paradis et al., 1993; Fallara et al., 1998).

Mineralogy

MVT deposits have simple mineral assemblages that consist of sphalerite, galena, pyrite, marcasite, dolomite, calcite, quartz, and occasionally barite, fluorite, celestite, gypsum, anhydrite, native sulphur, and pyrrhotite. Chalcopyrite, bornite, and other copper minerals are normally not constituents of MVT deposits and are only abundant in some districts,

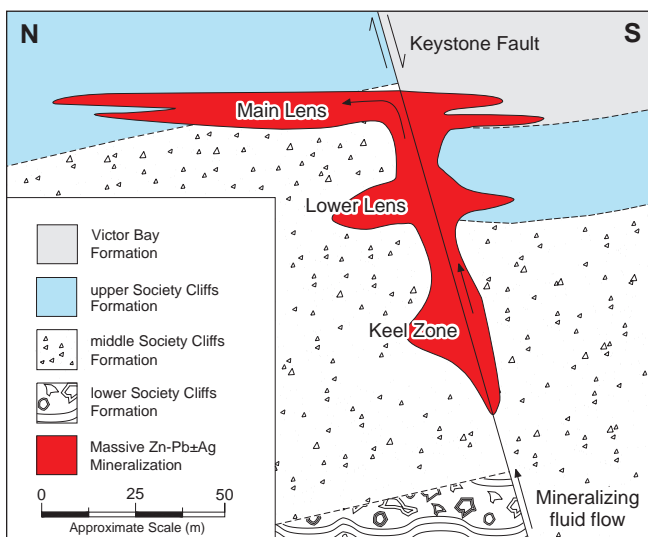


FIGURE 7. Schematic cross-section of the Nanisivik main lens and keel zone (modified from Patterson and Powis, 2002).



FIGURE 8. View eastward of the mined-out karst trend at Pine Point (courtesy of P. Hannigan).

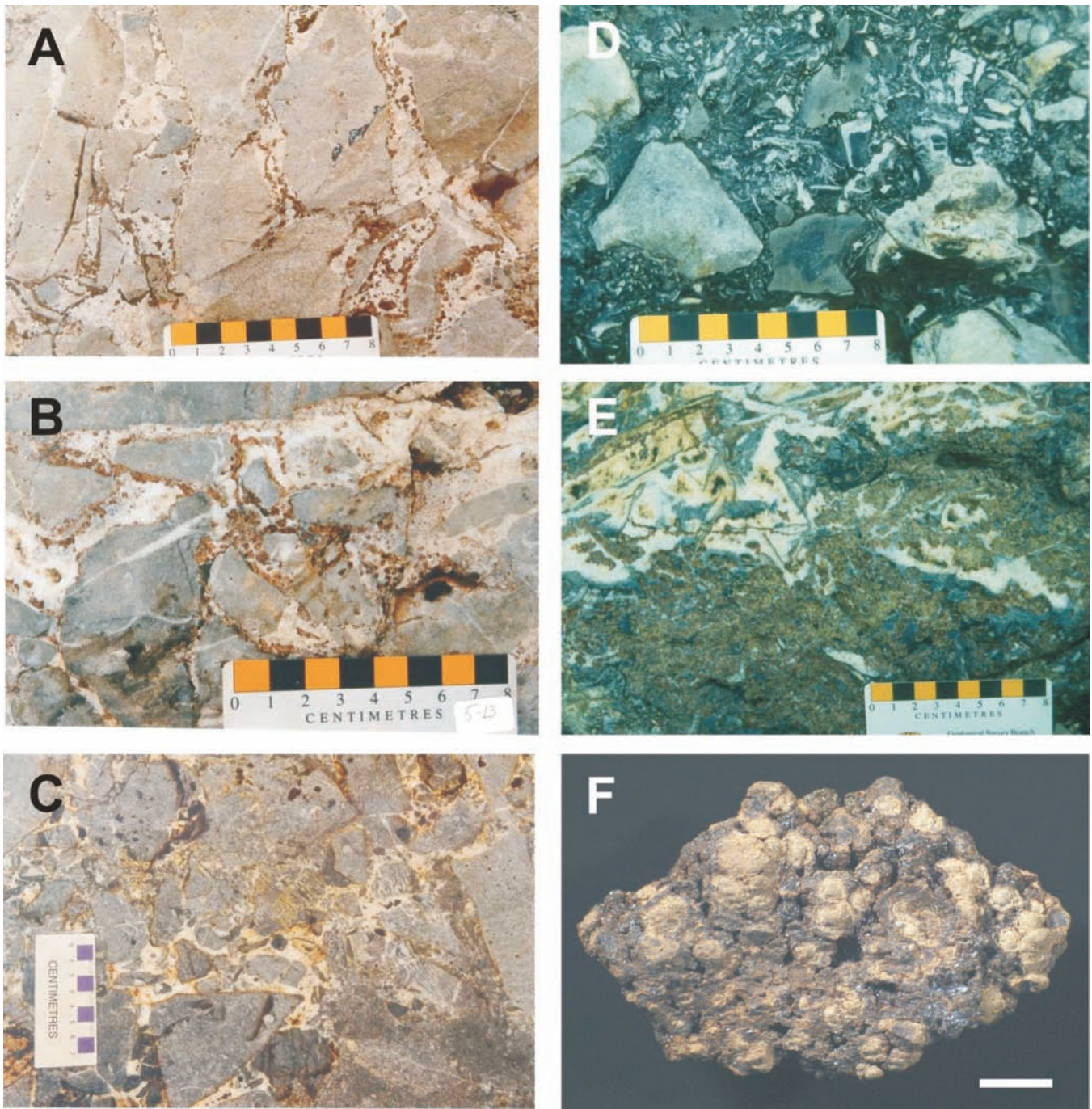


FIGURE 9. (A) Crackle breccia with disseminated sphalerite crystals in white dolomite cement, Robb Lake, British Columbia. (B) Mosaic breccia with sphalerite crystals in white dolomite cement, Robb Lake, British Columbia. (C) Rubble breccia consisting of variably altered dolostone fragments and shale fragments in white dolomite cement. Note the dolostone fragments with zebra texture, Robb Lake, British Columbia. (D) Rock-matrix breccia with dolostone, shale, and white sparry dolomite fragments in dark grey fragmental matrix, Robb Lake, British Columbia. (E) Aggregates of sphalerite crystals and white sparry dolomite along small fractures, Pine Point, Northwest Territories. (F) Aggregates of colloform sphalerite and skeletal galena completely replacing the carbonate, Polaris, Nunavut; scale bar is 1 cm.

such as the Cornwallis district in Canada (Randell and Anderson, 1996; Dewing et al., 2007) and the Viburnum Trend of the Southeast Missouri district in the US (Sangster, 1990; Leach et al., 1995; Foley, 2002). Deposits of the Viburnum Trend have a unique and complex mineralogy that is not typical of most MVT deposits, and includes siegenite, bornite, tennantite, bravoite, digenite, covellite, arsenopyrite, fletcherite, adularia, pyrrhotite, magnetite, millerite,

polydymite, vaesite, djurleite, chalcocite, anilite, and enargite (Leach et al., 1995). The carbonate-hosted, Cu-rich showings of the Cornwallis district are associated with Zn-Pb mineralization and are structurally and stratigraphically controlled. They consist of chalcocite and bornite, and lesser chalcopyrite, cuprite, covellite, and native copper as fracture-, vein-, and breccia-filling of the Silurian dolostone (Dewing et al., 2007).

The abundance of iron sulphides relative to other sulphide minerals in MVT deposits ranges from dominant to nil (Leach et al., 1995; St. Marie et al., 2001). For example, at Nanisivik, iron sulphides are abundant, whereas in some Appalachian deposits (e.g. Daniel's Harbour), only trace to minor amounts of iron sulphides are present. Deposits that contain significant iron sulphides can be detected by induced polarization (IP) surveys and ground electromagnetic methods (EM), whereas those that contain only sphalerite and minor galena are generally poor conductors and have variable resistivity (Summer, 1976). At Pine Point, the sphalerite is non-polarizable, however the high concentrations of conductive minerals in the orebodies (i.e. galena, pyrite, and marcasite) made the IP method very successful for locating orebodies (Lajoie and Klein, 1979). Sphalerite and gangue minerals have widely varying densities, so gravity surveys could prove useful in exploring for sulphide bodies containing mainly sphalerite. In the Cornwallis district, the Polaris deposit was drilled based on a gravity anomaly (Dewing et al., 2007).

Organic material, such as hydrocarbon, is common in some MVT deposits (e.g. Polaris, Pine Point, Robb Lake, Jubilee, Walton) but is not present in significant amounts in others (e.g. Monarch-Kicking Horse, Gays River). At Pine Point and Polaris, pyrobitumen is a common, though volumetrically small, component of the deposits that occurs in vugs as crusts or blobs (Dewing et al., 2007; Hannigan, 2007). Other evidence for hydrocarbon generation at Polaris is found in abundant bitumen, hydrocarbon fluid inclusions, thermal maturity values indicating passage into the oil window, and petrographic evidence for localized, direct transformation of alginite into bitumen (Randell, 1994; L.V. Stasiuk, pers. comm., 1992).

Textures

Sulphide textures are mostly related to open-space filling of breccias, fractures, and vugs. Replacement of carbonate host rocks and internal sediments, and sulphide disseminations are also observed (e.g. Polaris, Pine Point, Robb Lake deposits). Internal sediments are defined as well stratified materials that have partly or entirely filled the space between the breccia fragments (Leach and Sangster, 1993). The materials consist of dolomite grains, sand-sized sulphide crystals, and sulphide-carbonate fragments (Kendall, 1960; Sass-Gustkiewicz et al., 1982; Rhodes et al., 1984; Randell and Anderson, 1990; Leach and Sangster, 1993). The mineralized breccias are of several textural types: crackle, mosaic, rubble, and rock-matrix ("trash") breccias (Fig. 9A, B, C, D). Sulphides and white sparry and saddle dolomite constitute the cement between the fragments. Descriptions of the breccias can be found in Ohle (1959; 1985), Sangster (1988; 1995), Leach and Sangster (1993), Paradis et al. (1999), and Nelson et al. (2002). In these open-space features, mineral textures are varied (see Figs. 9 and 10). The sulphides are disseminated, massive, and banded. Disseminated sulphides occur as fine to coarse crystals of sphalerite and galena overlain by, or intergrown with, white, coarse, crystalline, sparry dolomite cement (Fig. 9A, B). Coarse sphalerite crystals occasionally coat the tops of fragments or line the bottoms of cavities creating a texture known as "snow on roof" (Leach and Sangster, 1993; Sangster, 1995). Sphalerite also forms

massive aggregates of coarse-grained colloform and botryoidal crystals (Figs. 9E, F, and 10A) and laminae of fine-grained crystals. At Nanisivik, replacement of the dolostone is the main mechanism of massive sulphide emplacement. The deposit consists of massive pyrite, sphalerite, and galena that replace the dolostone along high-angle normal faults and form mantos that shallowly crosscut bedding (Patterson and Powis, 2002). At Polaris, massive carbonate replacement, breccia-fill and vein sulphide ore form a 10 to 30 m thick, high-grade Zn-Pb-Fe, tabular unit hosted in the upper part of the deposit. Elsewhere, the replacement is selective and fol-

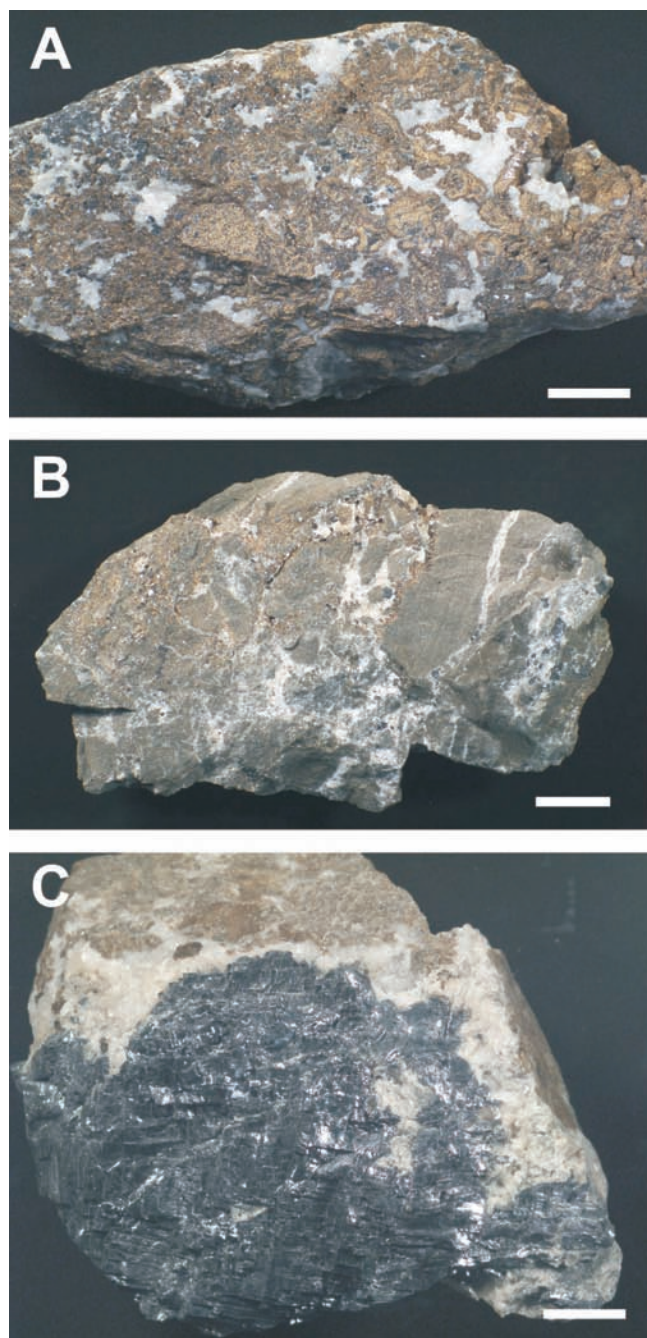


FIGURE 10. Various ore textures from Polaris, Nunavut; scale bar is 1 cm. (A) Sphalerite and skeletal galena are replacing the carbonate clasts. (B) Crystalline sphalerite in solution collapse breccia. (C) Massive galena and sparry dolomite in pseudobrecciated carbonate host rock.

lows stylolites, organic-rich layers, fossil-rich bands, and carbonate sand matrix (Randell, 1994). At Daniel's Harbour, selective replacement of the bioturbated limestone by the hydrothermal dolomite produced a pseudobreccia (Lane, 1984). At Monarch-Kicking Horse, Pine Point, and Robb Lake, selective replacement of a variety of primary rock fabrics by the hydrothermal dolomite formed a zebra texture (Fig. 11A, B).

In terms of geophysical parameters, the open-space filling nature of the MVT sulphide mineralization makes it a poor conducting medium for electrical geophysical surveys such as self-potential (SP) and electromagnetic (EM) (Lajoie and Klein, 1979). In most deposits, there is sufficient concentration of conducting minerals such as galena, pyrite, and marcasite, but the electrical continuity among these minerals is poor. This is due to the fact that these conductive minerals are often surrounded by non-conductive and non-polarizable sphalerite and abundant carbonate minerals, which interrupt the conducting paths (Lajoie and Klein, 1979).

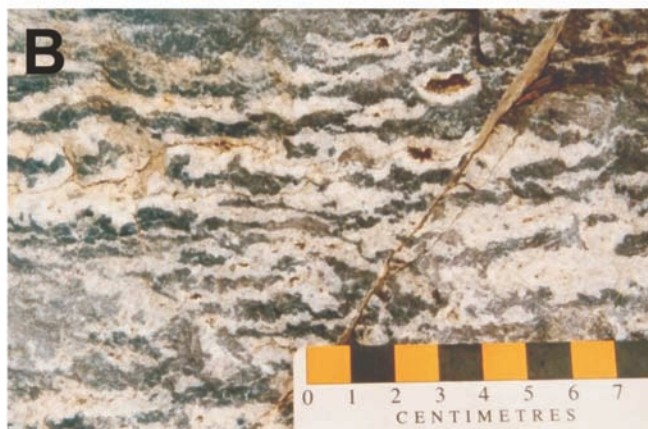


FIGURE 11. (A) Hydrothermal dolomite in bedding-parallel bands forming zebra texture (wall of pit N-42, Pine Point mine site, Northwest Territories). **(B)** Close-up of selective replacement of bedding-parallel bands by coarse-crystalline dolomite (Robb Lake, British Columbia).

Chemical Attributes of MVT Deposits

Ore Composition

Lead and zinc are the primary commodities recovered from MVT deposits. Silver, cadmium, germanium, copper, barite, and fluorite, although generally absent in most deposits, are by-products in some deposits. A complex suite of trace minerals may be present in some deposits, and may include some or all of the following minerals: arsenopyrite, bravoite, bornite, chalcophyrite, carrollite, celestite, chalcocite, covellite, digenite, djurleite, enargite, gallite, germanite, greenockite, linnaeite, marcasite, millerite, molybdenite, pyrrhotite, renierite, siegenite, tennantite, tungstenite, and vaesite (Foley, 2002). Elements associated with these minerals are As, Cu, Co, Ni, Cd, Ag, In, Ge, Ga, Sb, Bi, As, Mo, Sn, and Au. Cobalt and Ni are diagnostic accessory elements in deposits of the southeast Missouri and Upper Mississippi Valley districts in the US (Foley, 2002). Thallium and arsenic are enriched in sphalerite of the Polish deposits (Viets et al., 1996; Foley, 2002).

The majority of MVT deposits have essentially no geochemical signature because of limited primary dispersion of elements bound in sphalerite and galena within the carbonate rocks (Lavery et al., 1994). When weathering of the sulphides occurs and minerals such as limonite, cerussite, anglesite, smithsonite, hemimorphite, and pyromorphite are formed (e.g. Austinville-Ivanhoe district, US, and Silesia district, Poland), the soil and stream sediments of the regions surrounding the deposits may contain anomalous concentrations of Pb, Zn, Fe, and trace elements Sb, As, Bi, Ag, Tl, Cd, Mn, and Cu. In the East Tennessee district, detectable Zn, Fe, and Pb anomalies are found in residual soil and stream sediments (Leach et al., 1995).

In the Pine Point district, Pb, Zn, and Fe, which are anomalous in lake sediments, soils, and tills, are used for geochemical dispersion surveys in the exploration for orebodies. Zinc gives larger and more contrasting anomalies in lake sediments and soils than Pb; however, not all Zn anomalies are associated with an orebody. Shale units in the Western Canadian Sedimentary Basin, especially organic-rich ones, give high background values in Zn and Pb, similar in magnitude to those associated with orebodies. Relatively poorly defined Pb anomalies are often present near sulphide bodies, due to low Pb mobility and the generally low Pb/Zn ratios in MVT orebodies.

Alteration Mineralogy and Chemistry

Most MVT deposits show features of hydrothermal brecciation, recrystallization, dissolution, dolomitization, and silicification. The hydrothermal breccias known as collapse breccias result from the dissolution of underlying carbonate beds and are interpreted as meteoric karst or hydrothermal karst (Kyle, 1981; Sass-Gustkiewicz et al., 1982; Leach and Sangster, 1993).

Extensive hydrothermal dolomitization forms an envelope around most deposits, which extends tens to hundreds of metres beyond the sulphide bodies. According to Leach and Sangster (1993), the dolomititic halos can be pre-, syn-, or post-sulphides. This hydrothermal dolomitization consists of coarse crystalline white sparry dolomite and saddle dolomite cement. Dolomitized limestone forms a halo of minimum

Mississippi Valley-Type Lead-Zinc Deposits

TABLE 1. Summary of age dates (Ma) for Mississippi Valley-type deposits in Canada.

Deposit	Age of Host Rocks	Age of Mineralization		Date (Ma)	Method	Reference	Orogeny
		Period/Epoch	Epoch/Age				
Polaris	Late - Middle Ordovician	Late Devonian	Famennian	367±7	Paleomagnetism	Symons and Sangster (1992)	Ellesmerian
		Late Devonian	Famennian	366±15	Sphalerite Rb-Sr	Christensen et al. (1995)	Ellesmerian
Nanisivik	Middle Proterozoic (Neohelikian)	Middle Ordovician	Chazyian	461	Ar-Ar on adularia ¹	Sherlock et al. (2003)	?
		Proterozoic	Middle Proterozoic	1095±10	Paleomagnetism ²	Symons et al. (2000)	Rifting
Gays River	Early Mississippi (Late Tournaisian-Early Visean)	Pennsylvanian-Permian		297±27	Ar-Ar on biotite ³	Kontak et al. (1994)	Alleghenian
		Pennsylvanian		303±17	Paleomagnetism	Pan et al. (1993)	Alleghenian
Daniel's Harbour	Early Ordovician	Middle Devonian	Givetian	374±10	Paleomagnetism ⁴	Pan and Symons (1993)	Acadian
		Late Devonian-Early Mississippian	Famennian	360±10	Ar-Ar on authigenic feldspar	Hall et al. (1989)	Acadian
Monarch-Kicking Horse	Middle Cambrian	Late Cretaceous		100±12	Paleomagnetism	Symons et al. (1998)	Laramide ⁵
Pine Point	Middle Devonian (Late Eifelian-Late Givetian)	Late Devonian-Early Carboniferous		361±13	Sphalerite Rb-Sr ⁶	Nakai et al. (1993)	Antler
		Late Devonian-Early Carboniferous		374±21	Rb-Sr isochron	Brannon et al. (1995)	Antler
		Late Devonian-Early Carboniferous		362±9	Rb-Sr isochron on sphalerite + leachate	Nakai et al. (1993)	Antler
		Late Cretaceous-Paleocene		71±13	Paleomagnetism ⁷	Symons et al. (1993)	Laramide
Robb Lake	Late Silurian - Middle Devonian	Paleogene/Eocene	Lutetian	47±10	Paleomagnetism ⁸	Smethurst et al. (1999)	Laramide
		Paleozoic		No good isochron; but similar to Pine Point at 360	Sphalerite Rb-Sr ⁹	Nelson et al. (2002)	Antler
Upton	Early Ordovician	Middle to Late Ordovician			Sr-Sr on barite	Paradis and Lavoie (1996)	Taconian

¹ Ar-Ar on adularia was done on a 3 m-wide selvage of the diabase dyke referred to as the Mine dyke; Sherlock et al. (2003) argued that this alteration resulted from the hydrothermal system that emplaced the sulphides and that the Mine dyke (723 Ma) was emplaced before mineralization and therefore gives a maximum age on mineralization. Other geological evidence for this age include 1) sulphides emplaced post-tilting and folding of host strata; 2) sulphides show no displacement across Keystone fault; 3) fault displaced the host stratigraphy by ~150 m, and diabase dyke by 60 m, and 4) Rb-Sr dates on sphalerite similar to Ar-Ar on adularia (Sherlock, pers. comm., 2004).

² A paleomagnetic study of the dolostone around the Nanisivik Mine yielded an age of 1095±10 Ma (Symons et al., 2000). This age is interpreted to be coeval with the hydrothermal system that formed the sulphide deposit. Symons et al. (2000) argued that the Mine dyke gives a minimum age of mineralization because the main sulphide lens is bisected by the mine dyke.

³ Ar-Ar date is from biotite-muscovite alteration on the surface of breccia clasts under an encrustation of galena cement. This age overlaps the paleomagnetism age of 303±17 Ma (Pan et al., 1993). Other methods have been used to date material from the underlying footwall greywackes of the Meguma Group, which provide indirect evidence. Ravenhurst et al. (1987) obtained a maximum age of ≤330 Ma from a reset Ar-Ar spectrum on muscovite and a minimum age of ≥189±15 Ma from apatite fission tracks. Ravenhurst et al. (1987; 1989) obtained maximum ages between 308±37 and 342±33 Ma based on zircon fission tracks and a maximum age of ≤352±7 Ma based on K-Ar illite dating. Arne et al. (1990) reported a minimum age of 203 to 241±10 Ma from apatite fission track dates of post-ore cooling.

⁴ Paleomagnetic data indicate that the sphalerite ore acquired its characteristic remanent magnetization during ore genesis and its Early Ordovician carbonate host rocks were remagnetized in the same thermochemical event. Nakai et al. (1993) determined a poor Rb-Sr sphalerite isochron age of 375±75 Ma. Ar-Ar spectra analyses on potassium feldspars from the mine and other showings define thermochemical events at 360±10 Ma and at 210 Ma (Hall et al., 1989). Geological evidence listed by Lane (1990) suggested that ore genesis corresponded to the Acadian Orogeny at ~374±14 Ma.

⁵ Westervelt (1979), Nesbitt and Muehlenbachs (1991, 1994, 1995), and Yao and Demicco (1995) consider that dolomitization and mineralization predate the Late Jurassic initiation of the Laramide Orogeny because the strata appear folded. Nesbitt and Muehlenbachs (1991; 1994; 1995) obtained a late Paleozoic isotopic signature for MVT mineralization, which led them to support a Late Devonian to Carboniferous fluid flow event during the Antler Orogeny.

⁶ Rb-Sr sphalerite isochron gives Middle Devonian ages of 361±13 Ma (Nakai et al., 1993) and 374±21 Ma (Brannon et al., 1995). Combined sphalerite and fluid inclusion analyses form a well defined isochron with an age of 362±9 Ma (Nakai et al., 1993).

⁷ Paleomagnetism indicates that the deposits formed between the mid-Late Cretaceous and Paleocene (71±13 Ma, Symons et al., 1993). Arne (1991) found a maximum age of ~98 Ma and Ravenhurst et al. (1989) an age of ~50-60 Ma for ore formation from apatite fission tracks.

⁸ The Eocene paleomagnetism age of 47±10 (Smethurst et al., 1999) corresponds to the waning stages of the Laramide Orogeny and post-dates the main Laramide thrust-related deformation (i.e. ~185-60 Ma).

⁹ The combined sphalerite and fluid inclusion analyses do not form a single isochron with a well defined age on a Rb-Sr diagram. A Model 3 age calculation using Rb-Sr data for the sphalerite residues alone gives an apparent age of 348±130 Ma. A Model 3 age calculation using sphalerites and fluid inclusions gives an apparent age of 312±67 Ma. Three of the Robb Lake sphalerite residues fall on the Pine Point isochron. The calculated apparent age for these three samples is 350±100 Ma (Model 3 calculation). Although showing considerable scatter, the Rb-Sr data are permissive of a Paleozoic age for Robb Lake mineralization (Nelson et al., 2002).

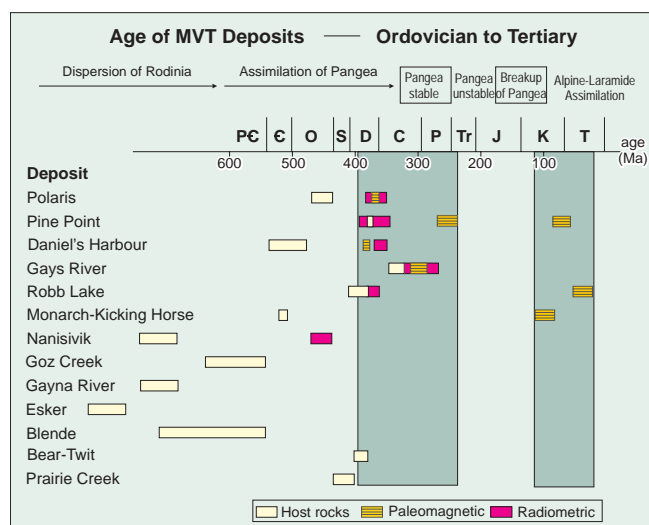


FIGURE 12. Distribution of radiometric and paleomagnetic ages of Canadian MVT deposits and their host rocks (modified from Leach et al., 2001a). The darker green shading indicates the two most important geo-logic periods for MVT genesis.

strike length of 1 km around and well below the orebody at Polaris (Randell and Anderson, 1996).

At Pine Point, calcite flooding forms halos around the orebodies, giving a coarsely granular appearance to the carbonate host rocks (Hannigan, 2007). Iron, Zn, and Pb display pronounced concentric distribution patterns in the Pine Point and Sulphur Point formations. Iron is the most widely distributed element, Zn is intermediate, and Pb occurs near the centre of the orebodies (Hannigan, 2007). These anomalous patterns decrease gradationally from maximum density and high-grade prismatic cores to barren country rocks. They are widespread in the Pine Point and Sulphur Point formations, negligible in Watt Mountain Formation, and confined to major solution collapse features in the Slave Point Formation (Turner et al., 2002). Iron dispersion highs tend to be displaced north of the deposit (Hannigan, 2007).

Silicification is not widespread in the Canadian MVT deposits, but when present, it forms small discontinuous zones of microcrystalline quartz peripheral to or enveloping the sulphides (e.g. Robb Lake, Esker, Prairie Creek, Goz Creek). Silicification is characteristic of the Tri-State district in the south-central US (Brockie et al., 1968; Sangster, 1995), and the northern Arkansas district (McKnight, 1935; Leach and Sangster, 1993), where it occurs as microcrystalline quartz that forms halos around or mantles the sulphide zones. According to Leach et al. (2001b), ore-related silicification of carbonate host rocks limits the buffering capacity of the rocks near the deposits and therefore influences the extent of metal-bearing water dispersion in some districts.

Formation of authigenic clay and feldspar minerals, as well as alteration of organic matter, is recognized at Polaris (Héroux et al., 1999), Jubilee, and Gays River (Héroux et al., 1996; Bertrand et al., 1998; Chagnon et al., 1998). Alteration of the organic matter and clays at Polaris, Pine Point, Gays River, and Jubilee forms halos of variable sizes around the deposits. The size and intensity of the alteration aureoles correlate with the temperatures of the ore formation and/or with the volume of ore-fluids responsible for ore deposition.

These anomalies can be useful exploration tools when integrated with geological data (Héroux et al., 1996; Randell et al., 1996; Sass-Gustkiewicz and Kwiecinska, 1999).

Geology – Continental, District, and Deposit Scale

Continental Scale

MVT deposits are found in shallow water carbonate rocks of platformal settings. Most are found in orogenic forelands where platformal carbonates have some hydrological connection to orogenic belts. A few, however, are found in, or are adjacent to, extensional environments, and fewer still are contained within intracratonic basins (i.e. basins lying entirely within and bounded by a craton). The orogenic foreland-type deposits occur in platform carbonate sequences of an orogenic forebulge, and in foreland thrust belts. MVT deposits of the Pine Point, Ozark, and central Tennessee districts are good examples of deposits in relatively undeformed carbonate sequences of orogenic forelands. Those of the Appalachians, Rocky Mountains MVT belt, and Cornwallis fold belt are examples of deposits in foreland thrust belts. Other deposits, such as those of the Nanisivik, Gays River, Lennard Shelf (Australia), and Alpine (Europe) districts, occur in or adjacent to rift zones. Deposits such as those of the Upper Mississippi Valley district in the US occur in intracratonic basins where numerous small orebodies occur in vertical veins, fractures, and faults along a broad north-west-trending and -plunging half-dome of the Wisconsin arch (Heyl, 1983; Arnold et al., 1996). In the Mackenzie Mountains of northwestern Canada, hundreds of small Zn-Pb showings occur as veins, breccias, and vugs in dolostone or limestone. These are grouped within the Gayna River, Goz Creek, Bear Twit, and Blende deposits.

Many of the MVT deposits of the world possibly formed during large contractional tectonic events at specific times in the Earth's history (Leach et al., 2001a). The most important periods for MVT genesis were during the Devonian-Permian and the Cretaceous-Tertiary (Fig. 12). The Devonian to Permian period saw a series of continental collisions that culminated in the formation of the supercontinent Pangea (Leach et al., 2001a). Over 70% of the total MVT Zn-Pb metals produced so far worldwide were formed at that time. Deposits such as Daniel's Harbour, Polaris, and those of the Lennard Shelf district in Australia are Devonian-Mississippian in age. The Cretaceous-Tertiary period saw the breakup of Pangea, punctuated by the Alpine and Laramide orogenies affecting the western margin of North America and Africa-Eurasia (Leach et al., 2001a). Deposits such as Robb Lake, Pine Point, and Monarch-Kicking Horse in North America may have formed during the Laramide Orogeny in Cretaceous-Tertiary time or during the Devonian-Mississippian Antler Orogeny. The controversy regarding the age of these deposits resides in the disagreement between the paleomagnetic and Rb-Sr dating methods (Table 1). Paleomagnetism at Monarch-Kicking Horse, Robb Lake, and Pine Point indicates that the sulphide mineralization formed between 47 ± 10 and 100 ± 12 Ma (Symons et al., 1993; 1998; Smethurst et al., 1999), whereas radiometric dating by Rb-Sr sphalerite isochron yields Late Devonian-Early Mississippian ages for Pine Point (Nakai et al., 1993; Brannon et al., 1995). Rb-Sr data on sphalerite from the

Robb Lake deposit, although showing considerable scatter due to heterogeneous $^{87}\text{Sr}/^{86}\text{Sr}$ values in primary fluids, suggest that the mineralization is also of Paleozoic age (Nelson et al., 2002). Radiometric dating has not been done at Monarch-Kicking Horse. The Silesian deposits in Poland are believed to have formed during the Outer Carpathian orogeny in the Tertiary period (Symons et al., 1995). Paleomagnetic, U-Pb, Th-Pb, and Sm-Nd dating of deposits in the Cévennes region of France yielded Early to Middle Eocene ages that correspond to the uplift of the Pyrenees during the closing stages of the Pyrenean orogeny (Rouvier et al., 1995; Lewchuk et al., 1998a; Lewchuk et al., 1998b; Lewchuk et al., 1998c; Henry et al., 2001; Leach et al., 2001a; Rouvier et al., 2001). Furthermore, preliminary paleomagnetic results from the Reocin deposit in Spain are consistent with a Tertiary age for mineralization (Lewchuk et al., 1998b; 1998c).

Criteria Indicating Good Potential for MVT Deposits

- 1) *Tectonic setting*: Deposits are hosted in platform carbonate successions developed on the flanks of sedimentary basins; most are found in orogenic foreland thrust belts, few are found in, or adjacent to, extensional environments, and fewer in intracratonic basins.
- 2) *Tectonic events and ages*: Deposits formed mainly during large contractional tectonic events at specific times in the history of the Earth, i.e. Devonian-Permian and Cretaceous-Tertiary; a few known deposits are associated with extensional tectonic events that occurred during the Ordovician (e.g. Nanisivik deposit) and Late Devonian-Early Mississippian (e.g. Lennard Shelf deposits in Australia).
- 3) *Coeval SEDEX deposits* may be present in adjacent continental rift basins. There is a geographic and temporal linkage between Phanerozoic MVT and SEDEX deposits, particularly in western Canada (Goodfellow et al., 1993; Nelson et al., 2002).

Knowledge Gaps

Given the great diversity of geological features and ore-forming processes for MVT deposits, the most significant obstacle in our understanding of MVT genesis has been the lack of information on the age of many MVT deposits in the world. Once the ages are known, formation of MVT deposits can be connected to large-scale tectonic events.

District Scale

MVT deposits characteristically occur in districts that cover hundreds of square kilometres, such as the Pine Point district (>1600 km²), Tri-State district (~1800 km²), southeast Missouri district (~2300 km²), Upper Mississippi Valley district (~10,000 km²) and east Alpine district (~10,000 km²). Within each district, deposits display similar geological features, such as mineralogy, textures, isotope signatures, and tectonic controls, but these characteristics change from district to district. This led Ohle (1959) to suggest that mineralization must be related to regional-scale events rather than to local and isolated events.

At the district scale, MVT deposits principally occur in dolostone (rarely in limestone or sandstone) of platform car-

bonate sequences, often below major unconformities. Ore controls such as barrier reef complexes, breccias, paleokarsts, depositional margins near carbonate/shale edges, facies tracts, faults, and basement highs, are typically district-specific (see Leach and Sangster, 1993, for further information).

Criteria Indicating Good Potential for MVT Deposits

- 1) *Tectonic setting*: The presence of platform carbonate sequences that commonly overlie deformed and metamorphosed continental crustal rocks, and have some hydrologic connection to sedimentary basins affected by orogenic events. Deposits usually occur in platform carbonates at shallow depths on flanks of sedimentary basins.
- 2) *District controls*: The deposits are localized by geologic features that permit upward migration of fluids, such as faults and basement highs. Other structures such as barrier reef complexes, breccias, paleokarsts, depositional margins near carbonate/shale edges, and facies tracts could also be important in trapping mineralized fluids.
- 3) *Paleolatitude*: Appropriate paleoclimatic conditions that lead to the formation and preservation of carbonate platforms and evaporites.
- 4) *Geophysical signature*: Induced polarization (IP) methods have proved successful in discovering orebodies in some MVT districts (e.g. Pine Point, Polaris), but only if sufficient conductive minerals such as galena, pyrite, and marcasite were present, and the chargeability of the host carbonates was low. Ground electromagnetic (EM) methods may work for deposits with sufficient concentrations of iron sulphide minerals (e.g. Nanisivik). Seismic, magnetic, and gravity methods can be used to identify some geological features associated with MVT deposits, such as basement highs beneath sedimentary successions, faults, sinkholes, paleokarsts and carbonate/shale facies. Airborne magnetic surveys were successfully used in delineating lineaments and buried Precambrian topography in the southeast Missouri district (Leach et al., 1995). Since sphalerite and gangue minerals have different densities, gravity surveys could prove useful in exploring for sulphide bodies containing mainly sphalerite (e.g. Daniel's Harbour). In the Cornwallis district, for example, the Polaris deposit was drilled based on a 2.2 milligal residual gravity anomaly over the deposit (Dewing et al., 2007). Airborne hyperspectral surveys also located numerous showings in the Cornwallis district.
- 5) *Geochemical anomalies*: Zinc, lead, iron, silver, and manganese can be detected in residual soil samples and stream sediments. Alteration of clay minerals and organic matter are useful exploration tools when integrated with geological data.

Knowledge Gaps

District scale questions that address key knowledge gaps relating to MVT deposits are listed below.

- Why are MVT deposits mostly associated with dolostone rather than limestone? Is it due to evidence that many dolomites are formed in evaporitic environments

and thus provide sulphates that can be reduced to sulphides? Or is it simply a physical relationship where dolomites having greater porosity provide an increased probability of deposition of open-space filling ore minerals?

- Are evaporites critical for the generation of metalliferous fluids?
- What is the contribution of organic matter to MVT ore deposition? Are hydrocarbons critical for mineralization to occur?
- What causes metal zoning in some MVT districts, as well as in individual sulphide bodies?
- What type of ground preparation process is needed for sulphide deposition, and also what governs the location of orebodies in a district?
- What function do regional tectonic processes, such as orogenies, plate-margin interactions, or eustasy, have in the mineralization process?
- How do the local and regional hydrology and paleohydrology relate to dolomitization as well as mineralization? What flow paths are involved and what is the duration of their operation?
- What is the regional extent of dolomitizing and mineralizing fluids and what pathways did they take?
- What were the interactions between fluids and rocks through which they flowed that led to sulphide localization?

Deposit Scale

MVT deposits typically occur in carbonate rocks associated with interconnected paleokarst networks, pre-existing solution collapse-breccias, and related carbonate dissolution features that are located beneath impermeable rock formation barriers such as shales, finely crystalline dolostones, and unconformities, and along faults and fracture zones. Thick porous beds and areas of fractured rocks are required to form mineable thicknesses of sulphides, so at the deposit scale, the ore-controlling structures are commonly zones of solution collapse-breccias. In some instances (e.g. Pine Point), these zones form linear solution channels (called karsts) at the base of a reef and barrier complex (e.g. the Presqu'île dolomite). They have remarkable continuity along the strike of the barrier and they form tabular orebodies. At intervals along these tabular solution channels, more intensive karstification produces either chimney-like karsts, called prismatic structures, or broader, more anastomosing areas of thicker tabular karsts (see Rhodes et al., 1984). These areas of enhanced solution activity, which are often associated with structural highs, frequently host orebodies. They are also loci for regional faults (extensional or strike-slip systems) that act as conduits for hydrothermal fluids. Major basement faults influence the alignment of orebodies within districts, however minor subsidiary faults, which may be splays off major faults, seem to be most efficient with respect to ground preparation by creating zones of weakness through which dolomitizing and mineralizing solutions can move freely. Porosity in these zones of weakness is enhanced by dolomitization and karsting.

Criteria Indicating Good Potential for MVT Deposits

1. *Local tectonic setting*: The presence of platform carbonate rocks.
2. *Deposit controls*: Barrier reef complexes, paleokarsts, solution-collapse breccias, faults, or fractures, and impermeable rock formation barriers, such as shales overlying porous carbonate rocks, are important ore-controls.
3. *Structures*: Identification of collapse depressions above hydrothermal breccia systems localized in dilatational fault arrays. Optimum fracturing, dilatational space creation, and mineralization may occur where these faults crosscut and intersect carbonates in outer shelf/platform settings. Localization of the hydrofracture system may be controlled by, or require the presence of, an overlying seal (e.g. shale) above the host carbonate; this maintains a "confined" pressure system in the underlying carbonate host (Davies, 1996).
4. *Sulphides*: Disseminated sulphides in the carbonate rocks may indicate proximity to sulphide deposits.
5. *Hydrothermal alteration*: Extensive hydrothermal dolomitization of precursor carbonate rocks is common and mostly appears as cement in sulphide-bearing breccias; this hydrothermal dolomite consists of coarse-grained white sparry dolomite and saddle dolomite. Silicification is also locally present, but is not as extensive as dolomitization. The alteration of clay minerals and organic matter is recognized in some deposits. Calcite flooding forms halos around orebodies.
6. *Geochemical anomalies*: Bitumen and pyrobitumen often occur in carbonate successions hosting MVT deposits and within the sulphide mineralization (e.g. Pine Point, Polaris, Robb Lake). Soft sticky bitumen masses, heavy oil, and pyrobitumen are present locally in the Pine Point district. Many levels of the Presqu'île barrier complex show an impregnation by heavy oil and bitumen where small pores are filled by droplets (Krebs and Macqueen, 1984). Near some orebodies, these liquid hydrocarbons have been altered to pyrobitumen, forming irregular concentrations in large vugs and glossy globules as well as thin coatings on carbonate crystals (Krebs and Macqueen, 1984). The mineral paragenesis suggests that bitumen was deposited during the ore-stage event at Pine Point. At Polaris, dating of pyrobitumen by Re-Os gives 368 ± 15 Ma, indicating that it is part of the mineralizing event (Selby et al., 2005).

Distribution of Canadian MVT Districts

Geological Distribution

For the purpose of this synthesis, a metallogenic district is defined as a continuous area that contains the expressions of the geological environment and tectonic events that controlled the formation of MVT deposits. In Canada, several MVT districts were identified. Most of these districts consist of several deposits, which comprise one to more than 100 sulphide bodies. For example, the Gayna River district contains more than 100 sulphide occurrences, and the Cornwallis district in Nunavut hosts one ore deposit, the Polaris mine, and approximately 80 showings (Dewing et al., 2007).

The Canadian deposits show a strong concentration along an arcuate circum-continental trend (Fig. 2). This trend is due to the fact that, by definition, MVT deposits are hosted in platform carbonate rocks, which are located around the periphery of the craton. The largest number of deposits is located in the Mackenzie Mountains of the Yukon and the Northwest Territories, where hundreds of small deposits and a few larger ones (Gayna River, Blende, Bear Twit, Goz Creek, and Prairie Creek; Appendix 1) occur in Proterozoic to Devonian dolostone and limestone. Further south, a linear series of MVT deposits occurs in Cambrian and Silurian-Devonian carbonate rocks of the Canadian Rocky Mountains within the Robb Lake and Monarch-Kicking Horse districts.

Most Canadian deposits are found in deformed carbonate rocks of foreland thrust belts. Districts such as Gayna River, Blende, Goz Creek, Bear Twit, Robb Lake, and Monarch-Kicking Horse are hosted in deformed and thrust-faulted carbonates adjacent to the shelf front in the northern and southern Canadian Cordillera. Only deposits of the Pine Point district occur in weakly deformed carbonate rocks of the orogenic forelands. Daniel's Harbour, Gays River, and Upton in eastern Canada are hosted in deformed carbonate rocks of the Appalachian foreland thrust belts. Nanisivik in northern Canada formed in an extensional environment associated with east-west trending normal faults that divided the area into a series of horsts and grabens (Sherlock et al., 2003).

Temporal Distribution

Canadian MVT deposits are found in rocks ranging in age from Early Proterozoic to Early Mississippian with the majority of deposits in rocks of Paleozoic age (Fig. 12). The absolute age of mineralization is not known for all Canadian deposits. Table 1 summarizes the ages for some deposits. Deposits such as Nanisivik, Pine Point and Robb Lake show contrasting results between radiometric and paleomagnetic methods; reasons for the discrepancy are unclear. Radiometric and paleomagnetic data show that mineralization is Paleozoic in age and coincides mainly with periods of orogenic uplift that occurred in regions adjacent to the respective deposits. These MVT deposits, and those of the Ozark district in the US, have been attributed to large-scale migration of fluids during convergent orogenic processes (Leach et al., 2001a). The association of mineralization with orogenic uplift in a convergent regime supports the topographically-driven fluid flow model of ore fluid migration in compressive tectonic regimes (see below). Only one Canadian deposit so far, Nanisivik, is not associated with a contractional tectonic event but is attributed to mid-Ordovician extensional tectonism (Sherlock et al., 2003).

Genetic and Exploration Models

Conventional Models for Fluid Transport

Recent advances in understanding large-scale fluid flow in the crust, coupled with new geochemical and geological studies of MVT districts, have established that most MVT mineral districts are the products of regional or subcontinental-scale hydrological processes. Deposits formed from warm, saline, aqueous solutions (similar to oil-field brines) that migrated out of sedimentary basins, through aquifers, to the basin periphery and into the platform carbonate

sequences. To affect this movement of sulphide-bearing brines, at least three different fluid flow processes have been proposed.

1. The topographic or gravity-driven fluid flow model (Garven and Freeze, 1984; Garven, 1985; Bethke and Marshak, 1990; Garven and Raffensperger, 1997).
2. The sedimentary-diagenetic model (Jackson and Beales, 1967; Sharp, 1978; Cathles and Smith, 1983; Oliver, 1986).
3. The hydrothermal convection model (Morrow, 1998).

The first model involves flushing of subsurface brines out of a sedimentary basin by groundwater flow from recharge areas in elevated regions of a foreland basin to discharge areas in lower elevated regions (Garven and Freeze, 1984; Garven, 1985; Bethke and Marshak, 1990; Garven and Raffensperger, 1997). In this model, subsurface flow is driven away from an uplifted orogen by the hydraulic head produced by tectonic uplift and tends to be concentrated in permeable units of a foreland succession. Considerable geologic evidence listed by Leach and Sangster (1993) supports this model. The model has been proposed for several MVT districts in the world, particularly those of the US mid-continent and the Pine Point district. At Pine Point and the Western Canada sedimentary basin (WCSB), Garven (1985) carried out some hydrogeological simulations and demonstrated that Pine Point formed in less than a million years from circulation of groundwater (rich in Pb and Zn) eastward from the elevated thrust belt of the Laramide Orogen through the Middle Devonian carbonates of the Keg River barrier.

The second model considers that compaction of sediments in a subsiding basin drives a continuous outward flow of pore fluids laterally along aquifers (Jackson and Beales, 1967). The basin-derived fluids or brines acquire heat, metals, and other solutes during migration and deposit sulphides in the host carbonates at favourable sites and under favourable physico-chemical conditions. Maintaining high initial fluid temperatures during transport of up to hundreds of kilometres from basin source to platform depositional site could be a problem. A variation of this model, episodic outward flow, was therefore proposed by Cathes and Smith (1983) and Bethke (1985). Their model involves overpressuring of subsurface aquifers by rapid sedimentation, followed by rapid and episodic release of basinal fluids. Another variation of the second model involves tectonic loading and compression of sediments during the development of orogenic thrust belts, which may have caused the rapid expulsion of formational fluids outward into the foreland basins with the thrust belts behaving like giant squeegees (Oliver, 1986).

The third model involves deep convection circulation of hydrothermal brines due to buoyancy forces related to temperature and salinity variations (Morrow, 1998). This model supports long-lived flow systems that are capable of recycling subsurface solutions many times through the rock mass, and has been invoked to explain regional hydrothermal dolomitization in the Western Canada sedimentary basin (Morrow, 1998), the Manetoe facies of the Northwest Territories (Aulstead et al., 1988; Morrow et al., 1990), the Ordovician gas-producing carbonates of the Michigan Basin (Coniglio et al., 1994), and MVT deposits of the northern

Canadian Rocky Mountains (Nelson et al., 2002). In the latter, Nelson et al. (2002) speculated that mineralization and dolomitization in the WCSB occurred in a far-field back-arc continental rift in response to the Late Devonian-Early Mississippian Antler Orogeny.

Conventional Models for Deposition of Sulphides

Three models involving 1) mixing, 2) sulphate reduction, and 3) reduced sulphur have been proposed for the chemical transport and deposition of sulphides.

The mixing model proposes transport of base metals in fluids of low sulphur content. Mixing of the metal-rich brines with fluids containing hydrogen sulphides at the depositional site triggers sulphide precipitation (Beales and Jackson, 1966; Anderson, 1975; Anderson and Macqueen, 1982; Sverjensky, 1984; Adams et al., 2000). Mixing of the ore fluids with a dilute or cool fluid, or reactions with host rocks to change the pH, are other variants on mixing.

The sulphate reduction model involves transport of base metals and sulphate in the same solution. Precipitation occurs at depositional sites when sulphate is reduced upon reaction with organic matter or methane (Anderson, 1975; Beales, 1975).

The reduced sulphur model requires that the base metals and the reduced sulphur be transported together in the same solution. Precipitation occurs either through cooling, mixing with diluted fluids, changes in pH, or loss of volatiles (Anderson, 1975; Anderson and Macqueen, 1982; Sverjensky, 1984, 1986).

Advances in Genetic and Exploration Models of the Last Decade

In the past, MVT deposits were considered to have few connections to global tectonic processes. Remarkable advances in age dating of MVT deposits in the last 10 years has resulted in improved understanding of the origin of MVT deposits, their links to global Earth tectonic events, and deposit modeling. However, there is still a paucity of information on the ages of MVT formation, and in some cases paleomagnetic and radiometric age dates show contradictory results.

MVT deposits that have been dated successfully show a relationship to large-scale tectonic events. Most MVT deposits formed during contractional tectonic events associated with the assimilation of Pangea in the Devonian to Permian, or during microplate assimilation on the western margin of North America and Africa-Eurasia in the Cretaceous to Tertiary. Few deposits correspond to extensional tectonic events in the Ordovician and early Mississippian time (Leach et al., 2001a). The latter are rare and poorly understood relative to global tectonic events, and more research needs to be done on the subject. Many important questions remain regarding the genesis of MVT deposits; some of them are listed below.

Knowledge Gaps

The current knowledge gaps in our understanding of MVT deposits concern mainly the following domains: 1) the role of tectonic processes, 2) the age of MVT ore-forming events, and 3) the chemical processes.

Tectonic Processes

Leach et al. (2001a) and Bradley and Leach (2003) stressed the genetic links between MVT mineralization and regional- and global-scale tectonic processes. It is now clear that MVT deposits are products of enormous hydrothermal systems that left trace mineralization over a wide area, and that the nearly ubiquitous occurrence of MVT deposits on the flanks of cratonic sedimentary basins reflects focused migration of deep-basin brines into shelf-carbonate sequences. Thus, the regional hydrogeologic framework is of paramount importance in the evaluation of large areas for their potential to contain MVT deposits.

MVT deposits in North America have been attributed to large-scale migration of fluids mainly during convergent orogenic processes. The topographically-driven fluid flow model associated with ore-fluid migration in compressive tectonic regimes best describes MVT mineralization in North America. Other deposits, such as Nanisivik and those of the Lennard Shelf and Alpine districts, have been attributed to continental extension and may require other fluid-driving mechanisms (Leach and Sangster, 1993).

Other questions that address key knowledge gaps also become important in understanding formation of MVT deposits, and could indirectly guide exploration for undiscovered MVT deposits. They are summarized below:

- What is the role of continental extension in the genesis of MVT deposits?
- What are the ages for ore formation in extensional regimes? The new ages will provide information on MVT genesis in the context of global crustal tectonic models and fluid migration.
- Why do MVT deposits form in some, but not all, carbonate platforms in collisional forelands? Certain carbonate platforms are fertile for MVT deposits while others are barren.
- What is it about the late stage of some collisions that induces regional-scale fluid migrations?
- Why are MVT deposits mostly associated with dolostones rather than limestones? Is it due to evidence that many dolomites are formed in evaporitic environments and thus provide sulphates that can be reduced to sulphides? Or is it simply a physical relationship where dolomites having greater porosity provide an increased probability of deposition of open-space filling sulphide minerals?
- What type of ground-preparation process is needed for sulphide deposition and also what governs the location of orebodies in a district?
- What function do regional tectonic processes such as orogenies, plate-margin interactions or eustasy have in the mineralization process?
- How do the local and regional hydrology and paleohydrology relate to dolomitization as well as mineralization? What flow paths are involved and what is the duration of their operation?
- What controls the hydrology of basins and carbonate platforms? Is it related to the distribution of fractures and

faults in the basement rocks and overlying sediments?
Do some faults serve to recharge or discharge fluids?

Age of Mississippi Valley-Type Ore-Forming Events

The need to know the absolute age of MVT mineralization remains one of the most critical aspects of research on MVT deposits, and an obstacle to our understanding of MVT genesis. Recent advances in age dating of MVT deposits provide new evidence that there are important genetic relationships between convergent and divergent orogenic events and the formation of MVT deposits (Leach et al., 2001a). The most important periods for MVT genesis are the Devonian-Permian and the Cretaceous-Tertiary when large-scale contractional tectonic events occurred. Other deposits such as Nanisivik and those of the Lennard Shelf district are associated with extensional events in the Ordovician and Early Mississippian, respectively. These may prove to be more abundant, but so far little is known about the role of continental extension and the formation of MVT deposits. There is a paucity of MVT deposits of Precambrian, Early Paleozoic, and Mesozoic ages despite abundant host rocks and seemingly suitable tectonic settings.

Even if important advances in dating have been achieved in the last decade, much still remains to be done, as many deposits and districts have not been successfully dated and there are still many questions to be answered:

- Why are there few known Proterozoic MVT deposits when there is an abundance of SEDEX deposits in Proterozoic time (Goodfellow et al., 1993)?
- What are the temporal and genetic links between MVT and SEDEX deposits? Is there a genetic/temporal link? If yes, could they have formed from the same hydrothermal system?
- What are the temporal and genetic links between MVT and oil/gas deposits?
- What is the age of deposits for which there is controversy regarding timing (e.g. Robb Lake, Pine Point, East Tennessee, Cévennes) due to conflicting results between paleomagnetic and radiometric dating techniques?

Chemical Processes

Chemical processes that localized the deposition of sulphides are critical to the development of models for MVT deposits, yet the specific chemical reactions that led to sulphide deposition remain one of the most controversial aspects of MVT deposits. Several questions remain as to:

- Why do these deposits contain mostly lead and zinc in economic quantities?
- What causes metal zoning in some MVT districts as well as in individual deposits?
- What is the contribution of organic matter to MVT sulphide deposition? Are hydrocarbons critical for mineralization to occur?
- What controls the chemical composition of sulphide-forming fluids? What are the chemical attributes of hydrothermal reaction zones that generate sulphide-forming fluids?
- What alteration vectors are most effective in exploring for MVT deposits?

Key Exploration Criteria For Canadian MVT Deposits

The major exploration criteria for Canadian MVT deposits are summarized below:

- *Geologic settings:* Platform carbonate rocks peripheral to cratonic sedimentary basins. Deposits are commonly located close to a carbonate shelf margin, at the transition into slope and basinal shales or argillaceous facies.
- *Ages:* Carbonate host rocks that range from Middle Proterozoic to Carboniferous with a majority of deposits in the Mid to Late Paleozoic period.
- *District-scale controls:* The deposits are localized by geologic features that permit upward migration of fluids, such as faults and basement highs. There could be a strong regional fault control system on the localization and emplacement of MVT deposits. Optimum fracturing, dilational space creation, and mineralization may occur where faults intersect barren carbonate rocks in outer shelf/carbonate margin (reef margin) settings. Basement highs are zones where fluid flow is laterally restricted and thus represent possible depositional sites. Basement highs are also sites of reef growth, which are potential host rocks for MVT deposits.
- *Deposit-scale controls:* Proximity of growth faults and intersection of faults, regional and local dolomitization and possibly laterally equivalent iron-formations (as Irish-type). Identification of potential conduits, traps, and prospective stratigraphy provides a means of predicting the potential locations of undiscovered massive sulphide bodies.
- *Paleolatitude:* Appropriate paleoclimatic conditions that lead to the formation and preservation of carbonate platforms and evaporites.
- *Hydrothermal event:* Evidence of hydrothermal fluid discharge may include 1) disseminated sulphides in the carbonate host rocks peripheral to the deposits; 2) SEDEX deposits in sedimentary basins adjacent to the carbonate platform; 3) distal hydrothermal sediments, such as Mn-Fe-Ca-Mg carbonates; 4) stream sediment and water that are enriched in MVT-forming and -associated elements.

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