

MISSISSIPPI VALLEY-TYPE PB-ZN DEPOSITS (MODELS 32a, b; Briskey, 1986a,b)

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SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Mississippi Valley-type (MVT) lead-zinc deposits are a varied family of epigenetic ore deposits that form predominantly in dolostone and in which lead and zinc are the major commodities. Most are found in rocks of Cambrian and Ordovician, Devonian and Carboniferous, and Triassic ages. Undeformed orogenic foreland carbonate platforms are the favored tectonic setting for MVT deposits; some are in carbonate sequences in foreland thrust belts bordering foredeeps and fewer still are associated with rift zones.

MVT deposits typically are in districts covering hundreds, or even thousands, of square kilometers. Within each district, deposits display remarkably similar features, including mineral assemblages, isotopic compositions, and textures. Ore controls typically are district-specific; examples include shale edges (depositional margins of shale units), limestone-dolostone transitions, reef complexes, solution collapse breccias, faults, and basement topography. Most MVT ore districts are the product of regional or sub-continental scale hydrological processes. Therefore, diversity among MVT districts is expected because of wide ranging fluid compositions, geological and geochemical conditions, fluid pathways, and precipitation mechanisms possible at the scale of MVT fluid migration.

Deposit geology

The most important characteristics of MVT lead-zinc deposits (Leach and Sangster, 1993) are: (1) most deposits are in dolostone, less commonly in limestone or sandstone, (2) ore is epigenetic and stratabound, (3) deposits are not associated with igneous activity, (4) deposits are at shallow depths at flanks of basins, (5) deposits are in platform carbonate sequences, located either in relatively undeformed rocks bordering foredeeps or in foreland thrust belts, (6) most deposits are in districts that cover hundreds of square kilometers; a number of districts may even form metallogenic provinces, (7) deposits form districts that are localized by geologic features, including breccias, depositional margins of shale units (shale edges), facies tracts, faults, and basement highs that permit upward migration of ore fluids, (8) ore deposition temperatures are low (50°C to 200°C), but typically higher than those attributable to local basement-controlled thermal gradients; districts are commonly in thermal equilibrium with respect to surrounding host rocks, (9) deposits are mineralogically simple; dominant minerals are sphalerite, galena, pyrite, marcasite, dolomite, calcite, and quartz, (10) associated alteration consists mainly of dolomitization, brecciation, host-rock dissolution, and dissolution/crystallization of feldspar and clay, (11) evidence of carbonate host rock dissolution, expressed as slumping, collapse, brecciation, or some combination of these, is common, (12) ore fluids were dense basinal brines, typically containing 10 to 30 weight percent salts, (13) isotopic data indicate crustal sources for both metal and reduced sulfur, (14) sulfide mineral textures are extremely varied; ore ranges from coarsely crystalline to fine-grained, massive to disseminated.

Examples

MVT deposits are found throughout the world (fig. 1); the largest and most intensely studied are in North America. Important North American districts include the Viburnum Trend and the Old Lead Belt (Southeast Missouri Lead district), Tri-State, Upper Mississippi Valley, Central Tennessee, East Tennessee (Mascot-Jefferson and Copper Ridge subdistricts), Austinville-Ivanhoe, Pine Point, Nanisivik, Polaris, Daniel's Harbour, and Gays River. Active MVT deposits in the United States are in the Viburnum Trend (southeast Mo.), Central Tennessee, and East Tennessee districts.

Spatially and (or) genetically related deposit types

Deposit types (Cox and Singer, 1986) associated with MVT deposits are believed to be part of a spectrum of sediment-hosted ore deposits (Sangster and Leach, 1995) that includes sedimentary exhalative lead-zinc-barite deposits (Model 31a), carbonate-hosted fluorite deposits (for example, Illinois-Kentucky fluorite deposits), carbonate-platform deposits (for example, Mt. Isa and Hyc, Australia; Balmat-Edwards, N.Y.), Kipushi copper deposits (Model 32c), and sandstone-lead deposits (Model 30a) (for example, Laisvall, Sweden; Largentiere, France).

Potential environmental considerations

Environmental concerns associated with mining MVT deposits are largely unrecognized due to the common assumption



Figure 1. Location of MVT deposits and districts throughout the World: 1, Polaris; 2, Eclipse; 3, Nanisivik; 4, Gayna; 5, Bear-Twit; 6, Godlin; 7, Pine Point district; 8, Lake Monte; 9, Nancy Island; 10, Ruby Lake; 11, Robb Lake; 12, Monarch-Kicking Horse; 13, Giant; 14, Silver Basin; 15, Gays River; 16, Daniels Harbour; 17, Metaline district; 18, Upper Mississippi Valley district; 19, southeast Missouri district (Old Lead Belt, Viburnum Trend, Indian Creek); 20, central Missouri district; 21, Tri-State district; 22, northern Arkansas district; 23, Austinville; 24, Friedensville; 25, central Tennessee district; 26, east Tennessee district; 27, San Vicente; 28, Vazante; 29, Harberton Bridge; 30, Silesian district; 31, Alpine district; 32, Pering; 33, Sorby Hills; 34, Coxco; 35-37, Lennard Shelf district (Cadjebut, Blendvale, Twelve Mile Bore); 38, El-Abad-ekta district. Adapted from Sangster (1990).

that the acid-buffering potential of typical carbonate host rocks controls the mobility of zinc, cadmium, iron, lead, and other metals. However, the influence of alteration halos, regional aquifers and karst, variable iron sulfide mineral content, climatic influences, and the presence of various trace elements in ore have not been adequately evaluated. Surface disturbance: MVT deposits characteristically are in districts that are distributed over hundreds of square kilometers. The widespread distribution of MVT deposits within a region requires a regional approach to environmental studies. The Southeast Missouri lead district covers more than 2,500 square kilometers, the Tri-State district is at least 1,800 square kilometers, the Pine Point district is more than 1,600 square kilometers, the East Alpine district is about 10,000 square kilometers, and the Upper Mississippi Valley district is about 7,800 square kilometers. Numerous open pits are present within some districts, especially in abandoned districts such as the Tri-State district, Okla., Mo., and Kans. Modern mining techniques return most waste rock to underground workings; surface tailings and mineral processing facilities pose the most serious environmental concerns.

Water quality: Because ore is dominantly carbonate-rock hosted, local rock buffers potential acid mine and tailings water. Therefore, significant mobility of heavy metals is likely to be spatially restricted. In some districts, water from underground MVT mines serves as a local domestic water source (for example, Viburnum, Mo. and Upper Silesia, Poland). Most MVT deposits are in carbonate aquifers that can have enormous fluid transmissivity of regional extent. Many ore districts contain one or more sandstone aquifers that potentially allow greater contaminant dispersion than carbonate aquifers. Low iron oxide and clay contents of carbonate aquifers could permit greater dispersion of some elements at neutral or slightly alkaline pH.

Mineral processing: Tailings ponds and smelter activities generally pose the greatest environmental concerns. Significant amounts of airborne lead, arsenic, cadmium, and other elements are known to be significant sources of

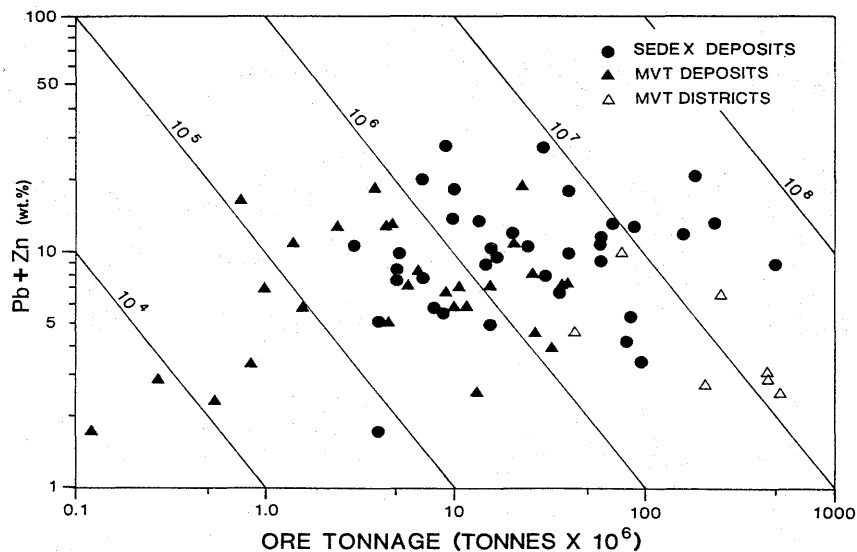


Figure 2. Grade-tonnage for MVT deposits and districts and for sedimentary exhalative deposits. Diagonal lines represent total tonnage of contained lead and zinc (adapted from Sangster, 1990).

metal contamination in many districts. In Upper Silesia, for example, soil in the vicinity of smelters contains thousands of ppm lead (Dudka and others, 1995).

Exploration geophysics

Geophysical exploration has been used successfully in some districts to map known geologic ore controls (Guinness and others, 1983). For example, airborne magnetic surveys have been used in Southeast Missouri to define buried Precambrian topography, an important control on the localization of some ore (Allingham, 1966; Cordell, 1979; Cordell and Knepper, 1987). Galena and pyrite are consistently conductive and have associated induced polarization anomalies, whereas sphalerite's resistivity is variable (Sumner, 1976). In Ireland, induced polarization and geochemical surveys have been combined to make discoveries of carbonate-hosted sulfide deposits (Halof, 1966); associated resistivity data have also been used to map subsurface faults that control mineralization and to map mineralized carbonate reefs (Halof, 1966; Hitzman and others, 1992).

References

General geology: Heyl and others (1959), a series of papers in Brown (1967), Anderson and Macqueen (1982), Kisvarsanyi and others (1983), Briskey (1986a, b), Sverjensky (1986), Leach and Sangster (1993), Leach (1994), and Sangster and Leach (1995).
Environmental geology: Smith and Schumacher (1991) and Dudka and others (1995).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

In Figure 2, data for deposits versus districts are identified by different symbols. District totals for metals may represent several dozen individual deposits; for example, the Pine Point and Upper Mississippi Valley districts contain more than 80 and nearly 400 deposits, respectively.

Individual deposits are generally small; most yield less than ten million tons of ore. An analysis of the Pine Point district, for example, showed that most deposits contained between 0.2 and 2 million tons of ore, and the largest had nearly 18 million tons (Sangster, 1990). For the Upper Mississippi Valley district, Heyl and others (1959) reported that the average deposit size was between 0.1 and 0.5 million tons, although a few contained as much as 3 million tons of ore.

Combined lead plus zinc grades in MVT deposits (districts) seldom exceed 10 percent. The Polaris deposit, in the Canadian Arctic Archipelago, is not only unusually large (22 million tonnes), but is anomalously high grade as well (18 percent lead plus zinc). A majority (about 85 percent) of deposits (districts) are zinc-rich relative to lead and have $Zn/(Zn+Pb)$ values between 0.5 and 1.0, with a distinct mode at 0.8. A smaller group, consisting of the entire Southeast Missouri district plus a few other small deposits, has a modal value of about 0.05 and is distinctly

anomalous in this regard.

Host rocks

Most MVT deposits are hosted by dolostone; less important hosts are limestone and sandstone.

Surrounding geologic terrane

MVT deposits commonly are at shallow depths along basin flanks. They form in platform carbonate sequences, located either in relatively undeformed rocks bordering foredeeps or in foreland thrust belts. Some deposits are associated with salt diapirs (for example, Bou Grine in Tunisia). Most deposits are surrounded by carbonate rocks with high acid buffering capacity.

Wall-rock alteration

Dissolution, recrystallization, and hydrothermal brecciation of host carbonate rocks within and peripheral to mineralized rock is common to virtually all MVT deposits. These effects may develop in conjunction with silicification and dolomitization and constitute the major form of wall-rock alteration in MVT districts. Ore-related silicification of host rocks limits the buffering capacity of rocks near ore deposits and therefore influences the extent of metal-bearing water dispersion in some districts (for example, Tri-State). Hydrothermal dolomite may be pre-, syn-, or post-ore and has commonly replaced pre-ore carbonate host rocks to form distinctive alteration halos around deposits (for example, the East Tennessee and Tri-State districts). Formation of authigenic clay and feldspar minerals and destruction of detrital potassium-silicate minerals are recognized in some districts.

Nature of ore

MVT ore is extremely varied in character and form. Orebodies range from massive replacement zones to open space fillings of fractures and breccias to disseminated clusters of crystals that occupy intergranular pore space. Crystal size ranges to as much as a meter or more in some "crystal caverns" in the Tri-State and Central Tennessee districts. In some districts, notably Pine Point, Silesia, Polaris, and Cadjebut, much of the ore forms extremely fine-grained, laminated aggregates of botryoidal (colloform) sphalerite, commonly with intergrown dendritic or skeletal galena. Most MVT deposits show clear evidence that open space deposition was accompanied by dissolution and replacement of host carbonate rocks. Carbonate host rock replacement is, in some cases, nearly complete, as in the massive sulfide zones at Nanisivik and Polaris. Ore-hosting structures are most commonly zones of highly brecciated dolomite; in some instances (for example, Pine Point and Daniels Harbour) these zones are arranged in linear patterns suggesting a tectonic control, although faults of large displacement are never present. In some districts, notably Upper Silesia and Ireland, faults, which reflect reactivated basement structures, are the most important ore control.

Deposit trace element geochemistry

Trace and minor element suites and abundances vary between districts; the trace element content of minerals from different paragenetic stages within a district often display significant variation. Table 1 summarizes metal abundances characteristic of some North American MVT districts. Arsenic, thallium, and cadmium contents of sphalerite from different MVT districts are compared in figure 3.

Ore and gangue mineralogy and zonation

Most MVT deposits have simple mineral assemblages that consist of galena, sphalerite, pyrite, and marcasite. The most important environmental consideration for MVT deposits may be their iron sulfide content. The abundance of iron sulfide minerals relative to that of other sulfide minerals in MVT deposits ranges from nil to dominant. Iron sulfide abundances vary not only between districts but among mines within single districts. The Appalachian districts contain trace to minor amounts of iron sulfide, whereas the sulfide mineral assemblage at Nanisivik is dominantly iron sulfide. MVT deposits in the Viburnum Trend contain from a few tenths percent to several percent iron sulfide minerals. Trace element abundances in iron sulfide minerals are often highly variable in different parts of a given mineral paragenesis. Chalcopyrite, bornite, and other copper sulfide minerals are abundant in some districts. Although most districts are characterized by rather simple mineral assemblages, Viburnum Trend ore contains a minor but complex suite of minerals that includes siegenite, bornite, tennantite, bravoite, digenite, covellite, arsenopyrite, fletcherite, adularia, pyrrhotite, magnetite, millerite, polydymite, vaesite, djurleite, chalcocite, anilite, and enargite. Some of these minor phases are present in trace amounts in many MVT districts.

With the exception of the Southeast Missouri district, all major MVT districts are zinc-rich relative to lead

Table 1. Geochemical characteristics of selected North American MVT Deposits.

District	Major	Minor	Trace
Viburnum Trend	Pb Zn Fe	Cu Co Ni	Cd Ag In Ge Ga Sb Bi As Mo Sn Au (1)
Old Lead Belt	Pb Zn Fe	Cu Ni Co	Cd Ag In Ge Ga Sb Bi As Mo Sn Au (1)
Central Missouri	Ba Zn Pb	Fe	Cd Cu
Northern Arkansas	Zn	Pb Fe	Cd Cu Ag Ge Ga In Bi As (1)
Tri-State	Zn Pb	Fe Cu	Cd Ba Cu Ag Ge Ga Co Ni In Sb Bi (1)
Upper Mississippi Valley	Zn Pb Fe	Cu Ba	Cd Ag Ge Ga Co Ni In (2)
Central Tennessee	Zn	Pb Fe F Ba	Cd Cu Ag Ge Ga Co Ni Hg As (1)
East Tennessee	Zn	Pb Fe	Cd Cu Ag Ge Ga (1)
Austinville	Zn Pb Fe	Cu	Cd Ge Ga F Ba (1)
Friedensville	Zn	Pb	Cd
Timberville	Zn Fe	Pb Cd	
Gays River	Zn Pb Fe	Cu Ba	F
Newfoundland Zinc	Zn	Pb Fe	Cd
Polaris	Zn Pb Fe		
Nanisivik	Zn Pb Fe		Ba Ag (3)
Pine Point	Zn Pb Fe		Cd Ag As Ni (3)
Gayna River	Zn Pb Fe	Ba F	

Ba, in barite; F, in fluorite.

The distinction between major and minor chemical characteristic is subjective because seldom are grades for minor metals published and there is an inherent high variability in minor metals even between deposits within a single district; typically the minor components are less than 1 percent but greater than 0.1 percent. Trace elements are a tabulation of elements detected in various mineral phases by a variety of techniques; therefore, they may be used as general guides for the deposits. Trace elements in bold type may be useful geochemical pathfinders. Trace element data from (1) Hagni (1983), (2) Heyl and others (1959), (3) Sangster (1968), and unpublished data.

and have Zn/(Zn+Pb) ratios greater than 0.5; this ratio is less than 0.1 in Southeast Missouri deposits. Some ore deposits, including many in the East Tennessee and Daniels Harbour districts, are essentially lead-free and have Zn/(Zn+Pb) ratios approaching 1.0. Although the Appalachian MVT deposits are generally galena poor, some contain significant amounts of galena (for example, Austinville, Va.).

Because most MVT deposits are mineralogically simple, mineralogic zonation has been described for only a few areas (Southeast Missouri, Pine Point, and Upper Mississippi Valley). Lead, zinc, iron, copper, nickel, and cobalt abundances are zoned in mineralogically complex deposits of the Southeast Missouri district (Grundmann, 1977; Rogers and Davis, 1977; Sweeney and others, 1977; Hagni, 1983; Mavrogenes and others, 1992). In the Upper Mississippi Valley district, a local zinc-copper belt is flanked by barite, whereas lead is widespread (Heyl and others, 1959). At Pine Point, Fe/(Fe+Zn+Pb) increases and Pb/(Pb+Zn) decreases outward from prismatic orebodies (Kyle, 1981).

The most abundant gangue mineral is hydrothermal dolomite, which may form alteration halos around MVT ore deposits (for example, northern Arkansas, East Tennessee, and Tri-State). Barite and fluorite are abundant gangue minerals in some districts. Other common gangue minerals include calcite and quartz.

Mineral characteristics

Sulfide mineral textures are extremely varied; ore ranges from coarsely crystalline to fine-grained, massive to disseminated.

Secondary mineralogy

Secondary minerals consist of smithsonite (the dominant ore mineral in some districts prior to the 1950s), calamine, anglesite, cerussite, malachite, sulfur, goslarite, epsomite, gypsum, melanterite, szomolnokite, copiatite, carphosiderite, diadochite, hydrous iron oxide minerals, hematite, greenockite.

Topography, physiography

Most MVT deposits are located in flat-lying carbonate sequences. However, some deposits are located in thrust and fold belts (for example, Monarch-Kicking Horse, British Columbia; Alpine district in Europe).

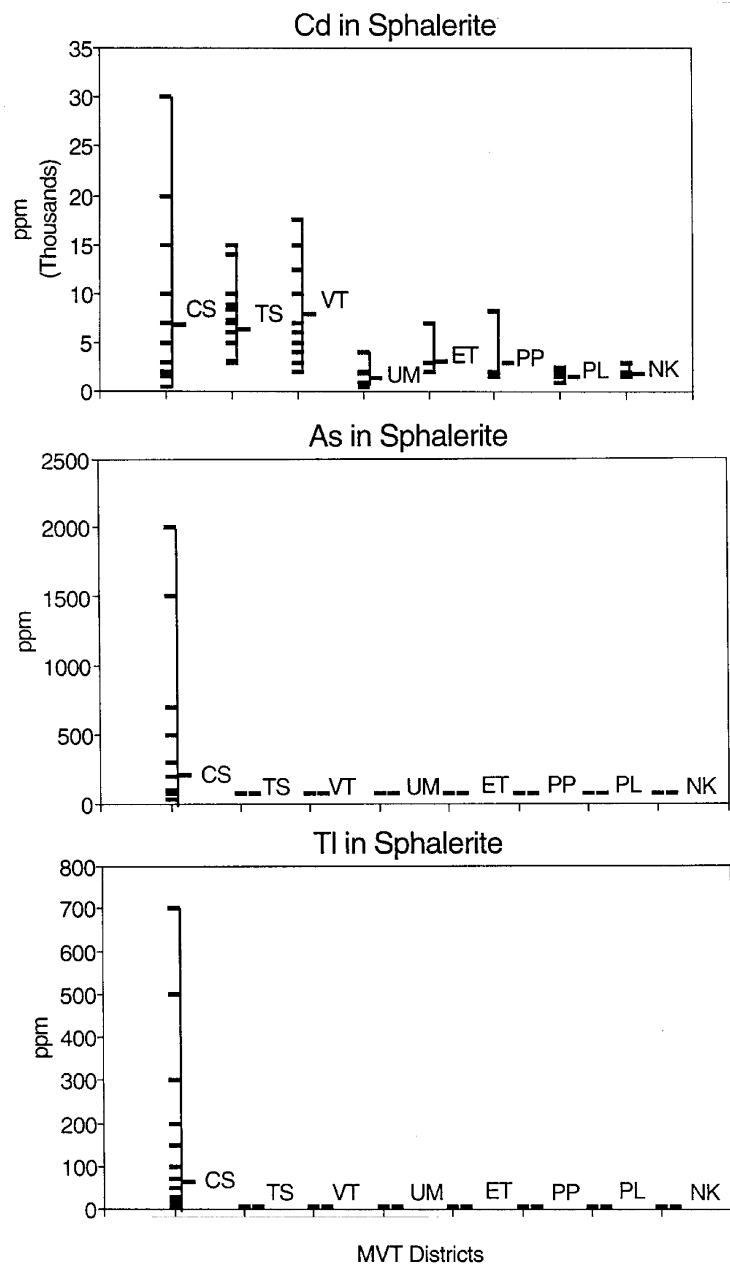


Figure 3. Range of concentrations and mean values, in parts per million, for cadmium, arsenic, and thallium in sphalerite from major Mississippi Valley districts: CS, Cracow-Silesia; TS, Tri-State; VT, Viburnum Trend; UM, Upper Mississippi Valley; ET, East Tennessee; PP, Pine Point; PL, Polaris; NK, Nanisivik (from Viets and others, in press).

Hydrology

The formation of MVT deposits requires enormous quantities of fluid; therefore, most districts have some spatial connection to major aquifers, karst systems, and faulted ground with high fluid transmissivity. However, present hydrology can be quite different from paleohydrology. Few generalizations on present hydrological environments are possible for MVT districts of the World; permafrost conditions prevail at the Polaris mine, whereas Saharan conditions prevail around North Africa deposits.

Mining and milling methods

Present mining is generally by underground room-and-pillar or by longwall methods. Ore is processed by pulverizing and flotation, concentrates are now generally shipped to smelters outside mining districts.

ENVIRONMENTAL SIGNATURES

Drainage signatures

Ground water: Water from a depleted part of one mine in the Viburnum Trend is used as the municipal water supply for Viburnum, Mo. This water meets all U.S. Environmental Protection Agency water quality standards with the exception of that for sulfate (Missouri Department of Natural Resources, 1991). Reported sulfate content is 436 mg/l, whereas the accepted water quality standard is 250 mg/l. Other parameters are pH=7; alkalinity=260; 0.18 mg/l iron; 5.7 mg/l sodium; 72 mg/l magnesium; 0.24 mg/l fluorine; 856 mg/l total dissolved solids; and lead, zinc, and cadmium abundances are in the $\mu\text{g/l}$ range. In addition, several communities in Upper Silesia, Poland, use water from underground lead-zinc mines as their only domestic water supply. The sulfate content of this water is variable but is commonly in the 400 to 800 mg/l range and lead is present in the $\mu\text{g/l}$ range.

Surface water: The Big River flows through the Old Lead Belt and near many waste piles. Water quality data (Smith and Schumacher, 1991) for a site about 15 km above mining and smelting activity reflect background water parameters: $\text{SO}_4 < 24$ mg/l, lead < 10 $\mu\text{g/l}$, cadmium < 2 $\mu\text{g/l}$, and zinc < 27 $\mu\text{g/l}$. During its flow through the district, carbonate buffering causes water pH (6.6-8.5) to be virtually unchanged. However, SO_4 , lead, and zinc abundances increase due to inputs primarily from surface mine wastes. At a site 5 km below the district, the water contains 40-140 mg/l SO_4 , 10 $\mu\text{g/l}$ lead, < 1 $\mu\text{g/l}$ cadmium, and 110-160 $\mu\text{g/l}$ zinc.

Metal mobility from solid mine wastes

Metal mobility away from MVT deposits is limited by the abundance of carbonate rock associated with these deposits; carbonate rock consumes acid mine drainage and inhibits aqueous metal mobility. Heavy metals abundances were determined at four seepage sites related to mine wastes in the Old Lead Belt (Smith and Schumacher, 1991). Maximum concentrations measured were: 850 mg/l SO_4 , less than 10 g/l copper, 80 $\mu\text{g/l}$ lead, 18,000 $\mu\text{g/l}$ zinc, and 28 $\mu\text{g/l}$ cadmium. During two years of monitoring at the four sites, pH of the seeps ranged from 6.23 to 8.61. A lead-zinc ratio of 5 for Old Lead Belt ore (Snyder and Gerdman, 1968) indicates that zinc is clearly more mobile than lead or cadmium in water leaching waste materials; these relative mobilities also appear to apply to Big River water.

Soil, sediment signatures prior to mining

In the region of the East Tennessee district, readily detectable zinc, iron, and locally lead anomalies are found in residual soil and stream sediment. For example, NURE data for stream sediment indicate that over 100 samples from the Bluefield 1°x2° quadrangle (Va., W. Va., Tenn., and N.C.) have anomalous lead and zinc abundances (> 20 ppm zinc and > 10 ppm lead) that may be attributable to lead and zinc deposits in the region. Proctor and others (1981) conducted a survey of the acid soluble lead content of 416 stream sediment samples collected from active streams throughout a 7,000 square mile area that includes much of the Southeast Missouri lead district. Samples from areas underlain by Paleozoic carbonate rock and considered to be largely non-mineralized have a mean lead content of 25 ppm, whereas samples from areas of active mining and milling contain an average of 393 ppm lead. The specific residence of lead was not identified but Proctor and others (1981) considered metal from insoluble rock residues, primary dispersion halos, secondary dispersion of primary mineralization, and recent dispersion due to mining and milling and smelting activities as possible lead sources.

Most MVT deposits have essentially no geochemical signature because of limited primary dispersion of ore related elements into the surrounding carbonate rocks (Lavery and others, 1994). However, in some districts where ore-bearing zones have been weathered, soil contains anomalous concentrations of lead and zinc. Soil geochemistry in the Irish district (Hitzman and others, 1992) and in the Newfoundland zinc district (Davenport and others, 1975) are effectively used in exploration.

Although MVT deposits are hosted by carbonate rocks, residual soil overlying some deposits can be acidic; it can have moderate to high permeability, medium to high erosion potential, and moderate to high water capacity. These factors can influence the mobility of metals into the environment.

In the area of the Austinville-Ivanhoe, Va., district background carbonate rocks typically contain about 20 ppm zinc and 9 ppm lead. However, extensive volumes of rock containing dolomite cement are widely peripheral to mineralized zones (for example, Wythe County, Va.; Barnaby, 1989); replacement dolomite and late calcite have considerably elevated abundances of some trace metals, including as much as 9,300 ppm iron, 200 ppm strontium,

1,500 ppm lead, 1,000 ppm manganese, and 10,000 ppm zinc.

Potential environmental concerns associated with mineral processing

Most modern underground carbonate hosted zinc-lead mining operations return a significant amount of mine waste and mill tailings to underground workings as fill. In the case of the Polaris mine in the Canadian Arctic, waste slurries are used to fill mining voids in their modified room and long pillar galleries. Once frozen, waste supports the roof and long pillars are mined so that essentially the entire deposit is mined. In Upper Silesia, Poland, surface disposal of iron sulfide-mineral-rich-tailings presents a potentially serious environmental problem in the district.

Surface mill tailings pose the major potential environmental concern associated with MVT deposits. Although modern processing facilities carefully monitor water draining from processing sites, some water, with elevated concentrations of lead, zinc, cadmium, arsenic, thallium, and a variety of trace elements characteristic of the ore deposit, may escape. Airborne dust from tailing ponds can potentially contribute ore particulates.

Smelter signatures

Studies of the effects of airborne smelter effluent in the Viburnum Trend of southeast Missouri by Bornstein and Bolter (1991) indicate that soil pH at distances of as much as 6.4 km from the smelter source and as deep as 15 cm are significantly reduced, ranging from 4.4 at 15 cm to 5.1 at 5 cm depths. At 9.6 km, pH ranged from 6.8 to 7.0. The sulfur content of the soil correlates with the pattern of pH depletion. Lead, zinc, copper, cadmium, cobalt and nickel contents of leaf litter and underlying soil decrease with distance from the point source and depth below surface. The extent of heavy metal enrichment was about half that of the area affected by sulfur enrichment suggesting that SO₂ is the principal sulfur species.

Palmer and Kucera (1980) conducted a similar study for lead, by sampling both sycamore leaves and twigs and soil, around four smelter sites in southeast Missouri. Their results were very similar to those of Bornstein and Bolter (1991) and indicate that dominant wind directions and degree of lead enrichment are correlated.

Climate effects on environmental signatures

Climate is extremely critical in assessing the environmental concerns associated with this deposit type. Potential acid-mine drainage problems related to MVT deposits in relatively dry climate settings are much less than those of deposits in warm, wet climates. Acid-rain aggravates potential environmental problems in the mid-Atlantic and northeastern United States, especially the Appalachians. Small MVT deposits are present throughout the Appalachians in Cambrian to Mississippian carbonate rock sequences (for example, Shady Dolomite and Knox Dolomite).

The Austinville-Ivanhoe, Va., deposit is a prime example of how climatic conditions and soil properties interact to increase potential environmental problems. For example, in Wythe County, Va., soil is moderately to very strongly acidic (pH 5.6 to <4.5) although as much as 30 percent of the surface may consist of dolomitic limestone outcrops; the soil has moderate permeability, medium to high erosion potential, and moderate water capacity. Much of the soil is deemed suitable for cultivated crops (legumes), hay, or pasture and much is prime farmland (corn, vegetables, small grain, and strawberries) (U.S. Department of Agriculture, 1992). Most of the area is in the drainage basin of the New River, which has water quality problems including excessive concentrations of trace metals such as zinc, copper, lead, iron, and locally acidification caused by mining activities (Virginia Water Control Board, 1990a,b). Prime farmlands of the valley and ridges within and adjacent to the Appalachian Mountains (near historic lead and zinc mines) may be affected by metal contamination resulting from past (and future) releases of lead and zinc into soil and ground water as a result of environmental conditions specific to the region.

In contrast to the Appalachian deposits, the Polaris deposit is in a region of permafrost with little opportunity for dispersion into the environment from surface or ground water. Likewise, deposits in arid regions such as Bou Grine in Tunisia, have little opportunity for metal mobility in water.

Geoenvironmental geophysics

In environmental and remediation studies, electrical, seismic surveys, and ground penetrating radar (for sources within meters of the surface) can help identify shallow mine shaft locations and map geologic structure within and beneath tailings. Induced polarization and resistivity surveys can be used to identify the source and extent of acid drainage. Seismic surveys can help distinguish sandstone aquifers from carbonate rocks. However, freshwater sandstone aquifers in dominantly carbonate rock, are associated with minor resistivity contrasts unless the water contains elevated abundances of dissolved metals.

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