MISSISSIPPI VALLEY-TYPE LEAD-ZINC DEPOSITS (MVT)

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Definition

Simplified Definition

Mississippi Valley-type (MVT) deposits are epigenetic stratabound carbonate-hosted sulphide bodies composed predominantly of sphalerite and galena. These deposits account for approximately 25 percent of the world's lead and zinc resources. They are so-named because several classic MVT districts are located in carbonate rocks within the drainage basin of the Mississippi River in the central United States (US). Important Canadian districts include Pine Point, Cornwallis, Nanisivik, Newfoundland Zinc, Gays River, Monarch-Kicking Horse, and Robb Lake.

Scientific Definition

MVT deposits are stratabound, carbonate-hosted sulphide bodies, composed predominantly of zinc and lead, bound in sphalerite and galena. The deposits occur mainly in dolostone 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 rock.

MVT deposits originate from saline basinal metalliferous fluids at temperatures in the range of 75°-200°C. 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).

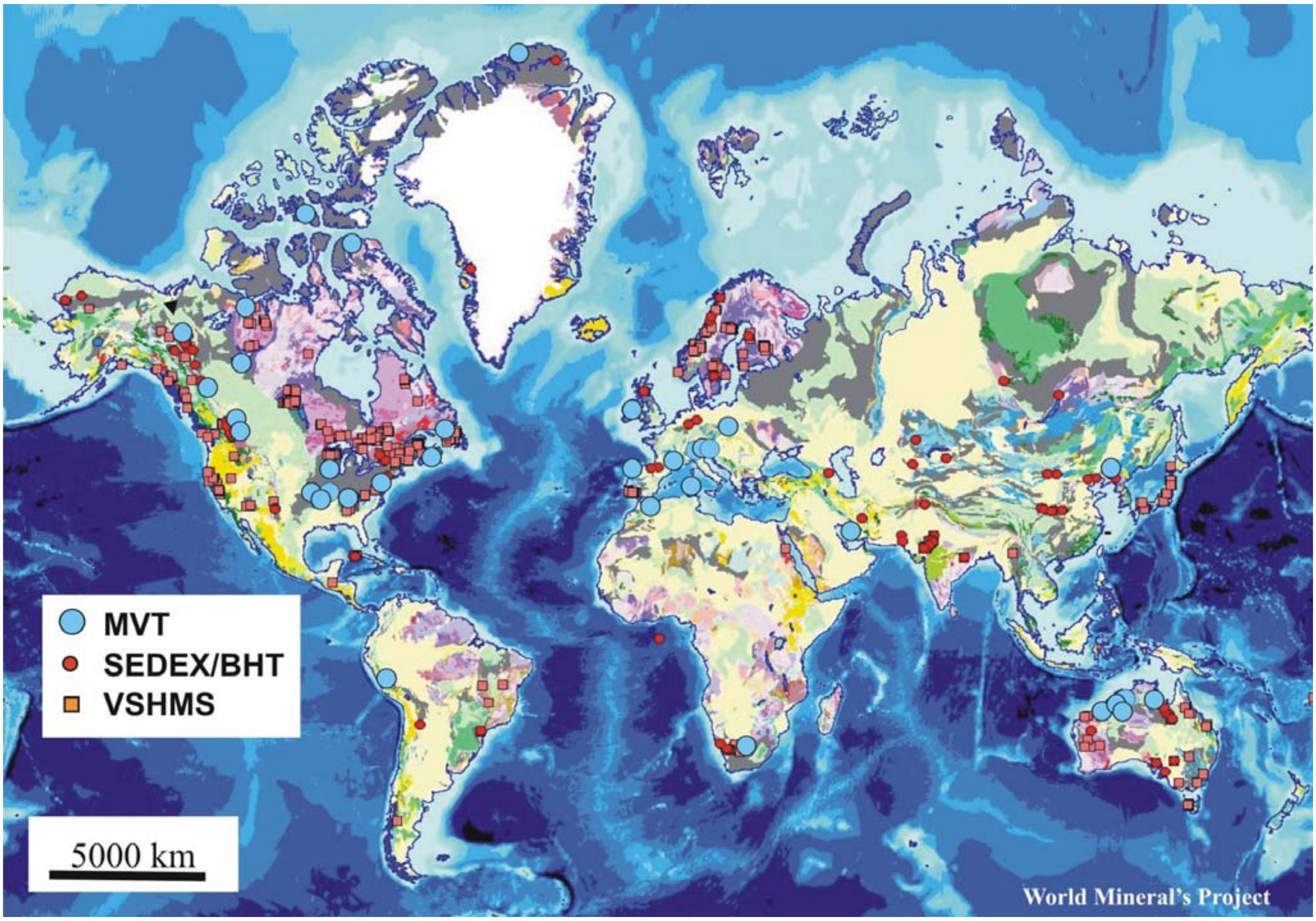

FIG. 1. Distribution of Mississippi Valley-type deposits and districts worldwide (from Sangster, 1990). Numbers on symbols are the deposit numbers of the World Mineral Deposits Database.

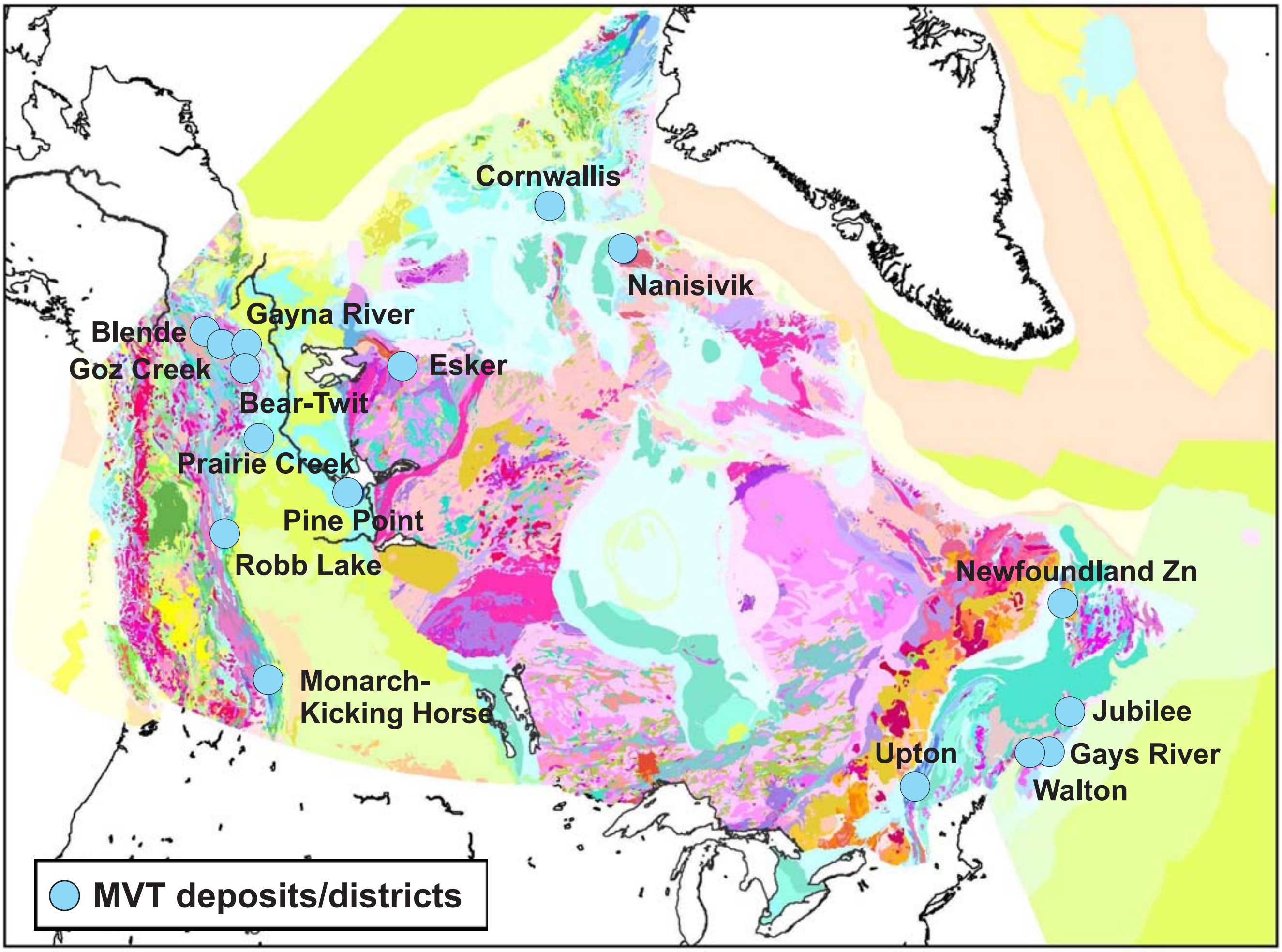

FIG. 2. Distribution of Mississippi Valley-type deposits/districts plotted on a simplified geological map of Canada (Map D1860A). Districts shown are, Cornwallis; Nanisivik, Pine Point, Prairie Creek, Robb Lake, Monarch-Kicking Horse, Blende, Bear-Twit, Gayna River, Goz Creek, Gays River, Jubilee, Walton, Newfoundland Zn, Upton, and Esker.

Individual ore bodies are generally <2 million tonnes, are zinc-dominant, and possess grades which rarely exceed 10% (Pb+Zn). They do, however, characteristically occur in clusters, referred to as "deposits" and "districts". For example, the Cornwallis district in Nunavut hosts at least 25 deposits and 75 ore bodies and the Pine Point district in the Northwest Territories hosts two deposits (Pine Point and Great Slave Reef) and more than 90 ore bodies. Other districts may contain a half-dozen to more than 300 ore bodies, which can contain up to several hundred million tonnes of ore scattered over hundreds to thousands of square kilometers (Sangster, 2002).

Mineral Deposit Subtypes

MVT deposit sub-types include those that are of high-temperature carbonate replacement Pb-Zn (±Fe, ±Ag) (Titley, 1996; Smith, 1996; Megaw et al., 1996) and the diapir-related deposits (Sheppard et al., 1996). The carbonate-hosted F-Ba deposits (Dunham, 1983; Rowan et al., 1996) and the sandstone-hosted lead deposits, and some "Irish-type" deposits (Hitzman and Beaty, 1996) are also included as "sub-types". The "Irish-type" deposits are stratabound, structurally controlled, carbonate-hosted, Pb-Zn deposits that have sedimentary exhalative (SEDEX) and/or MVT characteristics. The MVT-SEDEX relationship has been explored by Sangster (1990, 1993, 1995, 1998) with no firm conclusion save that a continuum does appear to exist between the two major deposit-types. Following the examples of Leach and Sangster (1993) and Sangster (2002) and in order to focus on typical MVT deposits, we exclude the above deposit-types, with the exception of the "Irish-type" deposits that have epigenetic features characteristic of MVT deposits (e.g., Navan, Lisheen, Courtbrown, etc.).

Associated Mineral Deposit Types

MVT deposits belong to a spectrum of "sediment-hosted base-metal deposits" that include SEDEX deposits, carbonate-hosted F-Ba deposits, sandstone-hosted Pb deposits, "Irish-type" Zn-Pb deposits, carbonate-hosted Cu-Pb-Zn deposits (or Kipushi type), carbonate-hosted manto-type Ag-Pb-Zn deposits, and Broken Hill-type Pb-Zn deposits.

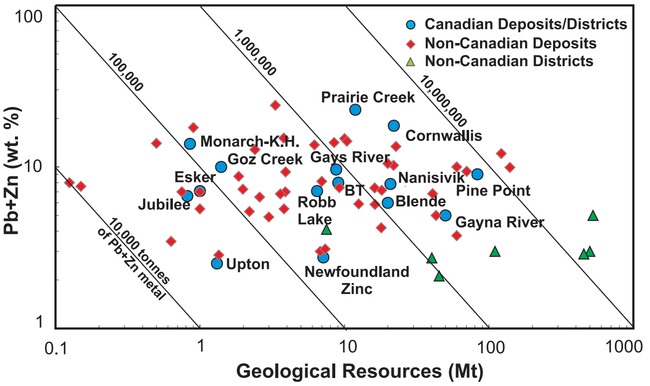

FIG. 3. Grade-tonnage for Canadian and worldwide MVT deposits/districts with geological resources. Diagonal lines represent total tonnage of contained lead and zinc (adapted from Sangster, 1990). Abbreviations: BT - Bear Twit, Monarch-K.H.- Monarch-Kicking Horse.

Economic Characteristics

Summary of Economic Characteristics

MVT deposits account for approximately 25 percent of the world's lead and zinc resources, and they are dispersed throughout the world (Fig. 1). 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. MVT deposits also occur in Canada, Europe (Poland, France, Ireland, Spain, Austria, Italy, former Yugoslavia), Australia, China, Peru, Morocco, and South Africa. In Canada, there are 16 districts (Fig. 2), each of which contains 2 to more than 100 deposits. The Pine Point district, for example, contains 2 deposits and more than 90 ore bodies distributed over 1,600 square kilometers.

MVT deposits contributed only negligibly to Canadian Zn and Pb production prior to the opening of the Pine Point deposit in 1964. Between 1964 and 2002, about 30% of the annual lead and zinc production was derived from MVT deposits (Sangster, 2002). With the closure of Pine Point in 1988, Newfoundland Zinc in 1990, and Polaris and Nanisivik in 2002, however, the proportion of Zn and Pb derived from MVT deposits in Canada dropped to nil.

At the present time (November 2003), there are no MVT mines in production in Canada.

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/districts were mined before accurate data were recorded; and the MVT deposits tend to occur in clusters and form districts, therefore the production and reserve data are usually presented as district totals, not for each individual deposit or ore body.

There are over 80 MVT deposits/districts (with grade and tonnage figures) worldwide (Fig. 1), sixteen of them in Canada (Fig. 2; Appendix 1). The best geological resource estimates for most individual Canadian deposits are 1 to 10 million tonnes with 4 to 10% combined Pb and Zn (Fig. 3); and the majority of these are Zn-rich relative to Pb (Fig. 4). The Polaris and Prairie Creek deposits are unusually large (22 and 12 million tonnes, respectively) and have anomalously high grades (17% and 22.6% Pb+Zn, respectively) (Appendix 1).

Most individual deposits worldwide yield less than 10 million tonnes of ore with combined Pb+Zn grades seldom exceeding 15%. The size of MVT districts is approximately an order of magnitude greater than the size of individual deposits with combined Pb+Zn grades between 2 and 6% (Fig. 3). The metal ratios in deposits/districts, expressed as Zn/(Zn+Pb) values (Fig. 4) show a weak bimodal distribution. The majority of deposits/districts have a Zn/(Zn+Pb) value around 0.85 with a smaller group around 0.45. The Canadian deposits/districts show a similar distribution compared to worldwide deposits. In his worldwide compilation of MVT deposits, Sangster (1990) shows a clear bimodal distribution with the majority of deposits around 0.8 and a smaller group at 0.05. The group at 0.05 corresponds to the deposits of the southeast Missouri district. Our data on the southeast Missouri district are incomplete and this explains the low value around 0.05. Figure 5 illustrates the similarity of Pb and Zn grades of the Canadian and worldwide deposits/districts. Most Canadian deposits have Zn grades between 3 and 8 wt.% and Pb grades between 0 and 5.2 wt.%.

Exploration Properties

Physical Properties

Nature of Sulphide Bodies

MVT deposits occur in clusters of a few to hundreds of individual ore bodies that vary in character and shape and are often interconnected (Fig. 6). Deposits and ore bodies 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). Ore-hosting structures are most commonly zones of highly brecciated dolomite; and in some instances (e.g., Pine Point, Robb Lake, and Newfoundland Zinc) these zones are arranged in linear patterns suggesting a tectonic control. 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 (Fig. 6). At Pine Point, the orebodies are either tabular or prismatic structures in interconnected pale-

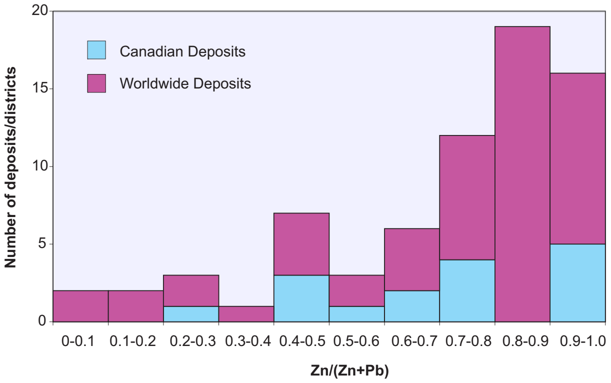

FIG. 4. Zn/(Zn+Pb) ratios in Canadian and worldwide MVT deposits/districts.

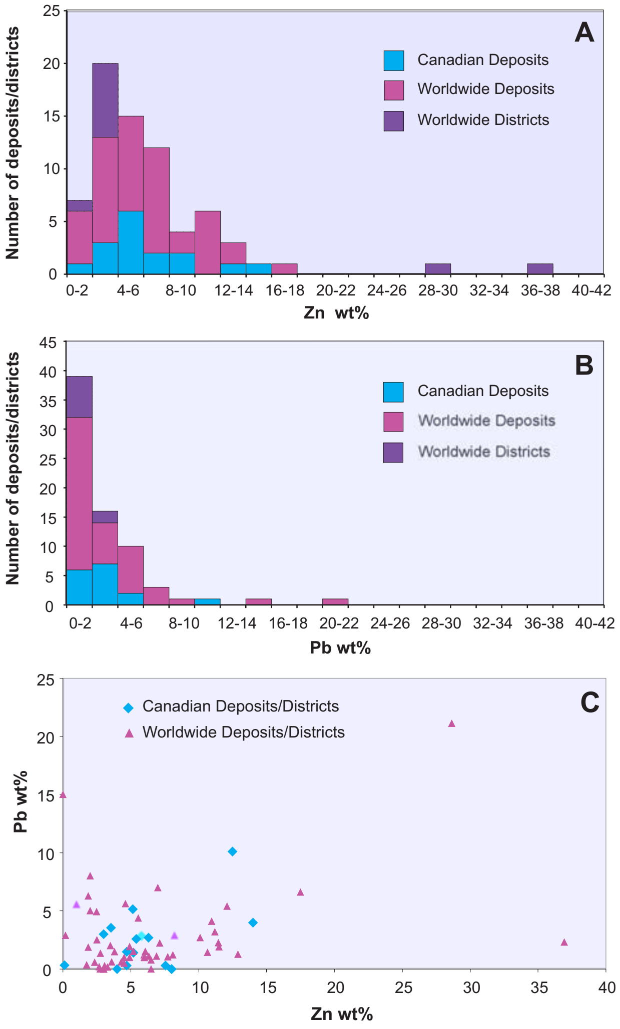

FIG. 5. A and B. Histograms comparing the lead and zinc grades of Canadian and worldwide deposits/districts. C. Pb wt.% versus Zn wt.% for MVT deposits/districts.

okarst networks. The karst networks are directly related to distinct facies and lithofacies features in the Presqu'ile Barrier Complex. The MVT ore bodies therefore, are discordant on the deposit scale, but stratabound on a district scale.

Dimensions

The dimensions of ore bodies can be difficult to measure because of their irregular and variable shape. At Pine Point, the L-36 ore body 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 ore body is 800 m in length, 400 m in width, and 20 to 30 m in thickness. 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 ore body had dimensions of 800 m in length, 300 m in width, and 150 m in thickness.

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 district host rocks are mostly fine-grained crystalline dolostone and local limestone. Gays River is an example of a deposit in early diagenetic dolostone without secondary sparry or saddle dolomite. In the East Tennessee, Alpine, and Newfoundland Zinc districts, the secondary dolomite is only locally developed, whereas at Jubilee in Nova Scotia, the deposit is exclusively hosted in limestone.

There is sufficient distinction of densities between sulphide and gangue minerals that make gravity surveys successful in geophysical exploration. The degree of porosity can vary significantly in the host-rocks, which may be detectable by gravity (Lajoie and Klein, 1979). Borehole geophysical surveys, such as sonic and density logs can differentiate between porous and non-porous horizons.

Mineralogy

MVT deposits have simple mineral assemblages that consist of sphalerite, galena, pyrite, and marcasite. Gangue minerals are dolomite, calcite, and quartz, and occasionally barite and fluorite. These are accessory minerals present in some but absent in most districts. Chalcopyrite, bornite, and other copper minerals are normally not constituents in MVT deposits and are only abundant in some deposits/districts, such as the Viburnum Trend of the Southeast Missouri district in the US and the Cornwallis district in Canada. Deposits of the Viburnum Trend have a unique and complex mineralogy that is not typical of most MVT deposits/districts 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 abundance of iron sulphides relative to other sulphide minerals in MVT deposits ranges from dominant to nil. Iron sulphide abundance may vary greatly from district to district and between deposits from the same district (Leach et al., 1995; St. Marie et al., 2001). For example, at Nanisivik, iron sulphides are abundant, whereas in some Appalachian deposits, only traces 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 IP proved to be successful for locating ore bodies. Sphalerite and gangue minerals have widely varying densities, so gravity surveys could prove useful in exploring for ore bodies containing mainly sphalerite. In the Cornwallis district and the "Irish-type" deposits, IP and geochemical surveys have been combined to discover ore bodies (Hallof, 1966).

Silver content in MVT deposits is low and often not reported. When reported, silver grades vary from 10 g/t to 161 g/t Ag. The Prairie Creek and Nanisivik deposits with

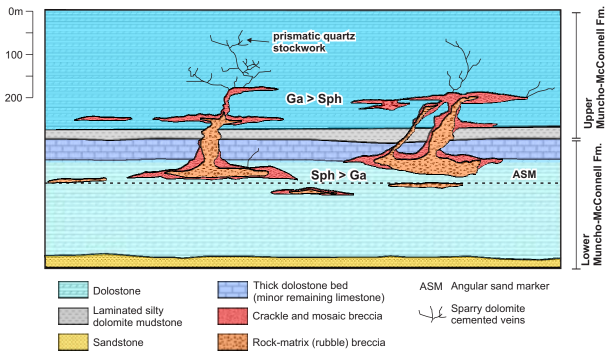

FIG. 6. Schematic representation of the Robb Lake breccia-hosted Zn-Pb ore, showing textural and mineralogical zoning and stratigraphic controls (from Paradis et al. 1999).

averages of 161 g/t and 34 g/t Ag, respectively, have the highest silver grades of MVT deposits in Canada.

Organic material, such as hydrocarbon (pyrobitumen) is common in some MVT deposits/districts (e.g., Cornwallis, Pine Point, Robb Lake, Jubilee, Walton) but is not present in significant amounts in others (e.g., Monarch-Kicking Horse, Gays River).

Most deposits/districts are zinc-rich relative to lead and have Zn/(Zn+Pb) ratios greater than 0.5 (Fig. 4). Some deposits, including many in the East Tennessee district and in the Newfoundland Zinc district are essentially free of lead and have Zn/(Zn+Pb) ratios close to 1.0.

Textures

Sulphide textures are mostly related to open-space filling of breccias, fractures, and vugs (Fig. 6). Replacement of carbonate host rocks and internal sediments, and sulphide disseminations are also observed (e.g., Polaris, Pine Point, Robb Lake deposits). The mineralized breccias are of several textural types: crackle, mosaic, rubble, and rock-matrix ("trash") breccias (Fig. 7A, 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, the sulphide and gangue mineral textures are varied (see Figs. 7 and 8). 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. 7A, B). Coarse sphalerite crystals occasionally coat the tops of fragments or line the bottoms of cavities forming a texture known as "snow on the roof" (Leach and Sangster, 1993; Sangster, 1995). Sphalerite also forms massive aggregates of coarse-grained colloform and botryoidal crystals (Figs. 7E, F, and 8A) and laminae of fine-grained crystals. Massive sulphides are found in replacement zones of the carbonate host rocks. At Nanisivik, replacement of the dolostone is the main mechanism of ore deposition. It 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 metre- to 30 metre thick, high grade Zn-Pb-Fe, tabular unit hosted in the upper part of the deposit. Elsewhere, the replacement is selective and follows stylolites, organic-rich layers, fossil-rich bands, and carbonate sand matrix. At Newfoundland Zinc, selective replacement of the bioturbated limestone by the hydrothermal dolomite produced a pseudobreccia (Lane, 1984). At Monarch-Kicking Horse, Pine Point, Robb Lake, and Pend Oreille deposits, selective replacement of a variety of primary rock fabrics by the hydrothermal dolomite formed a zebra texture (Fig. 9).

In terms of geophysical parameters, the open-space filling nature of the MVT ores makes it a poor conducting material for geophysical surveys. In most deposits, gangue minerals or sphalerite interrupts conducting paths between conductive minerals, thus poor EM and SP responses are generated (Lajoie and Klein, 1979).

Chemical Properties

Ore Chemistry

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, chalcopyrite, carrollite, celestite, chal-

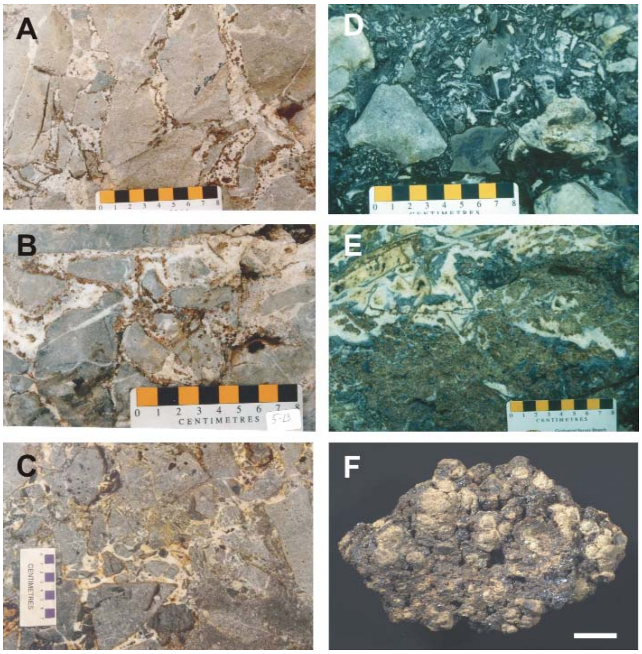

FIG. 7. A. Crackle breccia with disseminated sphalerite crystals in white dolomite cement, Robb Lake, BC. B. Mosaic breccia with sphalerite crystals in white dolomite cement, Robb Lake, BC. C. Rubble breccia consisting of variably altered dolostone fragments and shale fragments in white dolomite cement. Note the dolostone fragments with zebra texture, Robb Lake, BC. D. Rock-matrix breccia with dolostone, shale, and white sparry dolomite fragments in dark grey fragmental matrix, Robb Lake, BC. E. Aggregates of massive sphalerite crystals and white sparry dolomite along small fractures, Pine Point, NWT. F. Aggregates of colloform sphalerite and skeletal galena completely replacing the carbonate, Polaris, Nunavut; scale bar is 1 cm.

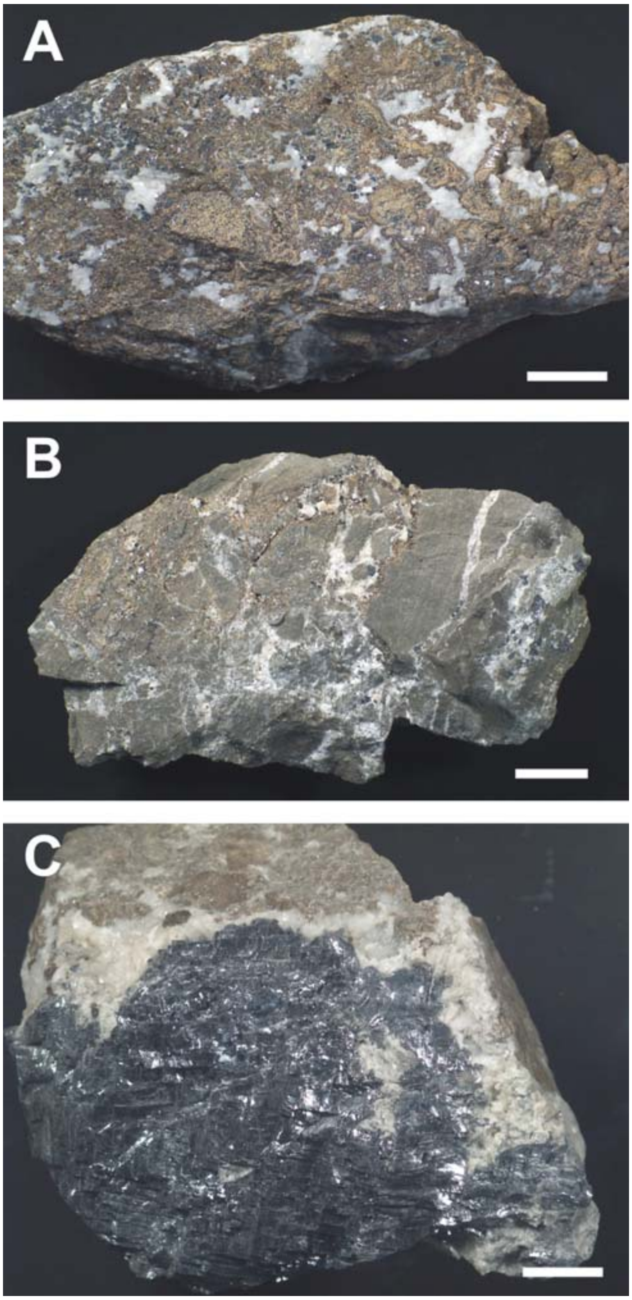

FIG. 8. Various ore textures from Polaris, Nunavut, NWT; scale bar is 1 cm. A. Keel ore: sphalerite and skeletal galena are replacing the carbonate clasts. B. Keel ore: crystalline sphalerite in solution collapse breccia. C. Ocean zone: Massive galena and sparry dolomite in pseudobrecciated carbonate host rock.

cocite, 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. Co, Ni, and Co are diagnostic accessory elements in deposits of the southeast Missouri and Upper Mississippi Valley districts (Foley, 2002). Thallium and As are enriched in sphalerite of the Silesian deposits (Viets et al., 1996).

The majority of MVT deposits have essentially no geochemical signature because of limited primary dispersion of elements bounded in sphalerite and galena into 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, 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 of 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, similar in magnitude to those associated with orebodies. Since the shales have relatively low Pb contents, composite Pb-Zn anomalies are likely mineralization-related. Relatively poorly defined Pb anomalies are often present near orebodies, due to low Pb mobility and the general low Pb/Zn ratios in MVT orebodies.

Alteration Mineralogy/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 dolomitic halos can be pre-, syn-, or post-sulphides. This hydrothermal dolomitization consists of coarse, crystalline, white, sparry dolomite and saddle dolomite cement.

At Pine Point, calcite flooding forms halos around the ore bodies giving a coarsely granular appearance to the carbonate host rocks. 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 ore bodies. These anomalous patterns decrease gradationally from maximum density and high-grade prismatic cores to barren country rocks. These anomalies 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. Iron dispersion highs tend to be displaced north of the deposits.

Silicification is not widespread in the Canadian MVT deposits, but when present, it forms small discontinuous zones of microcrystalline quartz enveloping the sulphides. 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

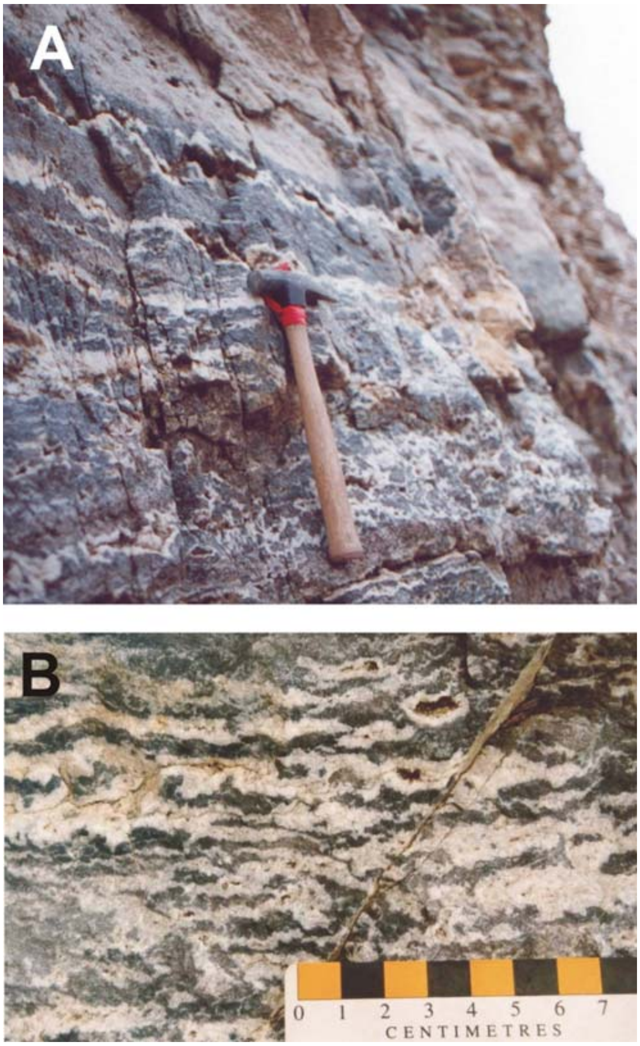

FIG. 9. A. Hydrothermal dolomite in bedding parallel bands forming zebra texture (N-42 deposit, Pine Point, NWT). B. Close up of selective replacement by coarse-grained white dolomite (Robb Lake, BC).

Sangster, 1993) where it occurs as microcrystalline quartz forming halos around or mantling the sulphides zones. According to Leach et al. (2001a), 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 and alteration of the organic matter are recognized in some districts (e.g., Polaris: Héroux et al., 1999; Jubilee, 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 (Randell et al., 1996; Héroux et al., 1996; Sass-Gustkiewicz et al., 1999).

Geological Properties

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 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 good examples of deposits/districts in foreland thrust belts. Other deposits, such as those of the Nanisivik, Gays River, Lennard Shelf (Australia) and Alpine districts (Europe), occur in or adjacent to rift zones. Rare deposits such as those of the Upper Mississippi Valley district in the US occur in intracratonic basins. In the Upper Mississippi Valley district, numerous small ore bodies occur in vertical veins, fractures, and faults along a broad NW-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 Pb-Zn showings are concentrated in veins, breccias, and vugs in dolostone or limestone. These are grouped within the Gayna River, Goz Creek, Bear Twit, and Blende districts.

Many of the MVT deposits of the world potentially formed during large contractional tectonic events at specific times in the Earth's history (Leach et al., 2001a). Formation of other deposits, such as Nanisivik in Canada and those of the Lennard Shelf in Australia, are potentially linked to extensional events. The most important periods for MVT genesis were during the Devonian-Permian time and the Cretaceous-Tertiary time (Fig. 10). 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 Pb-Zn metals produced so far worldwide were formed at that time. Deposits of the Lennard Shelf, Newfoundland Zinc, Cornwallis, and possibly East Tennessee, Pine Point, and Robb Lake districts 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). Districts such as Robb Lake, Pine Point, and Monarch-Kicking Horse in North America may have formed during the Laramide orogeny in Cretaceous-Tertiary time. The Cracow-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. Furthermore, preliminary paleomagnetic results from the Reocin deposit in Spain are consistent with a Tertiary age for mineralization (Lewchuk et al., 1998).

Criteria indicating good potential for MVT deposits include:

1) Tectonic setting: Deposits are hosted in platform carbonate sequences, in relatively undeformed or deformed cratonic sedimentary cover rocks surrounding 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: Deposits formed mainly during large contractional tectonic events at specific times in the history of the Earth; a few known deposits are associated with extensional tectonic events.

3) Age: For the deposits that have been dated, their ages range from middle Ordovician to Tertiary. Most deposits however formed during two main periods, the Devonian-Permian or the Cretaceous-Tertiary.

4) Coeval SEDEX deposits may be present in adjacent continental rift basins. There is an equivocal but strong geographic and temporal linkage between Phanerozoic MVT and SEDEX deposits (particularly in western Canada).

Knowledge gaps: Establishing the age and timing of MVT mineralization is a critical piece of information that can guide exploration for undiscovered deposits. 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 MVT mineralization (Leach et al., 2001a). 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 kilometers, such as the Pine Point district (>1600 km^2), Tri-State district (</= 1800 km^2), southeast Missouri district (~2300 km^2), Upper Mississippi Valley district (~10,000 km^2) and east Alpine district (~10,000 km^2). 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.

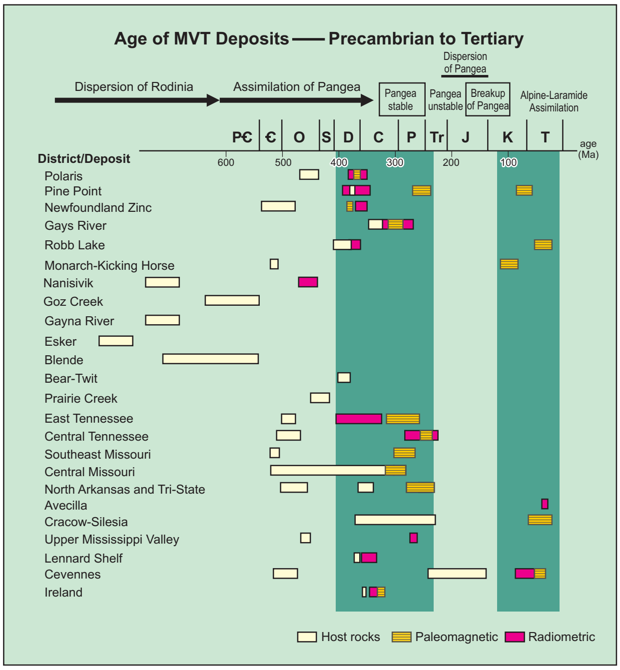

FIG. 10. Distribution of radiometric and paleomagnetic ages of MVT deposits/districts and their host rocks (modified from Leach et al., 2001a).

At the district scale, MVT deposits principally occur in dolostone (rarely in limestone or sandstone) of platform carbonate sequences; often occurring below major unconformities. Ore controls such as barrier reef complex, breccia, paleokarst, depositional margin near carbonate/shale edge, facies tract, fault, and basement high, are typically district-specific (see Leach and Sangster, 1993 for further information).

Criteria indicating good potential for MVT deposits include:

1) Tectonic setting: The presence of platform carbonate sequences which commonly overlie deformed and metamorphosed continental crustal rocks, and have some hydrologic connection to basins affected by orogenic events. Deposits usually occur at shallow depths on flanks of sedimentary basins.

2) District controls: The deposits/districts are localized by geologic features that permit upward migration of fluids, such as barrier reef complexes, breccias, paleokarsts, depositional margins near carbonate/shale edges, facies tracts, faults, and basement highs. Regional basement structures and faults are important; some deposits may be located at fault intersections.

3) Paleoclimate: Appropriate conditions that lead to the formation and preservation of carbonate platforms and evaporites.

4) Magmatic activity: Heat sources, such as buried intrusive rocks, are generally not present.

5) Geophysical signature: Induced polarization (IP) surveys are effective and ground electromagnetic (EM) methods may work for deposits with iron sulphides. If deposits consist mostly of sphalerite, however, these methods might fail. Deposits can show up as resistivity lows and gravity highs. Some geological features associated with MVT deposits, such as faults, sinkholes, paleokarsts and carbonate/shale facies can often be identified by seismic, magnetic, gravity, and EM methods.

6) Geochemical anomalies: zinc, lead, iron, silver, and manganese can be detected in residual soil samples and stream sediments. Alteration of the clay minerals and the organic matter are useful exploration tools when integrated with geological data.

Knowledge gaps: Major questions that address key knowledge gaps relating to MVT deposits concern the district scale. Some of them are listed below:

- 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 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 orebodies?
- What type of ground-preparation process is needed for ore 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 does 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 ore localization?

Deposit Scale

MVT deposits typically occur in carbonate rocks associated to interconnected paleokarst networks, pre-existing solution collapse-breccias and related carbonate dissolution features located beneath an unconformity or disconformity, and fractures and faults. At the deposit scale, the ore controlled structures are commonly zones of solution collapse-breccias. In some instances (e.g., Pine Point), these zones form linear solution channels (called karst) at the base of a reef and barrier complex (e.g., the Presqu'ile 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. 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) which 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 include:

1) Local tectonic setting: The presence of platform carbonate rocks.

2) Deposit controls: The presence of erosional discontinuities, which are required for karst development. Reef and barrier complexes, solution-collapse breccias, and faults or fractures, and an overlying seal (shale cap) also seem to be 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) Ore textures: Disseminated sulphides in the carbonate rocks may indicate the proximity to prismatic orebodies.

5) Hydrothermal alteration: Extensive hydrothermal dolomitization of precursor carbonate rocks is common and mostly appears as cement in ore-bearing breccia; this hydrothermal dolomite consists of coarse-grained white sparry dolomite and saddle dolomite. Silicification is also locally present but 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: Presence of bitumen and native sulphur in mineralized and non-mineralized strata.

7) Other features: The presence of internal sediments is an important exploration tool; in prismatic orebodies, internal sediments are thicker near the base of the karst network where tabular karst begins.

Distribution of Canadian MVT Districts

Geological Distribution of MVT Districts in Canada

For the purpose of this compilation and 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, 16 MVT districts were identified. Most of these districts consist of several deposits, which comprise two to more than 100 sulphide bodies. For example, the Gayna River district contains more than 100 sulphide occurrences and Pine Point has two deposits (Pine Point and Great Slave Reef), which consist of more than 90 individual ore bodies.

The Canadian deposits/districts show a strong concentration along an arcuate circum-continental trend (Fig. 2). They are hosted in relatively undeformed and deformed platformal carbonate rocks peripheral to cratonic sedimentary basins. Most districts are located in western and northern Canada, and few are located in the Maritimes provinces. The largest group of deposits (in terms of number of deposits) is located in the Mackenzie Mountains of the Yukon and the NWT, 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 of the 16 Canadian deposits/districts are found in deformed carbonate rocks of the 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 northern and southern Canadian Cordillera. Only deposits of the Pine Point district occur in weakly deformed carbonate rocks of the orogenic forelands. Newfoundland Zinc, Gays River, and Upton in eastern Canada are hosted in deformed carbonate rocks of the Appalachian foreland thrust belts. Nanisivik in northern Canada is in extensional environments associated with east-west trending normal faults that divide the area into a series of horsts and grabens (Sherlock et al., 2003).

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. 10). The absolute age of mineralization is not known for all Canadian deposits. Table 1 summarizes the most reliable ages for the deposits. Some deposits, such as Nanisivik, Pine Point and Robb Lake show contrasting results between radiometric and paleomagnetic methods, and the 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/districts. 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). This association - mineralization and orogenic uplift in a convergent regime - supports the topographically driven fluid flow model associated with ore fluid migration in compressive tectonic regimes (see below). Only one deposit so far, Nanisivik, is not associated with a contractional tectonic event but is attributed to mid-Ordovician extensional tectonism (Sherlock et al., 2003).

Summary of Economic Characteristics

Seven out of 16 MVT deposits/districts have been mined for a total of 112.5 Mt of ore. Pine Point was the largest district with close to 10 Mt Zn+Pb metal produced between 1964 and 1988 (Fig. 11). An analysis of the Pine Point district showed that most ore bodies range in size from less than 100,000 tonnes to the large X-15ore body containing geological resources near 17.5 Mt with average grades of 6.2% Zn and 2% Pb. Ore bodies average 1.32 Mt of Zn-Pb ore grading near 7% Zn and 3% Pb. Total geological resource (produced resource and remaining proven reserves) for the Pine Point district is estimated to be near 83.4 Mt. With the closure of Pine Point in 1988, Newfoundland Zinc in 1990, and Polaris and Nanisivik in 2002, there are no MVT deposits in production in Canada.

Genetic/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 hot to 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

Table 1. Summary of age dates (Ma) for MVT deposits/districts in Canada.

Deposit/District	Age of Host Rocks	Age of Mineralization					Orogeny
		Period	Epoch/Age	Date (Ma)	Method	Reference	
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)	Ordovician	Middle Ordovician	461	Ar-Ar on adularia	Sherlock et al. (2003)	?
		Proterozoic	Middle Proterozoic	1095+/-10	Paleomagnetism	Symons et al. (2000)	Rifting
Gays River	Early Mississippi (Late Tournaisian - Early Visean)	Pennsylvanian-Permian		297+/-27	Ar-Ar on biotite	Kontak et al. (1994)	Alleghenian
		Pennsylvanian		303+/-17	Paleomagnetism	Pan et al. (1993)	Alleghenian
Newfoundland Zn	Early Ordovician	Middle Devonian	Givetian	380+/-7	Paleomagnetism	Pan and Symons (1993)	Acadian
		Late Devonian-Early Mississippian		360+/-10	Ar-Ar on authigenic feldspar	Hall et al. (1989)	Acadian
Monarch-Kicking Horse	Middle Cambrian	Cretaceous	Late Cretaceous	100+/-12	Paleomagnetism	Symons et al. (1998)	Laramide
Pine Point	Middle Devonian (Late Eifelian-Late Givetian)	Late Devonian-Early Carboniferous		361+/-13	Sphalerite Rb-Sr	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		71+/-13	Paleomagnetism	Symons et al. (1993)	Laramide
Robb Lake	Late Silurian - Middle Devonian	Tertiary/Paleogene	Eocene / Lutetian	47+/-10	Paleomagnetism	Smethurst et al. (1999)	Laramide
		Paleozoic		no good isochron; but similar to Pine Point at 360	Sphalerite Rb-Sr	Nelson et al. (2002)	Antler

carbonate sequences. To effect this movement of ore-bearing brines, at least three different 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 and tectonic compaction model expulsion of basinal fluids through sediment diagenesis and tectonic sediment compaction and the episodic fluid release from overpressured aquifers (Jackson and Beales, 1967; Sharp, 1978; Cathles and Smith, 1983; Oliver, 1986).

3. The hydrothermal convection model (Morrow, 1998).

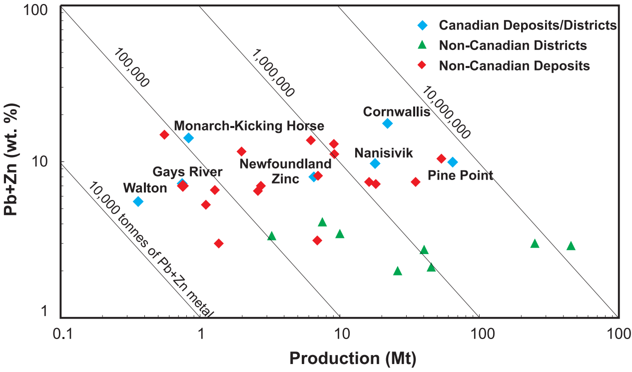

FIG. 11. Grade vs. tonnage for Canadian and worldwide MVT deposits/districts with production. Diagonal lines represent total tonnage of contained lead and zinc (adapted from Sangster, 1990). Abbreviations: PP - Pine Point, NF - Newfoundland Zinc, GR - Gays River, M-KH - Monarch-Kicking Horse.

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). Maintaining high initial fluid temperatures during transport of up to hundreds of kilometers from basin source to platform depositional site could be a problem. A variation of this model, episodic outward flow, was therefore proposed. The model involves overpressuring of subsurface aquifers by rapid sedimentation, followed by rapid and episodic release of basinal fluids (Sharp, 1978; Cathles and Smith, 1983). 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). Research on the MVT deposits of the Lennard Shelf area, Western Australia has demonstrated that mineralization is associated with compaction-driven dewatering and episodic fluid release from overpressured clastic sediments in the nearby Fitzroy Trough (Vearncombe et al., 1996).

The third model involves deep convection circulation of hydrothermal brines due to buoyancy forces related to temperatures and salinity variations (Morrow, 1998). It supports long-lived flow systems that are capable of recycling subsurface solutions many times through the rock mass. This model has been invoked to explain regional hydrothermal dolomitization in the WCSB (Morrow, 1998), the Manetoe facies of the Northwest Territories (Morrow et al., 1990; Aulstead et al., 1988), the Ordovician gas-producing carbonates of the Michigan Basin (Coniglio et al., 1994), and MVT deposits of 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 are 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; Sverjensky, 1984). 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.

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; Sverjensky, 1984, 1986).

Advances in Genetic/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 proved to be the best accomplishment in our effort to understand the origin of MVT deposits, their links to global Earth tectonic events, and to improve 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, and the collage of 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., 2001b). 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 age dating 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 three domains: 1) the role of tectonic processes, 2) the chemical processes, and 3) the age of MVT ore-forming events.

Tectonic Processes

Leach et al. (2001a) stressed the genetic links between MVT mineralization and regional- and global-scale tectonic processes. It is now clear that MVT deposits/districts 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 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 or districts.

MVT deposits in North America (such as those of the Ozark district) 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 the MVT mineralization in North America. Other deposits such as the Lennard Shelf in Australia, Alpine deposits in Europe and North Africa, and Nanisivik have been attributed to continental extension and may require other fluid-driving mechanisms (Leach and Sangster, 1993). What are these mechanisms?

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

- What are the fluid-driving mechanisms for ore formation in extensional regimes?
- What is the role of continental extension on 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 model and fluid migration?
- Why do MVT deposits form in some but not all carbonate platforms in collisional forelands?
- Why are certain carbonate platforms fertile for MVT deposits while others are barren?
- What is it about the late stage of some collisions that induces regional-scale fluid migrations?
- What is the role of paleoclimate in the formation of MVT deposits?
- Are evaporites critical to the origin of MVT deposits?
- 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 ore minerals?
- What type of ground-preparation process is needed for ore 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 does 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?

Chemical Processes

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

- Why do these deposits contain only lead and zinc in economic quantities? What is the mechanism that selects the lead and zinc?
- What causes metal zoning in some MVT districts as well as in individual orebodies?
- What is the contribution of organic matter to MVT ore deposition? Are hydrocarbons critical for mineralization to occur?
- What controls the chemical composition of ore-forming fluids? Were evaporates essential for the generation of metalliferous brines? What are the sources of metals? What are the chemical attributes of hydrothermal reaction zones that have generated ore-forming fluids?
- What alteration vectors are most effective in exploring for MVT deposits?

Age of MVT 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 in our understanding of MVT genesis. Recent advances in age dating of MVT deposits provide new evidence that there are important genetic relationships between convergent orogenic events and the formation of MVT deposits (Leach et al., 2001a). The most important periods for MVT genesis in the history of the Earth happened during 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 of Australia are associated to extensional events in Ordovician and Early Mississippian time, 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.

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:

- What controls the temporal distribution of MVT deposits?
- Why are there no 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 is the age of deposits for which there is controversy regarding timing (e.g., Robb Lake, Pine Point, East Tennessee, Cévennes), because of conflicting results between paleomagnetic and radiometric dating techniques?

Key Exploration Criteria For Canadian MVT Deposits

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

- Geologic settings: Undeformed and deformed platformal 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 lower to mid-Paleozoic period.
- District-scale controls: The deposits/districts are localized by geologic features that permit upward migration of fluids, such as barrier reef complex, breccias, paleokarst, depositional margins near carbonate/shale edges, facies tracts, faults, and basement highs.

There could be a strong regional fault control system on the localization and emplacement of MVT deposits. Optimum fracturing, dilatational space creation, and mineralization may occur where these faults crosscut and intersect barren carbonate rocks in outer shelf/carbonate margin (reef margin) settings (e.g., associated to transtensional or extensional structural settings).

- 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.
- Paleoclimate: Appropriate conditions that lead to the formation and preservation of carbonate platforms and evaporites.
- Hydrothermal event: Evidences 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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