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ARTICLE

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Mississippi Valley-type lead–zinc deposits through geological time: implications from recent age-dating research

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Abstract Remarkable advances in age dating Mississippi Valley-type (MVT) lead–zinc deposits provide a new opportunity to understand how and where these deposits form in the Earth's crust. These dates are summarized and examined in a framework of global tectonics, paleogeography, fluid migration, and paleoclimate. Nineteen districts have been dated by paleomagnetic and/or radiometric methods. Of the districts that have both paleomagnetic and radiometric dates, only the Pine Point and East Tennessee districts have significant disagreements. This broad agreement between paleomagnetic and radiometric dates provides added confidence in the dating techniques used. The new dates confirm the direct connection between the genesis of MVT lead–zinc ores with global-scale tectonic events. The dates show that MVT deposits formed mainly during large contractional tectonic events at restricted times in the history of the Earth. Only the deposits in the Lennard Shelf of Australia and Nanisivik in Canada have dates that correspond to extensional tectonic events. The most important period for MVT genesis was the Devonian to Permian time, which corresponds to a series of intense tectonic events during the assimilation of Pangea. The second most important period for MVT genesis was Cretaceous to Tertiary time when microplate assimilation affected the western margin of North America and Africa–Eurasia. There is a notable paucity of MVT lead–zinc ore formation following the breakup of Rodinia and Pangea. Of the five MVT deposits hosted in Proterozoic rocks, only the Nanisivik deposit has been dated as Proterozoic. The contrast in abundance between SEDEX and MVT lead–zinc deposits in the Proterozoic questions the frequently suggested notion that the two types of ores share similar genetic paths. The ages of MVT deposits, when viewed with respect to the orogenic cycle in the adjacent orogen suggest that no single hydrologic model can be universally applied to the migration of the ore fluids. However, topographically driven models best explain most MVT districts. The migration of MVT ore fluids is not a natural consequence of basin evolution; rather, MVT districts formed mainly where platform carbonates had some hydrological connection to orogenic belts. There may be a connection between paleoclimate and the formation of some MVT deposits. This possible relationship is suggested by the dominance of evaporated seawater in fluid inclusions in MVT ores, by hydrological considerations that include the need for multiple-basin volumes of ore fluid to form most MVT districts, and the need for adequate precipitation to provide sufficient topographic head for topographically-driven fluid migration. Paleoclimatic conditions that lead to formation of evaporite conditions but yet have adequate precipitation to form large hydrological systems are most commonly present in low latitudes. For the MVT deposits and districts that have been dated, more than 75% of the combined metal produced are from deposits that have dates that

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correspond to assembly of Pangea in Devonian through Permian time. The exceptional endowment of Pangea and especially, North America with MVT lead–zinc deposits may be explained by the following: (1) Laurentia, which formed the core of North America, stayed in low latitudes during the Paleozoic, which allowed the development of vast carbonate platforms; (2) intense orogenic activity during the assembly of Pangea created ground preparation for many MVT districts through far-field deformation of the craton; (3) uplifted orogenic belts along Pangean suture zones established large-scale migration of basin fluids; and (4) the location of Pangea in low latitudes with paleoclimates with high evaporation rates led to the formation of brines by the evaporation of seawater and infiltration of these brines into deep basin aquifers during Pangean orogenic events.

Introduction

Mississippi Valley-type (MVT) lead–zinc deposits are found throughout the world (Fig. 1), but the largest, and more intensely researched deposits occur in North America where the deposit-type was first recognized about 60 years ago (Bastin 1939). MVT deposits owe their commonly accepted name to the fact that several classic districts are located in the drainage basin of the Mississippi River in central USA. In the last 25 years, several studies have noted the close association of MVT deposits with widespread diagenetic alteration of rocks inboard of orogenic belts. These studies suggested that MVT deposits were the product of enormous hydrothermal systems related to major crustal tectonic events (e.g., Leach 1973; Garven 1985; Leach and Rowan 1986; Oliver 1986; Bethke and Marshak 1990; Oliver 1992; Symons et al. 1993, 1996b). In the last 10 years, remarkable advances in dating MVT deposits have provided a new opportunity to understand how and where these deposits form in the Earth's crust. In this paper, we summarize the new age dates and examine MVT lead–zinc deposits in a framework of global tectonics, paleogeography, fluid migration, and paleoclimates. Implications from this global view provide new perspectives into the genesis and exploration for these deposits.

Fig. 1 Distribution of Mississippi Valley-type deposits and districts: *1* Polaris; *2* Eclipse; *3* Nanisivik; *4* Gayna; *5* Bear-Twit; *6* Godlin; *7* Pine Point; *8* Esker; *9* Sardinia; *10* Washington land; *11* Robb Lake; *12* Monarch-Kicking Horse; *13* Giant; *14* Irankuh district; *15* Gays River; *16* Newfoundland; *17* Metaline; *18* Upper Mississippi Valley; *19* Southeast Missouri (Old Lead Belt, Viburnum Trend, Indian Creek); *20* central Missouri; *21* Tri-State; *22* northern Arkansas; *23* Austinville; *24* Friedensville; *25* central Tennessee; *26* East Tennessee; *27* San Vincente; *28* Vazante; *29* Ireland (e.g., Navan, Lisheen, Galmoy); *30* Cracow–Silesia; *31* Alpine district; *32* Pering-Bushy Park; *33* Sorby Hills; *34* Coxco; *35–37* Lennard Shelf (e.g., Cadjebut, Blendvale, Twelve-Mile Bore); *38* El-Abad-Mekta district; *39* Reocin; *40* Cévennes; *41* Bou Grine (Adapted from Sangster 1990)

The geological features and ore-forming processes responsible for MVT lead–zinc deposits are described in detail by Leach and Sangster (1993). In the present paper, we use the broad definition of MVT lead–zinc deposits (Leach and Sangster 1993) as a "varied family" of epigenetic ores precipitated from dense basinal brines at temperatures ranging between 75 and 200°C, typically in platform carbonate sequences and lacking genetic affinities to igneous activity. In using this broad definition for MVT deposits, we focus our discussions on the features that unite this important family of ore deposits rather than on the differences that makes each MVT district unique. As Leach and Sangster (1993) discussed, each MVT district has its own unique set of ore controls, such as geology, geochemistry, etc., which sets each apart in some way. Because we view diversity among MVT lead–zinc deposits as an important attribute of the deposit class, we choose not to use district names like "Irish-type", "Alpine-type", "Polish-type", "Appalachian-type", etc. However, it is this great diversity of geological and geochemical characteristics between MVT districts that has hindered development of more specific descriptive or genetic models for these seemingly simple deposits. Diversity among MVT districts is expected because of the wide range in fluid compositions, geological and geochemical conditions, fluid pathways, and precipitation mechanisms possible at the scale of MVT fluid migration. As Sangster (1986) correctly stated "Other than the general definition of MVT deposits given here, a single descriptive or genetic model for all MVT deposits is an unreasonable expectation".

We have chosen not to include in our discussions vein related MVT fluorite–barite deposits such as those in southern Illinois, central Kentucky, the Sweetwater district in Tennessee, Hansonburg in New Mexico, and the English Pennines. These deposits were considered by Leach and Sangster (1993) to be a genetic subtype or variant of MVT ore deposits and are excluded from this examination because they share features that set them apart from typical MVT lead–zinc deposits. Furthermore, we do not discuss the sandstone-hosted and lead-dominate deposits such as Laisvall, Sweden and sandstone lead–zinc veins of the Eifel, NW Rhenish Massif of Germany in our discussions. The vein deposits of fluorite–barite and lead–zinc sandstone-hosted deposits are the subject of another paper.

Age of MVT ore-forming events

Given the great diversity of MVT deposits (e.g., Sangster 1983, 1986; Leach and Sangster 1993), the most significant obstacle to understanding the origin of MVT deposits has been a paucity of information on the age of ore formation (Ohle 1980; Sangster 1986). Important advances in the last decade in dating MVT ore-forming events have been achieved through applications of improved radiometric dating and high precision paleomagnetic techniques. Table 1 summarizes the results of age dating studies on MVT deposits that have used paleomagnetic dating, radiometric dating by U–Pb, U–Th in calcite, Rb–Sr in sphalerite, Ar–Ar, K–Ar on feldspar and clay minerals, and fission track methods. We divided Table 1 into two groups. The first group contains dates that we believe best represent the ages of MVT ore deposition and that provide the basis for our interpretations and observations. The second group contains ages that were excluded from our interpretations because they provide only broad age constraints or there are various geological or geochemical reasons that justify omission with respect to the objectives of this paper.

Age-dating techniques

Radiometric technique

Radiometric dating of MVT ore minerals has been difficult because minerals commonly found in MVT deposits contain low abundances of the natural radioactive isotopes useful for geochronology. Although isotopic analysis of picogram quantities of parent–daughter pairs (^{87}Rb–^{86}Sr, ^{238}U–^{206}Pb, ^{235}U–^{208}Pb) is technically possible, maintaining low blank levels when large samples are chemically processed is problematical (e.g., a 50-mg sample of ore-stage calcite with a Pb concentration of 10 ppb contains 0.5 ng of Pb). Other crucial requirements for successful geochronology are that all the relevant samples be cogenetic (i.e., the minerals formed at the same time) and formed from an isotopically homogeneous reservoir and that the minerals have remained isotopically and chemically closed since formation. Selection of cogenetic minerals or even the same generation of a single mineral is seriously problematical. Different pulses or generations of fluids with distinct isotopic compositions can follow the same flow path; thus proximity does not ensure a cogenetic history. In addition, a homogeneous initial isotopic composition may not exist in deposits where incomplete mixing has been documented. For example, single crystals of galena from the Viburnum Trend contain Pb, S, and Sr isotopic variations on the scale of microns that are as large as the isotopic ranges found within the district (e.g., Sverjensky et al. 1979; Brannon et al. 1991, Goldhaber et al. 1995; McKibbon and Eldridge 1995). Despite these difficulties, radiometric techniques have been reasonably successful for dating MVT deposits. The Rb–Sr isotopic system has been used to date sphalerite (Nakai et al. 1990, 1993; Brannon et al. 1992a, 1992b; Christensen et al. 1993, 1995a, 1995b), U–Pb and Th–Pb isotopic systems were used to date ore-stage calcite (Brannon et al. 1995, 1996a, 1996b) and fluorite (Leach et al. 2001). The Sm–Nd isotopic system was used to date fluorite (Chesley et al. 1994; Leach et al. 2001).

Table 1 Summary of age dates (Ma) for world MVT deposits and districts. The ages excluded from interpretations are given and reasons for exclusion are discussed in the text

District	Region	Host rock	Paleomagnetic age	Paleomagnetic date (Ma)	Radiometric age	Radiometric date (Ma)	Mineral method	Orogeny	References[a]
Central Missouri Barite	Ozarks	L. Cambrian–E. Pennsylvanian		303 ± 17				Alleghenian	
Central Tennessee	Nashville Dome/Cinn. Arch	L. Cambrian–E. Ordovician	L. Permian–E. Triassic	245 ± 10				Alleghenian	2
Central Tennessee	Nashville Dome/Cinn. Arch	L. Cambrian–E. Ordovician			L. Permian	260 ± 42	Calcite (ore-stage) Th–Pb	Alleghenian	3
Cévennes	Southern France	Cambrian–Jurassic	U. Paleocene–L. Eocene	40–60				Pyrenean	4
Cévennes	Southern France	Cambrian–Jurassic			U. Cretaceous–Oligocene	25–80	Fluorite: U–Pb; Th–Pb; Sm–Nd	Pyrenean	17
Cracow-Silesia	Poland	L. Devonian–M. Triassic	L. Cretaceous–Oligocene	46 ± 20				Alpine/Carpathian	6
East Tennessee	Southern Appalachians	Lower Ordovician (505–478)	Late Pennsylvanian–Early Permian	286 ± 20				Alleghenian	7
East Tennessee	Southern Appalachians	E. Ordovician	E. Pennsylvanian	316 ± 8				Alleghenian	8, 48
East Tennessee	Southern Appalachians	E. Ordovician			Devonian	377 ± 29	Sphalerite Rb–Sr	Acadian	9
East Tennessee	Southern Appalachians	E. Ordovician			Mississippian	347 ± 20	Sphalerite Rb–Sr	Acadian	10
Gays River	North Appalachians	Mississippian (Visean)	Pennsylvanian	300–320				Alleghenian	11
Gays River	North Appalachians	Mississippian (Visean)			Pennsylvanian-Permian	297 ± 27	Ar–Ar biotite	Alleghenian	12
Ireland	Western Europe	E. Carboniferous	L. Mississippian	330 ± 7				Hercynian	13
Ireland	Western Europe	E. Carboniferous			Mississippian	337–350	Ar–Ar mica	Hercynian	14
Lennard Shelf	Australia	L. Devonian			L. Devonian–E. Mississippian	351 ± 15	Calcite (ore stage) U–Pb	Ext. of the Canning Basin	15
Lennard Shelf	Australia	L. Devonian			E. Mississippian	357 ± 3	Sphalerite Rb–Sr	Ext. of the Canning Basin	16
Monarch-Kicking Horse	Western Canada Basin	M. Cambrian	Cretaceous	100 ± 12				Laramide	18
Nanisivik	Canadian Arctic	Proterozoic	M. Proterozoic	,095 ± 10				Rifting of Beloit Supergroup	19
Newfoundland Zinc	Northern Appalachians	E. Ordovician	Devonian	380 ± 7				Acadian	20
Newfoundland Zinc	Northern Appalachians	E. Ordovician			L. Devonian–E. Mississippian	360 ± 10	Ar–Ar authigenic feldspar	Acadian	21
North Arkansas	Ozarks	E. M. Ordovician	Permian	265 ± 20				Alleghenian/Ouachita	22

Pine Point	Western Canada Basin	M. Devonian	L. Cretaceous–Paleocene	71 ± 13				Laramide	23
Pine Point	Western Canada Basin	M. Devonian			L. Devonian–E. Mississippian	61 ± 13	Sphalerite Rb–Sr	Antler	24
Pine Point	Western Canada Basin	M. Devonian			E. Devonian-E. Mississippian	374 ± 21	Sphalerite Rb–Sr	Antler	25
Polaris	Canadian Arctic	M.–L. Ordovician	L. Devonian	367 ± 7				Ellesmerian	26
Polaris	Canadian Arctic	M.–L. Ordovician			M. Devonian-E. Mississippian	366 ± 15	Sphalerite Rb–Sr	Ellesmerian	27
Robb Lake	Western Canada Basin	Silurian–Devonian	E.–M. Tertiary	47 ± 17				Laramide	28
SE Missouri	Ozarks	Cambrian	L. Pennsylvanian–E. Permian	286 ± 20				Alleghenian/ Ouachita	29
SE Missouri	Ozarks	Cambrian	E. Permian	273 ± 10				Alleghenian/ Ouachita	30
Tri-State	Ozarks	Mississippian to E. Pennsylvanian			Permian–E. Triassic	251 ± 11	Calcite (ore-stage) Th–Pb	Ouachita	31
Upper Miss. Valley	Central US	M. Ordovician			E. Permian	270 ± 4	Sphalerite Rb–Sr	Alleghenian/ Ouachita	32
Avecila Mine	Eastern Spain	Cretaceous			Paleocene	62.6 ± .7	Calcite (ore-stage) Th–Pb	Pyrenean	33
Excluded Dates									
Central Tennessee	Nashville Dome/ Cinn. Arch	L. Cambrian–E. Ordovician			Eocene and >	39 Ma	U–Pb, Th–Pb late calcite		34
Cévennes	Southern France	Cambrian–Jurassic			L. Triassic – M. Jurassic	190 ± 20	K–Ar on illite	Mesozoic Extension	
East Tennessee	Southern Appalachians	E. Ordovician			< = L. Mississippian	< = 330	Ar–Ar authigenic feldspar		35
Gays River	North Appalachians	Mississippian (Visean)			> E. Jurassic	> 189 ± 15 to > 241	Apatite fission track		36
Gays River	North Appalachians	Mississippian (Visean)			< L. Mississippian	< 330	Ar–Ar alt. of muscovite		37
Gays River	North Appalachians	Mississippian (Visean)			< = Carboniferous	< 308 ± 37 < 342 ± 33	Zircon fission track		38
Gays River	North Appalachians	Mississippian (Visean)			< E. Mississippian	< 352 ± 7	K–Ar illite		39
North Ark/Tri-State	Ozarks	Mississippian–Pennsylvanian			> L Jurassic	> 183	Apatite fission track		40
Pine Point	Western Canada Basin	M. Devonian			Max E. Cretaceous	max~100	Apatite fission track		41
Pine Point	Western Canada Basin	M. Devonian			Paleocene	50–60	Apatite fission track		42
SE Missouri	Ozarks	Cambrian			Devonian	392 ± 21	Galena Rb–Sr		43
SE Missouri	Ozarks	Cambrian			M. Devonian–E. Mississippian	380–350	Rb/Sr glauconites		44

Table 1 Contin

	Region	Host Rock	Paleomagnetic Age	Paleomagnetic Date (Ma)	Radiometric Age	Radiometric Date (Ma)	Mineral Method	Orogeny	References[a]
SE Missouri	Ozarks	Cambrian			L. Proterozoic–E Cambrian	549 ± 20	Ar–Ar on pyrite		45
SE Missouri	Ozarks	Cambrian			E. Ordovician–E Permian	489 ± 8 to 297 ± 7	K–Ar illite		46
SE Missouri	Ozarks	Cambrian			L. Permian to Eocene	50–250	Apatite fission track		47

[a]References for the dates are (*1*) Symons and Sangster 1991; (*2*) Lewchuk and Symons 1996; (*3*) Brannon et al. 1996a; (*4*) Rouvier et al. 1995; Lewchuk et al. 1998a, 1998b, 1998c, 1998d; Henry et al. 2001; Rouvier et al. 2001; (*5*) Toulkeridis et al. 1993; Clauer and Chaudhuri 1995; (6) Symons et al. 1995; (7) Bachtadse et al. 1987; (*8*) Symons and Stratakos 2000; (*9*) Nakai et al. 1990; (*10*) Nakai et al. 1990; 1993; (*11*) Pan et al. 1993; (*12*) Kontak et al. 1994; (*13*) Smethurst et al. 1998; (*14*) Hitzman 1994; (*15*) Brannon et al. 1996a; (*16*) Christensen et al. 1995b; (*17*) Leach et al. 2001; (*18*) Symons et al. 1996a, 1998b; (*19*) Symons et al. 2001; (*20*) Pan and Symons 1993; (*21*) Hall et al. 1989; (*22*) Pan et al. 1990; (*23*) Symons et al. 1993; (*24*) Nakai et al. 993, 1995; (*25*) Brannon et al. 1995, personal communication; (*26*) Symons and Sangster 1992; (*27*) Christensen et al. 1995a; (*28*) Smethurst et al. 1999; Symons et al. 1999a; (*29*) Wisniowiecki et al. 1983; (*30*) Symons et al. 1998a; (*31*) Brannon et al. 1996b; (*32*) Brannon et al. 1992a' (*33*) Grandia et al. 2000; (*34*) Brannon et al. 1995; (*35*) Hearn et al. 1987; (*36*) Ravenhurst 1987; Arne et al. 1990; (*37*) Ravenhurst 1987; (*38*) Ravenhurst et al. 1987; 1989; (*39*) Ravenhurst et al. *1987*, 1989; (*40*) Arne et al. 1992; (*41*) Arne 1991; (*42*) Ravenhurst et al. 1989; (*43*) Lange et al. 1983; (*44*) Stein and Kish 1985, 1991; (*45*) York et al. 1981; (*46*) Hay et al. (*47*) Arne et al. 1990; (*48*) Symons and Stratakos 2001

Paleomagnetic techniques

Remagnetization or resetting of the magnetic signature by fluid-related chemical reactions has been well documented (e.g., McCabe and Elmore 1989) and thus the resetting a paleomagnetic signature in rocks is an expected consequence of the migration of MVT ore-forming fluids. With the advent of sensitive, modern cryogenic magnetometers, it has become possible to date MVT deposits using paleomagnetism. MVT deposits are ideal candidates for the paleomagnetic technique because they commonly occur in relatively undisturbed, tectonically stable, platforms. Symons et al. (1996b) summarized the methodology, as well as the results from several districts. The paleomagnetic method relies on the presence of minute concentrations of magnetic minerals such as magnetite, hematite, or pyrrhotite that record the direction of the Earth's magnetic field at the time of mineral development or growth. It is important to note that these minerals do not have to be the dominant iron species in the rocks in order to get a readable signal. Even though other iron-rich minerals, such as pyrite, may be present in much higher concentrations, they will have no effect on the paleomagnetic signature because they do not retain remnant magnetizations.

Excluded dates

Several results have been excluded from our analysis. It is important to note that these dates are not necessarily wrong, but, rather, they do not place adequate constraints on the time of mineralization. Nevertheless we report them here for reference.

Fission track dates

The dates in Table 1 that were excluded from our interpretations include fission track dates (Ravenhurst et al. 1989, 1994; Arne 1990, 1991) for the Pine Point, Gays River, southeast Missouri, and Tri-State districts because they yield only maximum or minimum ages for ore deposition. The fission track dates only provide estimates of the time at which cooling occurred to below the annealing temperature of either apatite or zircon. Generally, the fission track studies assume that the thermal regime related to track annealing relates to the thermal event associated with MVT mineralization. However, the temperature of final annealing for apatite, for example, may be post-mineralization cooling or to thermal events unrelated to ore deposition. Despite these limitations, the reported fission track studies yield ages that are generally in broad agreement with reported paleomagnetic and/or radiometric dates (Table 1). The only significant disagreement is for the fission track date for Pine Point (Arne 1991; Ravenhurst et al. 1994), which conflicts with the Rb–Sr date reported by Nakai et al. (1993). However, the fission track dates are in broad agreement with the paleomagnetic date for Pine Point as reported by Symons et al. (1993).

Radiometric dates for Viburnum Trend/southeast Missouri districts

The first attempt to radiometrically date the ores in southeast Missouri was by York et al. (1981), who used $^{40}Ar/^{39}Ar$ methods on pyrite. This attempt yielded an impossibly old date of 549 ± 20 Ma, which is older than the host rocks. Several attempts have been made to date the southeast Missouri ores using Rb/Sr techniques. Lange et al. (1983) used fluid inclusions in galena to obtain a date of 392 ± 11 Ma, which was contested by Ruiz et al. (1985) and partially retracted (Lange et al. 1985). Several Rb–Sr dating attempts were made on glauconites from the Bonneterre Formation that yielded dates ranging from about 350 to 400 Ma (Posey et al. 1983; Grant et al. 1984; Stein and Kish 1985, 1991). The available evidence suggests that the ore-forming fluids in the Viburnum Trend varied substantially in isotopic composition. For example, Sverjensky et al. (1979) found that Pb and S isotopic compositions in galena varied as much on a scale of microns within single crystals as over the entire range for the ore district. Moreover, Brannon et al. (1991) showed that initial Sr isotopic compositions for multiple wafers of single-crystal vug-filling sphalerite, chalcopyrite, and galena were highly variable. Because the variations were large compared with subsequent in situ generation of radiogenic ^{87}Sr, these minerals were found to be unsuitable for radiometric dating because they failed to satisfy the crucial requirement of formation from a reservoir of uniform isotopic composition. In view of the evidence for highly variable ore-forming fluids, radiometric dates of authigenic glauconite, which were reported to have obtained uniform initial Sr isotopic composition from such fluids (Stein and Kish 1985 , 1991), must be considered suspect.

Potassium–argon dates on samples of illite in the Viburnum Trend range from 489 ± 8 to 297 ± 7 Ma, which are interpreted to indicate a minimum date of < 297 ± 7 Ma (Hay et al. 1995) for mineralization. This minimum date is consistent with regional geological and geochemical evidence (Leach and Rowan 1986; Leach 1994; Goldhaber et al. 1995), which suggests the ore in southeast Missouri is related to widespread MVT mineralization younger than Mid-Pennsylvanian rocks (about 300 Ma).

Potassium–argon dating of illite in the Cévennes region, southern France

Results of K–Ar dating on illite in rocks of the Cévennes region of southern France has been interpreted to reflect deposition of the ores during Mesozoic extension (Toulkeridis et al. 1993; Clauer et al. 1996, 1997) whereas paleomagnetic dating (Lewchuk et al. 1998b, 1998c, 1998d; Henry et al. 2001; Rouvier et al. 2001;) yielded an age of mineralization of Early–Middle Eocene, corresponding to Pyrenean compression. Recent U–Pb, Th–Pb, and Sm–Nd dating of fluorite associated with the lead–zinc ores in the Cévennes region are consistent with the paleomagnetic dates (Leach et al. 2001). In view of the correspondence of dates from several paleomagnetic studies, and of three radiometric systems, the illite dates are believed to represent widespread diagenesis of rocks in Liassic time and do not yield reliable ages for MVT mineralization. This disagreement will be discussed in more detail below.

Radiometric dates for Gays River

Excluded from our discussion are several Ar–Ar and K–Ar studies on feldspar and mica minerals by Ravenhurst (1987), Ravenhurst et al. (1989), and Arne et al. (1990) for the Gays River deposit. The reported dates are excluded only because the results are given in terms of maximum or minimum dates. Although these dates were excluded, each of the reported dates is consistent with the paleomagnetic date (Pan et al. 1993) and in broad agreement with the Ar–Ar date on biotite by Kontak et al. (1994) for the Gays River deposit.

Other exclusions

Excluded from our consideration is the result from Brannon et al. (1995) for late-stage calcite from central Tennessee because the calcite dated post-dates ore emplacement. Also excluded from consideration is the Ar–Ar date (322 Ma) for pre-ore feldspar from East Tennessee (Hearn et al. 1987) because the reported date provides only a minimum age for the East Tennessee mineralization (Middle Carboniferous). This minimum date (Hearn et al. 1987) is generally consistent with the paleomagnetic date (316 ± 8 Ma) reported by Symons and Stratakos (2000, 2001). As discussed later, the Ar–Ar as well as the paleomagnetic dates by Symons and Stratakos (2000, 2001) do not agree with the Devonian dates (377 ± 29 and 347 ± 20 Ma) reported by Nakai et al. (1990, 1993).

General observations

Correspondence with convergent orogenic events: The majority of the dates presented in Table 1 show a remarkable correlation with broadly coeval convergent events within the orogen or adjacent to the orogenic belt that hosts the ore deposits (Symons et al. 1996b). Only the deposits in the Lennard Shelf of Australia and Nanisivik in Canada have dates that do not correspond to compressional tectonic events.

The deposits with dates that correspond to convergent orogenic events comprise the vast proportion of all MVT ores mined in the world. Although this relationship has been frequently hypothesized in the past (e.g., Leach 1973; Garven 1985; Leach and Rowan 1986; Oliver 1986; Bethke and Marshak 1990), the new dates provide compelling proof that there are important genetic relationships between convergent orogenic events and the formation of MVT deposits. Despite the fact that the vast majority of MVT ores formed during continental compression, the few MVT deposits that formed during continental extension underscores the diversity of MVT ore-forming processes (Leach and Sangster 1993). The best documented example of MVT formation in an extensional environment is the deposits of the Lennard Shelf, Australia. For the Lennard Shelf deposits, the age obtained for ore deposition coincides with crustal extension of the Fitzroy Trough. There are no compressive tectonic events that have affected the region since the time that the host rocks were deposited.

Correspondence between radiometric and paleomagnetic dating methods

One very important auxiliary observation obtained from the data presented in Table 1 is that there is a broad agreement between the dates obtained by radiometric methods and dates determined by paleomagnetic techniques. For the deposits or districts that have been dated by both radiometric and paleomagnetic methods, eight are in agreement whereas only two differ (Pine Point and East Tennessee). For the MVT deposits in the Cévennes region of France, the paleomagnetic and radiometric dates (Sm–Nd, U–Pb, and Th–Pb on the ore) are consistent; however, these dates do not agree with K–Ar dates on illite in the host rocks. There are three districts that have only radiometric dates and four that have only paleomagnetic dates. For these seven districts we propose that significant geological evidence exists to accept the validity of the reported age dates.

The general agreement between paleomagnetic dates yields added confidence to both the reliability of the radiometric dates and the application of paleomagnetic dating techniques to MVT systems. Because radiometric dating and paleomagnetism have so little in common, it is highly unlikely that they would yield identical but incorrect dates. Furthermore, the excluded Ar–Ar dates for feldspar in East Tennessee and the fission track dates for Pine Point (Table 1) are more consistent with the paleomagnetic dates than with the radiometric dates. However, some general comments are needed regarding the conflicting age dates.

Pine Point

The ore deposits of the Pine Point district are located along the northeastern flank of the Western Canada Sedimentary Basin and are hosted by Middle Devonian dolostone. The age of ore deposition in the Pine Point district has been central to the often contentious debate about fluid-flow in the basin. It is not an intention of this paper to dwell on the debate about the age of fluid flow in the Western Canada Sedimentary Basin; however, it is important to summarize briefly the scope of the problem and to present some information that is central to the debate because Pine Point is the one large MVT district where there is a major difference between radiometric and paleomagnetic dates. Additional discussions are given by Symons et al. (1998b), Qing and Mountjoy (1990, 1992, 1994, 1995), Nesbitt and Muehlenbachs (1993, 1994, 1995a, 1995b), Symons et al. (1999a), and Lewchuk et al. (1998a).

Garven (1985) first suggested that fluid-flow from the emergence of the Rocky Mountains in Laramide time was responsible for ore formation at Pine Point. Paleomagnetic dating of the Pine Point deposits indicates that the ore formed between Mid-Late Cretaceous and Paleocene (71 ± 13 Ma) (Symons et al. 1993) whereas radiometric dating by Rb–Sr sphalerite isochron yields Middle Devonian ages of 361 ± 13 and 374 ± 21 Ma (Nakai et al. 1993; J. Brannon, personal communication in Symons et al. 1996b). Additional support for a Laramide age for fluid flow in the Western Canada Sedimentary Basin is presented by the paleomagnetic dates determined for the MVT deposits at Monarch-Kicking Horse (Symons et al. 1996a, 1998b ,) and Robb Lake (Smethurst et al. 1999; Symons et al. 1999b) as well as from hydrocarbon reservoirs (Cioppa and Symons 2000; Cioppa et al. 1998a). All of these studies are from the western part of the Western Canada Sedimentary Basin and have a Laramide age. Further support for a Laramide age is given by the fission track dates in Table 1 provided by Ravenhurst et al. (1994).

Despite the evidence that supports the paleomagnetic date for Pine Point, the two independent Rb–Sr dates for deposition of sphalerite (Nakai et al. 1993 and J. Brannon, personal communication in Symons et al. 1996b) also must be considered valid dates. Although the reason for the discrepancy is unclear, it is possible that the two sets of dates are both correct in the sense that the deposits could have formed during two separate fluid events (Symons et al. 1996b): one related to the Devonian Antler orogeny, and another related to the Laramide orogeny in Late Cretaceous to Tertiary. As pointed out by Symons et al. (1996b), this possibility is consistent with the bimodal fluid inclusion compositions reported by Viets et al. (1996) for sphalerite from the Pine Point district.

East Tennessee

The East Tennessee ores are hosted by Lower Ordovician Knox Formation. Paleomagnetic dating of the ores has yielded Middle Pennsylvanian to Early Permian dates of 286 ± 20 Ma (Bachtadse et al. 1987) and 316 ± 8 Ma

(Symons and Stratakos 2000; 2001), whereas the Rb–Sr isochron method for sphalerite (Nakai et al. 1990, 1993) yielded slightly older Middle Devonian dates (347 ± 20 and 377 ± 29 Ma). Hearn et al. (1987) determined that feldspar that pre-dated deposition of sphalerite formed at ~322 Ma, which provides an apparently older age limit for sphalerite deposition. Elliot and Aronson (1987) determined that widespread K-bentonite illitization in the southern Appalachian basin, including some samples 20 km north of the Mascot–Jefferson City subdistrict, formed at 291 ± 9 Ma. They suggested that this was the age for the nearby MVT ores. In addition, Sedivy et al. (1984) used K–Ar methods to date metamorphism by Alleghenian thrusting of the underlying Conasauga shales at 300 ± 20 Ma. Kesler et al. (1988) used Sr isotopic modeling for fluid inclusions in host rock, ore, and gangue minerals and obtained an estimated 408- to 320-Ma range for dates of MVT formation in the district. Taylor et al. (1983) noted that Alleghenian-age fractures that cut ore and detrital sphalerite in pre-deformation internal sediments require ore deposition to pre-date Middle Permian Alleghenian (> = 265 Ma). Considering the range of dates permitted by the 95% confidence level for the two paleomagnetic dates, the two reported dates differ by only 2 Ma; thus, the disagreement is not great. Likewise, the reported K–Ar dates on unmineralized rocks in the region (Sedivy et al. 1984; Elliot and Aronson 1987; Hearn et al. 1987) do not differ much from the range in the paleomagnetic dates. Symons and Stratakos (2000; 2001) propose that the Mascot–Jefferson City subdistrict recorded the early to mid-Alleghenian orogeny with fluids coming from more core regions of the orogen to the southeast. In contrast, the Rb–Sr method for sphalerite yielded dates that are distinct from the paleomagnetic results. Nakai et al. (1990, 1993) proposed that the ore fluid migrated during the Acadian orogeny. The cause of this disagreement remains unclear.

Cévennes

Many occurrences and deposits of lead–zinc mineralization in the Cévennes region of southern France are hosted by Triassic and Jurassic carbonates (Macquar et al. 1990). The most important MVT lead–zinc deposit in the Cévennes region is Les Malines. The Triassic sandstone-hosted lead deposit at Largentière is second only to Les Malines deposit in importance. Although we have excluded sandstone-hosted lead–zinc deposits in this discussion, it should be noted that the ores of Largentière are similar to the nearby carbonate-hosted ores (e.g., Macquar et al. 1990; Macquar and Leach 1995). Possibly, the sandstone-hosted ores of Largentière have a genetic affinity with the nearby carbonate-hosted ores.

The host rocks for the Les Malines ores are Cambrian and Jurassic carbonates A Liassic age (about 190 Ma) was reported by Toulkeridis et al. (1993) and Clauer and Chaudhuri (1995) for mineralization at Les Malines using K–Ar dating of illite in the host rocks together with Pb–Pb isotope data. Although the Liassic age of about 190 Ma could be ascribed to the Cambrian-hosted ores at Les Malines, this age cannot be applied to the Bathonien-hosted ores (Jurassic, between 160 and 167 Ma), which accounts for more than 50% of total production. To explain the relatively invariant lead-isotope composition of the Cambrian and Jurassic-hosted ores at Les Malines, deposition of ores in the Jurassic rocks was attributed to the remobilization of a homogeneous Triassic lead-reservoir (Le Guen et al. 1991) without contamination by radiogenic lead produced in the surrounding rocks. Although it is remotely conceivable that such a remobilization occurred, this scenario would require remarkably difficult geochemical and hydrological conditions. These conditions include (1) unusually low amounts of uranium in the source rocks or aquifers that would yield radiogenic lead; (2) fluid migration pathways that restrict geochemical communication of the ore fluid with external sources of radiogenic lead; and (3) a fluid that is capable of leaching lead from one reservoir but not from another and transporting the lead to another location without isotopic contamination. Considering the large amount of fluid necessary to form MVT deposits and the large scale of MVT ore-forming processes, it seems rather improbable that such conditions could have existed.

Paleomagnetic studies of MVT deposits in the Cévennes region (Rouvier et al. 1995; Lewchuk et al. 1998b, 1998c, 1998d; Henry et al. 2001; Rouvier et al. 2001) have argued that the MVT deposits in the Cévennes region are related to a regional fluid-flow event in the Early–Middle Eocene. The magnetic overprint in this region is believed to be related to fluid migration during the end of the main uplift and metamorphism in the axial part of the Pyrénées mountains located to the south of the Cévennes. Uplift of the Pyrénées orogenic belt, formation of the MVT deposits, and widespread chemical remagnetization are all inter-related aspects of the convergence of the Iberian block with the European plate during the Pyrenean orogeny (Lewchuk 1998b, 1998c, 1998d; Henry et al. 2001; Rouvier et al. 2001). The paleomagnetic date also corresponds to apatite fission-track dates that apparently record the uplift and cooling of rocks of the southeast sedimentary basin on the eastern border of the Cévennes region (Pagel et al. 1997). Thus, the inversion of the southeast basin, and uplift of the Pyrénées Mountains, and widespread fluid flow in the region were broadly coeval.

Recent radiometric dating of fluorite (Leach et al. 2001) from several MVT deposits in the Cévennes region by U–Pb, Th–Pb, and Sm–Nd dating of fluorite yields dates that are consistent with the paleomagnetic dates. The fluorite dated includes samples that lie within and bracket sphalerite paragenetic stages in the Durfort deposit. Each of the three radiometric systems (Th–Pb, U–Pb, and Sm–Nd) on the same sample yielded dates of about 78 ± 25 Ma. The radiometric and paleomagnetic dates confirm that at least some of the ores in the Cévennes region formed during the Pyrénées orogenic cycle.

Consistent with the proposal that MVT mineralization was the result of fluid-flow during uplift of the Pyrenean orogenic belt, U–Pb dating of ore-stage calcite from MVT ores in the Cretaceous Maestrat Basin of eastern Spain yielded a date of 62.6 ± 0.7 Ma (Grandia et al. 2000). These ores are situated on the southern foreland of the Pyrénées. This date is consistent with the paleomagnetic date for MVT deposits in the Cévennes region north of the Pyrénées and suggests that fluid flow related to the Pyrénées uplift may have occurred on both sides of the orogen.

Duration of MVT mineralization

Despite the progress that has been achieved in obtaining ages for MVT ore-forming events, few studies have focused on the duration of MVT mineralizing events. Information on the duration of the MVT event is clearly needed in view of evidence that the ores in some MVT districts were deposited during multiple ore-forming events (e.g., Leach 1994; Brannon et al. 1997). In addition, the mere presence of a mineral paragenetic sequence for ore and gangue mineral deposition implies an evolving fluid system that could have existed for considerable amounts of time. A better understanding of the duration of MVT ore-forming events is also needed to evaluate better the results from different age-dating approaches. For example, most radiometric studies on MVT deposits provide the age of deposition for a single stage of the paragenetic sequence. In contrast, paleomagnetic methods typically use more than 100 specimens from more than ten sites and, therefore, probably reflect broader information of the MVT hydrothermal event.

Rowan and Goldhaber (1995) used fluid inclusion data together with thermal alteration of biomarkers to calculate the duration of the ore-forming event in the Upper Mississippi Valley district. They determined that the duration could have been between 37,000 yrs. to 1.4 m.y., depending on whether the highest or the lowest group of fluid inclusion homogenization temperatures was used for the calculations. The best fit of the fluid inclusion data to the biomarkers yielded a probable duration of about 200,000 yrs, consistent with the 250,000 yrs estimated from fluid–rock (mass transfer) arguments for the Upper Mississippi Valley district (Lavery and Barnes 1971). Repetski and Narkiewicz (1996) used fluid inclusion data together with time–temperature-dependent thermal alteration of conodonts in the Cracow–Silesia zinc-lead district in southern Poland. Their calculations indicate that the Polish ore-forming event could not have lasted for more than about 50,000 yrs.

Symons et al (1998a) used paleomagnetic techniques in the Viburnum Trend to determine that the time span between the deposition of main-stage (cube–octahedral galena) and late-stage (cubic galena) ore was between 5 and 12 m.y. An interesting side result of the paleomagnetic work is the tendency for the paleomagnetic data to have an oval rather than circular distributions about their mean (Lewchuk and Symons 1995). In the absence of other possible explanations (such as faulting, differential tilting, etc.) and recognizing the tendency for the elongation direction to match the trend of the apparent polar wander path, it is likely that the data are recording continental drift during the acquisition of the remanence component. Lewchuk and Symons (1995) attempted to quantify this effect by comparing the amount of elongation in a given data set to the expected rate of apparent polar wander for that time. They found that at an average rate of apparent polar wander of 0.3° of arc per m.y., it would take several million years to produce enough elongation in the distribution to be visible in a paleomagnetic data set. When the paleomagnetic data from six major North American MVT districts were combined, they indicated that the upper limit for mineralization process may be as great as 25×10^6 years. It should be noted that any estimate generated in this manner would include the effects of precursor fluids associated with, but not necessarily directly depositing the MVT ones. Thus, this conclusion from the paleomagnetic data should be considered an upper estimate for the duration. For example, Lewchuk and Symons (1995), and Symons and Stratakos (2000) provided paleomagnetic evidence that pre-ore dolomitization in some MVT districts occurred approximately 20 ± 10 m.y. prior to sulfide mineralization.

The limited number of studies that address the duration of MVT systems do not permit us to draw significant conclusions about this important question. However, it is interesting to point out that estimates of the duration of MVT ore-forming events, based on time–temperature data for thermal alteration of organic matter are of the order of tens to several hundreds of thousands years whereas paleomagnetic studies indicate durations on the order of about a million to several million years. This contrast between estimated durations from paleomagnetic and thermal alterations techniques seems to support the conclusions of Appold and Garven (1999) that topographically driven fluid formed the ores of the Viburnum Trend district. Based on transient numerical modeling of mass and energy transport by topographic gradients, the period of mineralization in southeast Missouri was relatively short (of hundreds of thousands of years) relative to the lifetime of the gravity-flow system that could have persisted for tens of millions of years. Thus, we speculate that paleomagnetic studies may yield dates that reflect the life of the regional hydrological system whereas the thermal alteration of organic matter reflects the duration of the more time-restricted thermal-pulse within a regional hydrological event.

MVT deposits through geologic time

Precambrian

No MVT deposits are known to be in Archean rocks and only five deposits (Nanisivik, Gayna River, Coxco, Pering-Bushy Park, and the recently discovered Esker deposit in Canada) are known to be hosted by rocks of Proterozoic age (Fig. 1). The willemite deposit of Vazante, Brazil has long been considered to be an MVT deposit hosted by Proterozoic rocks. However, recent work on the deposit suggests that it may not be a MVT deposit (Murray Hitzman, personal communication 2001). The presence of these deposits in Proterozoic rocks does not imply that they necessarily formed in Proterozoic time. The Nanisivik deposit located on Baffin Island, Canada, is the only MVT deposit hosted in Proterozoic rocks that has been successfully dated (Symons et al. 2000). They report a paleomagnetic date of 1,095 ± 10 Ma.

The hypothesized locations of Nanisivik and other Proterozoic-hosted MVT deposits are shown on a reconstruction of the supercontinent Rodinia at 1,000 Ma (Fig. 2). In view of the common association of MVT deposits inboard of orogenic zones, the possible positions of the Grenvillian orogenic belts are also shown in Fig. 2. Granted that the positions of the continental segments that formed Rodinia, together with its orogenic belts and possible MVT deposits, are poorly known, there is still no clear spatial relationship between the location of the ore deposits with respect to the Grenvillian orogenic belts.

In contrast to the few MVT deposits hosted in Proterozoic rocks, SEDEX (sedimentary exhalative) lead–zinc are rather abundant (Sangster 1990). This observation is inconsistent with the commonly suggested notion that SEDEX and MVT deposits probably have common genetic processes (e.g., Hutchinson 1980; Goodfellow et al. 1993, p. 242). As Sangster (1990, p. B30) noted " Curiously, MVT deposits are relatively scarce in rocks of Proterozoic age, particularly considering the fact that the Proterozoic represents nearly six times the length of Paleozoic time". This paucity is not related to a lack of carbonate rocks because carbonate rocks of Proterozoic age are reasonably abundant. An especially curious aspect is that rocks of Proterozoic age are the host of many of the world's SEDEX lead–zinc deposits (e.g., McArthur basin, Australia, and the Sullivan deposit in the Belt basin, Canada). The relative abundance of SEDEX lead–zinc deposits in large Proterozoic basins attests to the fact that lead–zinc ore-forming processes involving basinal brines were present in many sedimentary basins. One possible explanation for the scarcity of MVT ores in Proterozoic rocks is that they may have been destroyed by erosion. However, considering the relative proportion of Proterozoic SEDEX lead–zinc deposits preserved relative to MVT lead–zinc deposits, more fundamental issues may be involved that we do not understand.

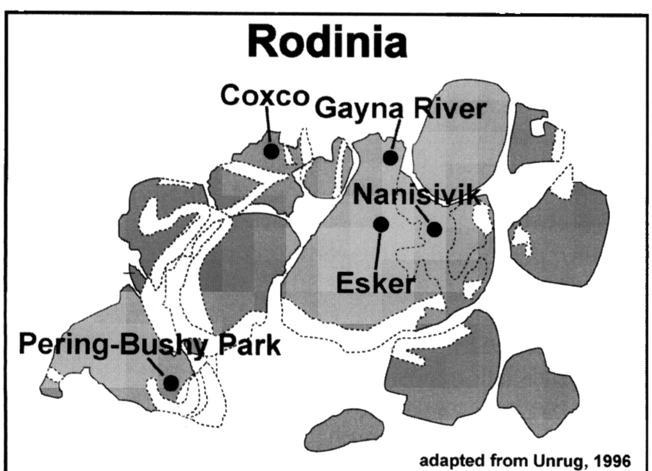


Fig. 2 Reconstruction of Rodinia at 1,000 Ma from Unrug (1996) and Weil et al. (1998) with the positions of MVT deposits that are hosted in Proterozoic rocks. Position of the Grenvillian orogenic belts is *stippled*

Phanerozoic

Figure 3 shows the distribution of published Phanerozoic ages for MVT deposits and districts together with the ages of their host rocks. The length of the bars shown in this figure for the ages of ore formation represent the uncertainty reported (usually at the 95% confidence level) for each age determination (Table 1). Two important observations are evident from Fig. 3. First, there is general agreement between the dates reported by paleomagnetic and radiometric techniques. Secondly, it is remarkable that the ages of MVT formation are grouped into two distinct windows of time: one spans the Devonian to Late Permian and the second spans Cretaceous to Late Tertiary. Equally impressive is the absence of ages in the Early Paleozoic and that there are only three dates that fall in Mesozoic. We estimate that the dated deposits shown in Fig. 3 have yielded about 80% of the total combined lead–zinc metal (based mainly on unpublished data, Sinclair et al. 1999) produced from all known MVT lead–zinc deposits. Thus, Fig. 3 reflects the age of MVT formation for most of the MVT lead–zinc ores mined on the globe.

The deposits of the Cévennes region of France could be Mesozoic if the K–Ar dates for illite formation in the host rocks are accepted as representative of MVT deposition (Toulkeridis et al. 1993; Clauer and Chaudhuri 1995). The acceptance of the illite age dates requires the rejection of Early–Middle Eocene paleomagnetic age (Rouvier et al. 1995; Lewchuk et al. 1998b, 1998c, 1998d; Henry et al. 2001; Rouvier et al. 2001), which is consistent with the U–Pb, Th–Pb, and Sm–Nd radiometric dates (Leach et al 2001). The best-fit

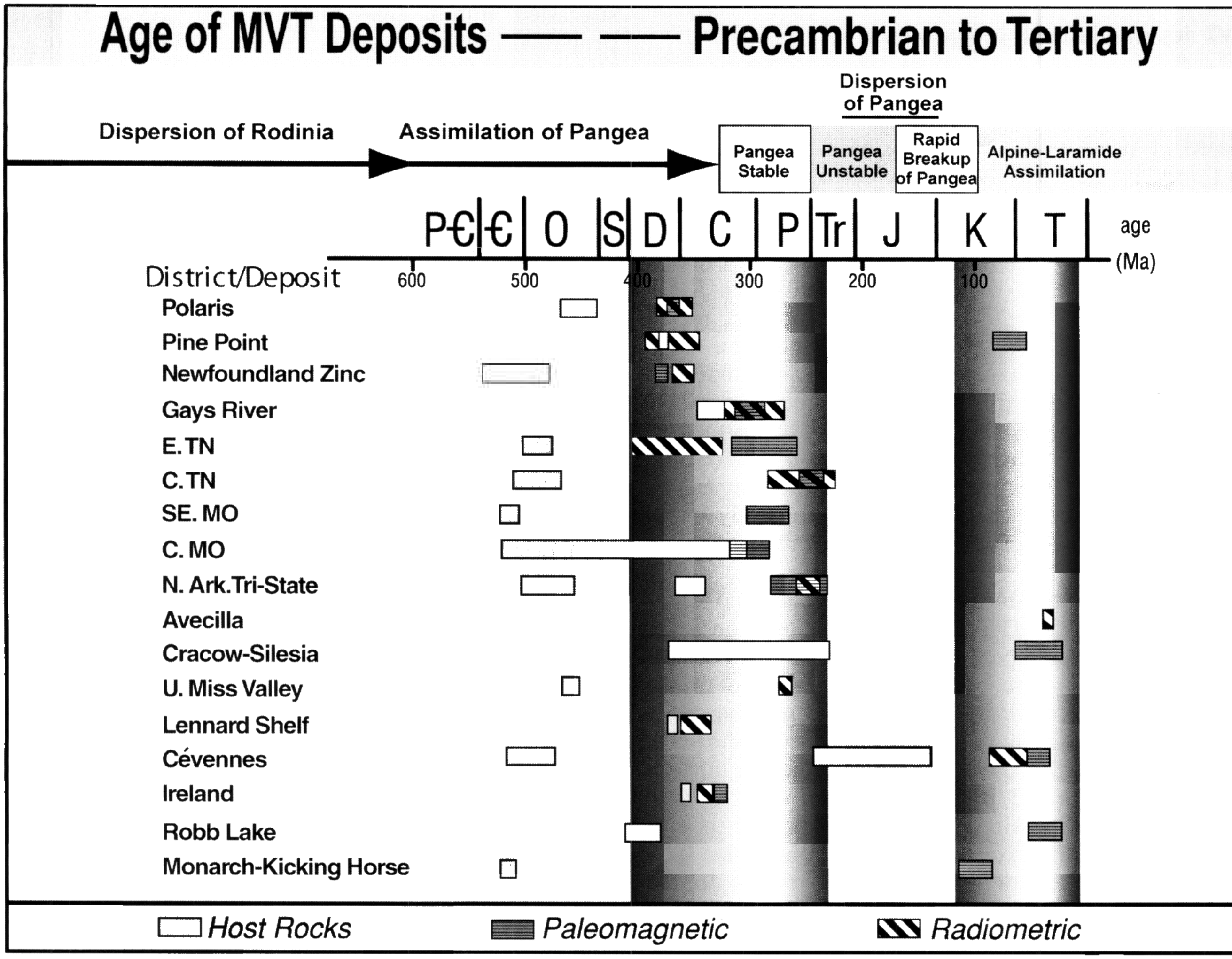


Fig. 3 Distribution of radiometric and paleomagnetic ages of MVT deposits and their host rocks in the Phanerozoic

paleomagnetic age for central Tennessee (Lewchuk et al. 1996a) is Late Permian; however, the mineralization could have continued until the earliest Triassic.

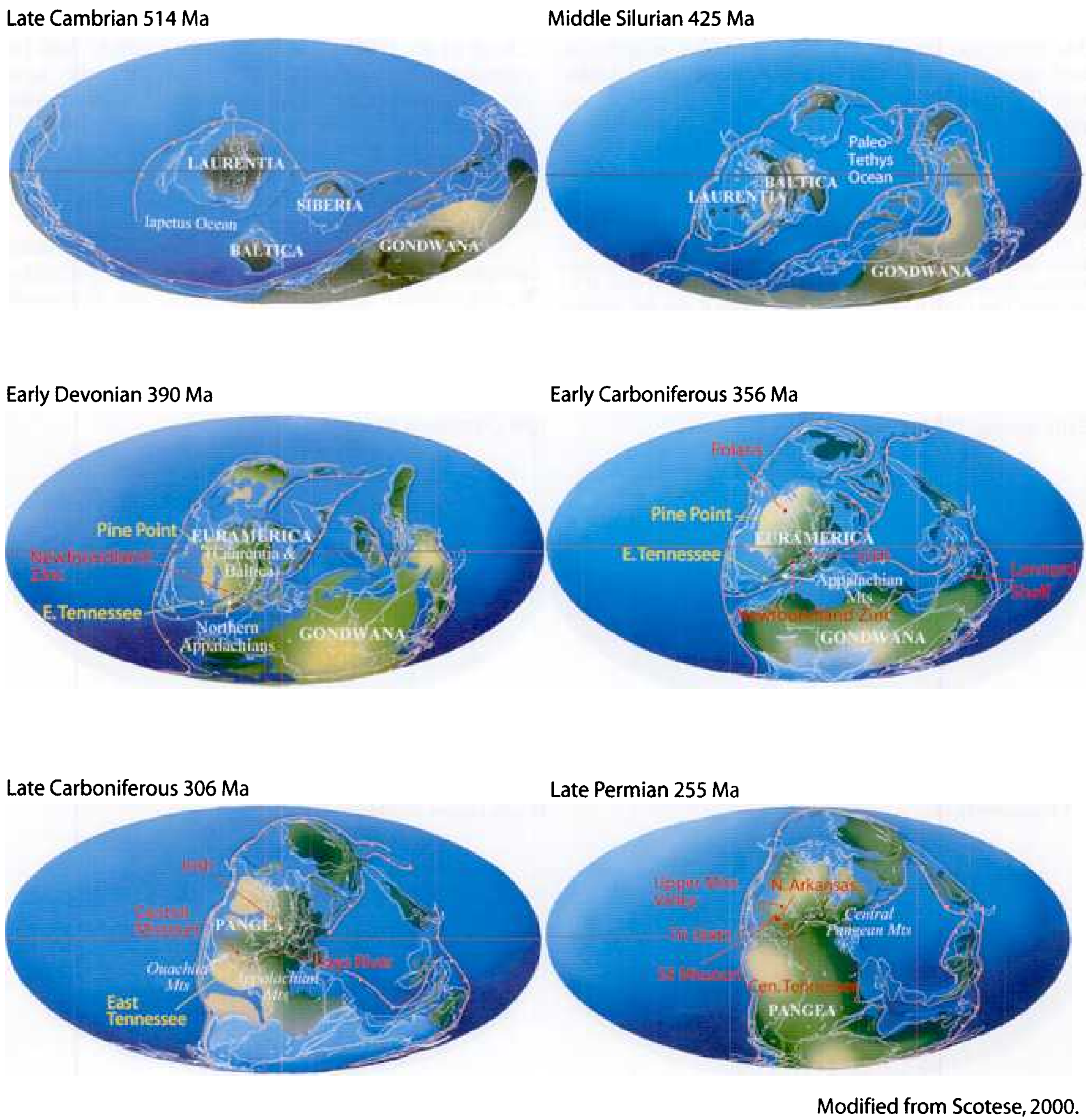
Paleozoic

The formation of MVT deposits with respect to paleogeographic positions of the continents through the Paleozoic is illustrated in Fig. 4. The paleogeographic reconstructions have been modified from Scotese (2000) and the discussions of plate motions are excerpted from Ziegler (1992), and Scotese (2000). The reader is referred to these publications and the references therein for more elaborate discussions of the interpreted plate motions and interactions. Despite the simplification of the paleogeographic positions shown in Fig. 4, this illustration does highlight some interesting possibilities regarding the genesis of MVT deposits. Late Proterozoic and Paleozoic time marked the dispersal of various continental components of Rodinia and their eventual amalgamation into a new supercontinent, Pangea, by Late Permian. Early Cambrian was the time of the final assembly of Gondwana and a period of divergence between Laurentia, Baltica, and Siberia. Late Cambrian is considered to be the beginning of the Caledonian orogenic cycle that continued into the Devonian. Ordovician and Silurian convergence of Laurentia–Greenland with Fennoscandia–Baltica resulted in their suturing along the Arctic-North Caledonides and the creation of Laurentia (Ziegler 1992). Although there are no dates available for the stratabound, sandstone-hosted lead–zinc deposits of the northern Caledonides (e.g., Laisvall, Sweden), geological evidence points to these deposits as products of continental-scale fluid migration during the Caledonian orogenic cycle (Rickard et al. 1979; Duane and de Wit 1988). Paleomagnetic dating was attempted at the Laisvall deposit but failed (A. Bjørlykke and D.T.A. Symons, personal communication 2001).

As noted by Christensen et al. (1996) and Symons et al. (1996b), the Devonian to Late Permian was a significant period for MVT formation in geologic time. This period marked a series of continental collisions that culminated in the formation of Pangea. The first age dates in the Paleozoic for MVT mineralization are the

Devonian ages for the deposits of the Lennard Shelf, Newfoundland Zinc, Polaris, and possibly East Tennessee. The Rb–Sr dates for the Pine Point district are Early to Late Devonian to Mississippian. By Permian time, many of the world's great MVT districts had formed, including the MVT districts of the US mid-continent, eastern United States and Canada, and Ireland. With the exception of the Lennard Shelf MVT deposits, these deposits formed during or shortly after periods of continental suturing and inboard of the orogenic zones. Data from the World Minerals Geoscience Database (Sinclair et al. 1999) show that the total metal produced from the deposits that formed during the final assembly of Pangea, from Devonian through Permian, account for about 75% of the combined metal produced from all MVT deposits that have been dated. Of all

Fig. 4 Selected paleogeographic reconstructions of the continents in Late Cambrian to Late Permian showing the progressive formation of MVT during the assimilation of Pangea. The reconstructions shown were modified from Scotese (2000). The paleogeographic reconstructions were selected because they best approximate the ages of the MVT deposits. Pine Point and East Tennessee are shown in *yellow* on different paleogeographic reconstructions because they have several reported dates. Some MVT deposits or districts appear on two plate reconstructions because their date falls between the available paleogeographic time slice



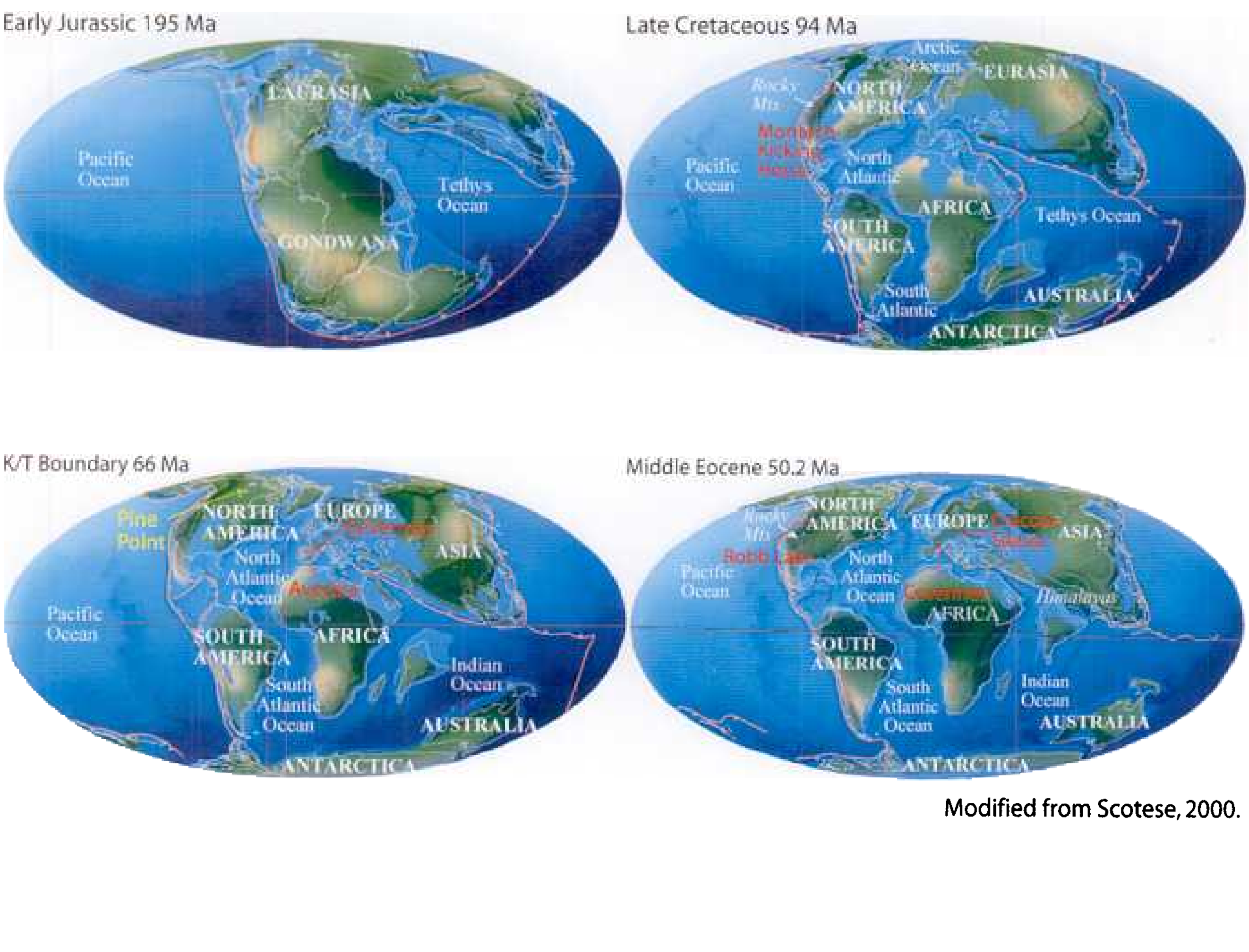
MVT deposits, including both dated and undated, the Pangean ores total at least 60% of all MVT metals mined.

Triassic–Jurassic

Late Permian–Early Triassic time (Fig. 5) marked the beginning of the breakup of Pangea (e.g., Ziegler 1992) as reflected by the propagating Tethys rift system across the interior of the Pangean supercontinent. By Early Jurassic, the accelerated opening of the Gulf of Mexico–Central Atlantic Tethys rift zone (Ziegler 1992) led to the development of a new divergent zone separating Gondwana and Laurasia. Continental extension in the Mesozoic was accompanied by extensive magmatism and anomalous heat flow in the Pangean crust (Anderson 1982). This period is widely believed to be an important time for extensive hydrothermal mineralization in Europe, especially for the formation of fluorite–barite veins (Joseph et al. 1973; Mitchell and Halliday 1976; Baubron et al. 1980; Marcoux et al. 1990). In the United States, the important fluorite deposits in Illinois and Kentucky formed during Permian to Upper Jurassic time (Chesley et al. 1994; Symons 1994; Brannon et al. 1997). In addition to fluorite vein formation in Europe, the sandstone-hosted lead–zinc veins in Maulbach–Mechernich deposits in the Eifel basin of Germany yielded a Middle Jurassic Rb–Sr age of 168 ± 6 Ma. (Schneider et al. 1999). As far as MVT deposits, only the deposits of the Cévennes region in France are suggested to be of Liassic age based on K–Ar dating of clays and assumed lead isotope relationships to the ore deposits (Toulkeridis et al. 1993; Clauer and Chaudhuri 1995, Clauer at al. 1996). This K–Ar date conflicts with the paleomagnetic and radiometric dates for the same district. Nevertheless, it is clear that the widespread Mesozoic extension was not an important time for MVT ore deposition. Perhaps, as Leach and Sangster (1993) suggested, the geologic setting and ore-forming processes were distinctly different for MVT lead–zinc ores and fluorite–barite deposits.

Many European MVT deposits have been broadly assigned a Mesozoic age despite the limited geochronological evidence to support this conclusion. For example, the MVT lead–zinc deposits of the Cévennes region are assumed to have formed during the same mineralizing event responsible for the uranium deposits in

Fig. 5 Selected paleogeographic reconstructions of the continents in Early Jurassic to Middle Eocene showing the formation of MVT deposits and districts. The reconstructions shown were modified from Scotese (2000). The paleogeographic reconstructions were selected because they best approximate the ages of the MVT deposits. Pine Point is shown in *yellow* because it also has reported ages of Late Devonian–Early Mississippian (Fig. 4). The Cévennes district appears on two plate reconstructions because its date overlaps both the Middle Eocene and the Cretaceous–Tertiary reconstruction



Modified from Scotese, 2000.

southern France (Lancelot et. al. 1995), despite the fact that uranium and MVT lead–zinc deposits form by extremely different fluids and processes. The Polish MVT zinc–lead ores have long been thought to have formed in the Triassic (e.g., Sass-Gustkiewicz et al 1982; Sass-Gustkiewicz and Kwiecinska 1999) despite the fact that paleomagnetic age dates in the district yield a Tertiary age (Symons et al. 1995) and field relationships show that the ore must be post-Jurassic in age (Kibitlewski 1991; Gorecka 1993). Perhaps this attraction to Mesozoic ages is caused mainly by the fact that many important MVT deposits in Europe are hosted by Triassic and Jurassic rocks in which a variety of primary and diagenetic sedimentary features and Mesozoic age faults served as important ore controls. This European situation is similar to that in North America where the MVT deposits are mainly hosted by rocks of Cambrian to Ordovician age, but, as yet, there is no evidence that the mineral deposits formed during this time.

Liassic thermal event

Much attention has been drawn to the frequently postulated associations of MVT mineralization in Western Europe and northern Africa to the "Liassic hydrothermal event". In view of the broad acceptance of a widespread Liassic mineralizing event, additional discussions are warranted. Recognition of this Liassic hydrothermal event is based in part on abundant K–Ar dates on clay-to-mica material in sedimentary rocks (Clauer and Chaudhuri 1995; Clauer et al. 1996, and references therein), which clearly demonstrate some significant thermal event produced new mineral growth or reset the K–Ar ages of clay-to-mica material over a large area in Europe and North Africa. This "Liassic thermal event" is also based in part on fluid inclusion studies of diagenetic phases in rocks such as quartz overgrowths in sandstones (Clauer et al. 1996, and references therein), despite the fact that clear contemporaneous relationships between the clay-to mica material and the minerals that host the fluid inclusions have not been established. We recognize that the Mesozoic, and especially the Liassic time in Europe and North Africa, was a period of extensive breakup of the Pangean platform, continental rifting and rapid basin subsidence. Therefore, it is not surprising that there were widespread diagenetic effects on the rocks such as dolomitization, clay transformations, hydrothermal fluid-flow, and some ore deposition (Mitchell and Halliday 1976; Lancelot et al. 1995; Schneider et al. 1999).

It is important to note that direct evidence (i.e., age dates on ores) for extensive MVT lead–zinc mineralization of Mesozoic ages in Europe is problematic at best. Toulkeridis et al. (1993) used the correspondence of lead isotope ratios obtained on illite in host rocks with ratios from galena at Les Malines, France, to argue that ore deposition was of Liassic age. However, the similar lead isotope ratios do not require that the illite and sulfides formed at the same time because the lead isotopic ratios of the illite may have been acquired after crystallization by adsorption of lead from hydrothermal fluids that deposited the galena. Therefore, we question the assumption that the Liassic event of Europe and North Africa was also a period of significant MVT mineralization (Lancelot et al. 1995; Clauer et al. 1996).

Cretaceous–Tertiary

Second only to the Devonian to Permian period, the Cretaceous to Tertiary time was also important for MVT ore genesis (Fig. 3). The dispersal of the fragments of Pangea has continued up to the present with the opening of the Atlantic (Fig. 5). The dispersion of Pangea was punctuated by the important Alpine and Laramide orogenies. The Alpine collision of Africa with Europe was accompanied by complex changes in plate boundaries and plate motion that produced orogenic belts in Europe and North Africa. Laramide time was important for ore genesis in North America where the MVT districts of Robb Lake, Monarch-Kicking Horse, and Pine Point (if the paleomagnetic age for Pine Point is correct) districts formed. During the Outer Carpathian orogeny in the Tertiary, the largest European MVT district formed in the Cracow–Silesian region of southern Poland (Symons et al. 1995). In the south of France, paleomagnetic dating of deposits in the Cévennes region yielded an Early–Middle Eocene age (Table 1) that corresponds to the uplift of the Pyrénées during the closing stages of the Pyrenean orogeny. Although the deposits of Mezica in Slovenia, Raibl in Italy and Bleiberg in Austria have not been dated, some ore deposition was localized in faults of Alpine age. In the large Moroccan MVT district, ore deposition was controlled by thrust faulting of Miocene age (Bovabedellah et al. 1995). Furthermore, preliminary paleomagnetic results for the MVT deposit at Reocin in northern Spain appears to be most consistent with a Tertiary age for mineralization (Lewchuk et al. 1998c, 1998d).

Implications of the age dates

The formation of MVT deposits requires the rare combination of geologic, tectonic, and geochemical controls. If we are able to understand better what controls are most likely to produce MVT ores and how these controls are determined by fundamental crustal processes, we would greatly increase our ability to assess the potential for undiscovered MVT lead–zinc resources. The placement of the most basic requirements for MVT ore genesis into the global perspective revealed by the new age dates is one important approach. Below, we briefly summarize the most fundamental requirements for MVT ore genesis and then examine these with the global perspective provided by age dates.

Fundamental requirements for MVT genesis

Carbonate rocks

It is important to note that MVT deposits do not occur in most carbonate platform sequences and, in fact, they are seldom present in most sedimentary basin sequences. In view of the restricted spatial and temporal distribution in the crust with respect to the variety of geological and geochemical controls known to form MVT lead–zinc deposits (Leach and Sangster 1993), we suggest that MVT deposits are not simply the products of the "normal evolution" of sedimentary basins. If these ores were the product of normal sedimentary basin processes, we would expect MVT deposits to have a significantly greater spatial and temporal distribution.

Heat

Exotic sources of heat (e.g., buried intrusives) are generally not required to form MVT lead–zinc hydrothermal ore fluids (Garven 1985; Leach and Sangster 1993). However, some MVT districts (e.g., Ireland, Upper Mississippi Valley) apparently required additional heat over what could be reasonably obtained from burial or advecting basin fluids to explain the fluid inclusion temperatures in the ores (see discussions in Bjørlykke et al. 1991; Rowan and Marsily 2001).

Sources of sulfur and metals

We also accept that the ore fluids extracted metals from crustal rocks and that sulfur, originally present in seawater, was obtained from connate fluids or sulfates in sedimentary sources (Leach and Sangster 1993). Although some types of rocks are better suited to be source-rocks than others, the point to be made is that these source rocks are not exotic, but, rather, are typical rocks present in most carbonate platform sequences.

Availability of brines

At the relatively low temperatures of the MVT environment, it is the high salinity that permits a potential MVT ore fluid to carry sufficient metal in solution. Therefore, a source of the dissolved salts is essential for the extraction of metals from crustal sources and to transport the metals to the site of deposition.

Fluid migration

Most MVT ore fluids have migrated considerable distances into relatively undisturbed rocks. It is reasonable to consider that some significant input of potential energy must be required in order to move the large quantities of brines necessary to form MVT deposits. This potential energy may have been in the form of heat or mechanical energy (compaction, elevation, or tectonic).

Fluid focusing

In order to form economic concentration of ore minerals, there must have been some mine- or district-scale geological and hydrological features that permitted the ore fluids to be focused into areas where they could mix with other fluids or to react with rocks at the site of ore deposition. Many geological and hydrological controls are present in carbonate platform sequences (Leach and Sangster 1993).

Tectonics, fluid flow, and MVT mineralization

Considering the age of the Earth, it is rather remarkable that the vast majority of MVT lead–zinc ores formed during two relatively restricted windows in geologic time that correspond to periods of major orogenic activity. The most important period of MVT ore formation was Devonian to Late Permian that corresponds to the assembly of the super-continent Pangea. The second most important period was Cretaceous–Tertiary, which corresponds to the Laramide and Alpine orogenic cycles. Only two MVT deposits or districts in Phanerozoic rocks yielded age dates that lie outside of these windows of geologic time and they are dominated by continental extension (Late Proterozoic–Early Paleozoic and the Triassic–Jurassic rifting of Pangea).

The new age dates for MVT lead–zinc deposits strongly support a genetic connection between the formation of MVT lead–zinc deposits and large-scale tectonic events. Although this connection has been postulated from empirical evidence for some time (e.g., Leach 1973; Garven 1985; Leach and Rowan 1986; Oliver 1986; Bethke and Marshak 1990; Oliver 1992), the correlation of MVT ages of deposition with orogenic events in adjacent orogens is rather convincing in itself. These periods of intense global tectonic activity most likely resulted in the movement of groundwater at continental scales (e.g., Bethke and Marshak 1990; Garven and Raffensperger 1997) and provided opportunities for MVT ore formation. Beyond this obvious conclusion, the age dates also provide insights into likely fluid migration mechanisms that may have been important in the formation of MVT deposits. Here, we discuss only general aspects of fluid flow because detailed discussions about the specifics of the hydrology are beyond the scope of this paper. However, the time of MVT ore formation with respect to the orogenic cycles of the associated orogen provides an interesting view of how fluid may have migrated.

Contractional regime

Because most MVT deposits formed during convergent orogenic cycles, our discussion will initially focus at fluid flow associated with convergent tectonic margins. Most models for MVT formation call upon tectonic squeezing (Oliver 1986) or fluid expulsion during sediment compaction, free convection, and topographic or gravity-driven systems (see summary by Garven and Raffensperger 1997).

Transient groundwater conditions are a natural consequence of the evolution of a foreland basin (e.g., Ge and Garven 1989; Garven et al. 1993; Garven and Raffensperger 1997; Appold and Garven 1999). Groundwater flow early in the history of a foreland basin occurs mainly as free convection and/or compaction-driven systems, established as a consequence of the rapid sedimentation and down-warping of the lithosphere. The tectonic squeezing model of Oliver (1986, 1992) would also apply to the early and most intense contractional phase of the orogenic cycle. However, Ge and Garven (1989 , 1992) show that the rates of fluid flow from tectonic compression are too slow to be an effective fluid drive for long-distant fluid transfer; however, higher flow rates could be achieved near the orogenic front. Topographic-driven fluids can occur at any time during the orogenic event, provided there is sufficient hydraulic head from an elevated recharge area in the orogenic profile. Ge and Garven (1989) showed that gravitational systems are the dominant fluid-flow mechanism during the late orogenic stages and are related to post-contractional uplift of the orogen. With this hydrological framework in mind, it is useful to examine possible implications provided by the ages of MVT formation.

Ozark region of the US Mid-continent

The MVT deposits in the Ozark region provide the best-documented examples of MVT mineralization late in the evolution of an orogen. MVT deposits of the southeast Missouri, northern Arkansas, Tri-State, and central Missouri barite districts lie in the foreland of the Ouachita collisional orogen; none of these districts are far enough south to have been directly involved in Ouachita contractional deformation. Onset of collision along the former southern (present coordinates) passive margin of Laurentia began in late Meramecian time (~333–327 Ma), as revealed by the onset of flysch sedimentation on the continental slope-rise. By Atokan time (~317–311 Ma), the former passive margin platform was being down-flexed and buried beneath a thick foreland-basin siliciclastic wedge – the Arkoma Basin. Contractional deformation continued into Desmoinesian time (~311–303 Ma), which also corresponds to the age of the youngest preserved foreland-basin strata. The paleomagnetic and isotopic ages in Table 1 show that mineralization post-dated Ouachita plate convergence and foreland sedimentation, thereby post-dating the optimum time for fluid-flow-driven by sediment compaction or tectonic compression. The ages for Ozark MVT deposits correlate best with the post-contractional uplift of the Ouachita orogen and are, therefore, most consistent with models that call upon regional topographic-driven fluid-flow for the ore-forming fluids in the Ozark region (Bethke et al. 1988; Bethke and Marshak 1990; Ge and Garven 1989).

Polaris

The Polaris deposit, in the Canadian Arctic is hosted in Ordovician carbonates that formed along the northern (present coordinates) passive margin of Laurentia. Collisional orogeny along this margin probably began during Silurian time with the arrival of Pearya, an exotic terrane (Trettin et al. 1991; Bjornerud and Bradley 1994). This Silurian phase of orogeny was characterized by flysch sedimentation and drowning of the outer edge of the carbonate platform. Flysch gave way to molasse, which prograded craton-ward from Emsian to mid-Famennian (~409–370 Ma). Foreland thrust deformation affected even the youngest Upper Devonian molasse. Late Devonian paleomagnetic and isotopic dates for Polaris thus place mineralization at the end of a very long orogenic interval, and, as in the Ozarks, the location was a distal orogenic foreland. Thus, the age of MVT deposition at Polaris seems to be most consistent with a topographic-driven mechanism for the ore fluids.

Cracow–Silesia, Poland

The Cracow–Silesia MVT deposits are hosted in rocks of the Middle Triassic Muschelkalk Formation. Recent dating by paleomagnetic methods (Symons et al. 1995) shows the age of ore formation to be mid-Tertiary, coincident with intense closing stages of the Alpine orogeny in the Carpathian orogenic belt. Cretaceous through Miocene Alpine tectonics in the Carpathian orogen produced uplift, erosion with periods of marine transgression, and widespread faulting in the region. The "extensive horst and graben system" (Kibitlewski 1991; Leach et al. 1996), is one of the most important ore controls in the district, most likely formed and/or was accentuated by flexural extension during Carpathian thrust loading. The youngest Alpine faults of Miocene age in the district displace some ore deposits, thus establishing an upper age for the ores. Kibitlewski (1991) and Gorecka (1993) show that the ores are syntectonic as shown by some ores that cut Tertiary faults.

The Carpathian orogen formed by the complex suturing of continental fragments against an irregular European plate boundary, which began in Middle Cretaceous and continued to Recent time (Burchfiel 1990). Two tectonic cycles of Alpine orogenic events are distinguished in the Silesia–Cracow district (Gorecka

1993): Early Alpine (Cimmerian–Laramide) and Late Alpine (Tertiary). The Cimmerian phase produced broad, low amplitude folds and widespread fractures and faults with minor displacement that generally reflect reactivated basement fractures (Gorecka 1993). Intense faulting of the Laramide phase produced an extensive network of faults and fractures and formed the Cracow–Silesia monocline.

The Mid-Tertiary age (Symons et al. 1995) for ore deposition coincides with the closing stages of the Carpathian orogeny in which uplift of the orogenic belt was also broadly coincident with final contractional deformation in the foreland region. Although topographically-driven fluid migration is consistent with the rapid uplift of an orogenic belt, the rapid deposition of Middle Tertiary flysch deposition in the Carpathian fore-deep could have provided compaction-driven fluids for the ore-forming system. Therefore, the drive for the ore fluid could have been topographic, compaction, or tectonic compression.

Appalachians

A view of possible fluid drive mechanisms for the Appalachian MVT districts is most difficult because (1) there is disagreement between radiometric and paleomagnetic dates for East Tennessee; (2) three collisional orogenies took place in the Appalachians; the multiple orogenic cycles makes the reported ages post-orogenic for one phase equivalent to pre-orogenic for another phase; and (3) post-mineralization thrusting has involved the more proximal (easterly) deposits so that some are still flat-lying whereas others are in the thrust belt.

Central Tennessee

Central Tennessee lies beyond the deformation front on the crest of the fore-bulge of the Alleghenian orogenic belt. The Pennington-Lee clastic wedge gives a good indication of the age of Alleghenian deformation in this part of the southern Appalachians: it ranges in age probably from late Meramecian (~332–327 Ma; Visean) at its southeastern edge to Early Permian (~286–266 Ma) near its northwestern limit (Hatcher et al. 1989). The Late Permian to earliest Triassic paleomagnetic date (Lewchuk et al. 1996) is entirely consistent with ore formation late in the orogenic cycle. Therefore, the age for central Tennessee is most consistent with a topographic fluid-drive system.

East Tenn

Interpreting the age of MVT mineralization in East Tennessee is complicated by the conflict in ages obtained by paleomagnetic and Rb–Sr dating studies. Geological arguments that propose a pre-folding age include the presence of apparently detrital sphalerite grains in internal sediments (Matlock and Misra 1993) that have the same attitude as the host rocks. The absence of apparent structural control of the ore (Crawford and Hoagland 1968; Hill et al. 1971a) and the tilting and offset of bedded ores by thrust faulting (Fulweiler and McDougal 1971; Hill 1971b; McCormick et al. 1971). In many MVT districts, selective replacement of more favorable lithologies of the carbonate rocks can lead to misinterpretations regarding the emplacement of the ores. However, the observed internal deformation observed in sphalerite crystals (Taylor et al. 1983) does appear to require increased post-mineralization stress from burial or tectonism. Therefore, it appears that mineralization must pre-date fault-bend folding in this part of the Alleghenian thrust belt. Assuming that thrusting followed the normal hinterland-to-foreland sequence, thrusting in East Tennessee probably took place during late Mississippian or Pennsylvanian. Thomas (1966) documented a late Mississippian synsedimentary syncline roughly along a strike in Virginia. These geologic constraints are consistent with the older portion of paleomagnetic and isotopic ages from East Tennessee (Table 1).

The Rb–Sr dates determined for the East Tennessee ores (377 ± 29 and 347 ± 20 Ma; Nakai et al. 1990, 1993) correlate with the Acadian orogeny in the central Appalachian orogen. Osberg et al. (1989) gave a span from about 415 to 360 Ma with peak orogenesis at about 390 Ma. Evaluating the possible fluid-flow mechanisms for the East Tennessee ores with respect to the Rb–Sr dates is difficult because the Acadian orogeny did not greatly affect the southern Appalachians and Appalachian Valley and Ridge Province.

Newfoundland Zinc distric

Interpreting the age of MVT mineralization in Newfoundland is complicated by a variety of factors (Bradley 1984). The strata that host the ore deposit at Newfoundland Zinc were buried by thrusts in Ordovician time. During Middle Devonian time (i.e., the paleomagnetically determined age of mineralization), this area was probably still buried by these thrusts, and certainly did not occupy a typical MVT setting on the cratonic flank of a foreland basin. This observation calls into question a foreland-basin hydrologic model for this ore-forming system. A similar argument also applies to the Friedensville MVT deposit in New Jersey (Bradley 1993).

Western Canada Basi

The difficulties relating the age of MVT formation here to possible fluid-drive mechanisms are similar to those for the Appalachians. Pine Point is located in the undeformed foreland and there is disagreement between the paleomagnetic (Late Cretaceous–Paleocene) and radiometric dates (Early Mississippian to Early Devonian). Robb Lake and Monarch-Kicking Horse are in the thrust belt. At Pine Point, it is entirely possible that two MVT events did take place as suggested by Symons et al. (1995), one in Devonian associated with the Antler orogeny (Smith et al. 1993), and the other in Early Tertiary associated with the Andean-type thrust belt and foreland basin. Assuming a Late Cretaceous age for Pine Point, this age would correspond to mineralization in a distal Andean-type foreland near the end of a long period of convergent tectonism (early Late Jurassic to at least Paleocene, according to McMechan and Thompson 1993). Before being caught up in the thrust belt, Robb Lake and Monarch-Kicking Horse host rocks were also situated in the Canadian Rockies foreland. However, the Eocene paleomagnetic age of mineralization at Robb Lake (Smethurst et al. 1999) post-dates the main thrust-related deformation. Therefore, tectonic compression as a fluid drive for Robb Lake is unlikely. A topographically-driven regional fluid-drive system is possible.

Gays River and Ireland

On a Bullard-type North Atlantic reconstruction, these two districts are not far apart and occupy a comparable tectonic situation in the Carboniferous. The Visean host rocks of Gays River formed within a broad intracontinental strike-slip system, which, upon collision between North America and Africa later in the Carboniferous, occupied a foreland position north of the orogenic belt. This collision (the suture presumably laying somewhere offshore) probably occurred during the Mid-Pennsylvanian Westphalian B stage (~310 Ma), based on major changes in basin subsidence, deformation, and strike-slip fault activity at this time (Bradley 1984). This overlaps the paleomagnetic (Smethurst et al. 1998) and isotopic dates (Hitzman 1994) so all that can be said is that mineralization was likely syncollisional.

Along the strike in Ireland, Tournaisian to early Visean MVT-hosting carbonates were laid down in a region undergoing extension or transtension (Mitchell 1985; Hitzman and Large 1986). The active Hercynian (Variscan) orogenic front lay some 250 km to the south of the Irish MVT district by Visean time (Hazlett and Garven 1995; Hazlett 1997). These observations, coupled with Early Carboniferous paleomagnetic and isotopic dates, suggest that mineralization was syncollisional and took place in a distal orogenic foreland.

Cévennes

Assuming that the paleomagnetic Early–Middle Eocene age for the Cévennes is correct (Table 1), mineralization was coincident with Pyrenean orogenies to the south. The Early–Late Eocene mineralization is slightly younger than a major phase of uplift in the North Pyrenean zone, which is approximately Early Paleocene in age (Mattauer and Proust 1967; Freytet 1970; Meurisse 1975). Field evidence shows that the ore deposits are displaced by Late Eocene to Miocene deformation (Macquar 1973; Macquar et al. 1990). Thus, the paleomagnetic date best corresponds to uplift in the Pyrénées and suggests that topographic-driven fluid-flow was the most likely mechanism to explain the Cévennes MVT deposits (Lewchuk 1998b, 1998c, 1998d; Henry et al. 2001; Rouvier et al. 2001).

Continental extensional

The MVT deposits in the Lennard Shelf of Australia and Nanisivik in Canada have age dates that coincide with extensional tectonic events. The Cévennes deposits have been suggested to have formed during Liassic continental extension (Toulkeridis et al 1993; Clauer et al. 1996). However, as discussed previously, this date conflicts with the paleomagnetic dates (Table 1) that correspond to the Pyrénées contractional tectonic regime.

Fluid-flow mechanisms for extensional environments also show temporal variations in mechanisms that reflect the evolving geology of the basin. The most commonly proposed mechanisms for fluid flow, summarized by Person and Garven (1992) and Garven and Raffensperger (1997), include (1) fluid expulsion because of sediment compaction and over-pressuring caused by diagenesis; (2) free convection from density gradients (salinity or thermal gradients); (3) seismic pumping; and (4) topography or gravity-driven pressure. For sediment-hosted lead–zinc deposits in extensional environments, the most accepted fluid-flow mechanisms are fluid expulsion through sediment compaction diagenesis and free convection along bounding faults of the subsiding basin. Unfortunately, the few dates that correspond to extensional MVT systems provide limited new insights into MVT genesis in extensional environments. However, the new dates do show that, although significant MVT lead–zinc are typically products of contractional tectonics, they can also form in extensional basins.

The clearest example of MVT formation during continental extension is the carbonate-hosted zinc–lead deposits in the Lennard Shelf, Australia. The age dates (Table 1) correspond to the rapid extension of the Fitzroy trough adjacent to the Lennard shelf (Verncombe et al. 1995). The ore deposits are localized by extensional faults and are believed to have formed as a consequence of fluid expulsion during episodic dewatering of the sediments in the Fitzroy trough (Verncombe et al. 1995).

The deposit at Nanisivik in the Canadian Arctic hosted in Borden Basin has generally been considered to be related to rifting. In light of Hoffman's (1989) suggestion that this basin evolved from rift to passive margin to foreland basin, the tectonic setting of mineralization at Nanisivik bears re-examination. Nevertheless, it is rather puzzling why there are so few MVT deposits related to crustal extension. This paucity of MVT ore genesis during continental extension is partly due to the fact that we deliberately excluded sandstone-hosted lead–zinc and fluorite–barite vein-controlled deposits despite our belief that these represent a variant of a broader spectrum of MVT ores. However, even if we had included these deposits (e.g., southern Illinois, Pennines, UK, Sweetwater, Tennessee) in our discussion, this would not have changed the fact that the vast proportion of sedimentary lead–zinc ores (excluding SEDEX) are from MVT districts and deposits that have age dates that correspond to contractional tectonics.

There is no question that crustal extension leads to fluid-flow that can produce ore deposits. This is reflected by the spectrum of shale-hosted and SEDEX lead–zinc deposits, lead–zinc vein deposits in sandstone, and the common association of fluorite–barite vein deposits during continental extension. However, it is not clear why more MVT lead–zinc deposits are not related to continental extension.

Other observations related to fluid-flow

Far-field deformation of the craton

The limited association between crustal extension and MVT deposits applies only to the broad-scale view of the tectonic regime because many MVT districts and deposits formed within extensional domains that developed because of lithospheric flexure, or in large dilational zones within bounding strike-slip faults during large-scale contractional events. Bradley and Kidd (1991) discussed extensional domains that frequently occur in collisional fore deeps and may extend several hundred kilometers into the foreland. The location of many deposits in the Cracow–Silesia district, Poland, are believed to be controlled by Tertiary grabens that formed in the foreland of the Carpathian orogenic zone (Kibitlewski 1991). Some ore deposits in the Ozark region were localized by Carboniferous extensional faults during Ouachita collision (Bradley and Kidd 1991; Horrall et al. 1996, and reference therein; Hudson 2000). Similarly, Carboniferous normal faults related to flexural extension in the Variscan foreland control the Irish deposits (Hitzman 1999) and, in part, Ordovician normal faults related to Taconic collision control MVT mineralization in the Newfoundland Zinc district (Bradley 1993). In addition to normal faults formed by flexural extension, the far-field tectonic effects observed in the host rocks for MVT deposits have frequently been controlled, in part, by pre-existing faults and fractures in the basement.

Climatic factors

Christensen et al. (1996) suggested that the concentration of MVT ore-forming events in Late Devonian to Early Carboniferous time may be related in part to climatic and environmental effects associated with widespread oceanic anoxic events. Furthermore, they suggested that these oceanic anoxic events not only produced SEDEX Pb–Zn deposits during this time, but also provided for the incursion of anoxic bottom waters into carbonate platforms to produce MVT deposits. Although this is an interesting suggestion, it does not explain the formation of MVT deposits in carbonate rocks distal from sources of anoxic marine waters, nor is it consistent with the general poor correspondence of ages of SEDEX and MVT Pb–Zn deposits through geologic time (Sangster 1990).

Although global paleoclimate patterns are poorly understood, they were probably similar to present climates in that a first-order control is related to zonal atmospheric circulation because of the rotation of the earth (Witzke 1990). This zonal control is reflected by the pronounced latitude relationship to climate, which can be highly modified by interactions of the zonal circulation with mountain belts, land and water masses, monsoonal, and other factors (Parrish and Barron 1986). Arid belts occur at approximately 5–10° to 35–45° north and south whereas humid belts occur in equatorial and temperate latitudes (Witzke 1990, and references therein). Witzke (1990) prepared a series of paleogeographic maps for Laurentia and Euramerica for different time slices in the Paleozoic that are based on lithic indicators for paleoclimate conditions. These lithic indicators include shelf carbonates that form within 45° of the equator (Ziegler et al. 1984); carbonate oolites and evaporites that indicate arid condition; coal and bauxite that indicate humid conditions; and glacial deposits that reflect cold climates.

It is clear that MVT deposits have a close spatial and temporal association with orogenic belts and their forelands; however, they are not equally distributed along these belts. Despite the fact that the locations of the cratonic blocks are imprecisely known, it appears that the formation of many MVT deposits during the assembly of Pangea in Devonian to Late Permian (Fig. 4), not only formed inboard of orogenic belts but also in relatively low to middle latitudes (generally less than 30° from the paleoequator but typically not more than 50 to 60°). However, the paleogeographic reconstruction for the Mesozoic and Cenozoic (Fig. 5) do not show a consistent relationship between MVT genesis and low latitudes. This is especially true for the MVT deposits in the Western Canada Basin (Robb Lake, Monarch-Kicking Horse, and Pine Point if the paleomagnetic age for the Pine Pont district is used). However, a potential recharge area for the ore fluids in the Western Canada Basin was south of the ore deposits and located at lower latitudes during the time of ore deposition. Also, the Nanisivik deposit formed at a paleolatitude of about 60°N and the Cracow–Silesia district formed at about 47°N. However, considering that more than about 80% of the combined Zn and Pb metal from deposits that have been dated (Table 1) are from deposits that formed at low latitudes (less than about 50°N), is at least suggestive of a possible relationship between paleolatitude of the ore district and genesis of the MVT ores. This possible relationship between MVT genesis and paleolatitude is consistent with a possible connection to paleoclimate during MVT ore genesis. The paleogeographic and climatic reconstructions for the Late Carboniferous and Permian (Fig. 9 in Witzke 1990) show the humid equatorial and arid belts in northern Pangea; these climatic zones correspond to the areas that contain the important MVT deposits that formed during the final assembly of Pangea in Devonian to Late Permian.

Despite the apparent connection between paleolatitude, paleoclimatic zones, and ore genesis, the most simplest explanation for this apparent relationship is that there is a greater chance for most ore deposits, including MVT deposits, to form in low latitudes simply because about 75% of the Earth's surface occurs at latitudes less than 45°. Although this is correct for the Earth's surface, it may not be true for the continental crust throughout geologic time. For example, in the Early Paleozoic, more of the Earth's continental crust was located at low latitudes than is today. Nevertheless, the most convincing arguments for a possible connection between paleoclimate and MVT ore genesis are from observations on the evaporated seawater origin for the ore-fluids (conditions that require high evaporation rates), and hydrological considerations (adequate precipitation to drive large ground water systems). If this apparent relationship between latitude and paleoclimate with MVT ore genesis is more than just "chance", there are some reasonable explanations that are consistent with our understanding of the processes that form MVT deposits. These possibilities are discussed below.

Carbonate platforms

The most obvious connection between latitude and MVT formation is the observation that MVT deposits formed almost exclusively in platform carbonate sequences. Potential MVT ore-forming fluids along an orogenic front must have access to carbonate rocks for a variety of reasons that are mainly related to fluid migration and fluid mixing processes (Leach and Sangster 1993). The formation of MVT deposits in carbonate platform sequences does not reflect a direct relationship between the ore-forming processes and the environmental conditions that form platform carbonate. If this were true, there would be a much closer correlation between the age of MVT genesis and age of the carbonate host-rocks (Table 1, Fig. 3). Rather, the location of MVT deposits in carbonate rocks can be viewed as a "pre-existing climatic factor" in that the formation of platform carbonate rocks required environmental conditions present at low latitudes. Thus, the longer a particular continent stayed in low latitudinal zones, the greater the chance of developing carbonate platform sequences. Consequently, an increase in the abundance of platform carbonate in a given continental mass leads to a greater chance of hosting MVT deposits during a subsequent orogenic event. For example, this basic relationship provides a rather simple explanation for the abundance of MVT deposits in North America that flank the Appalachian–Ouachita orogenic belt relative to the absence of MVT deposits across the same Late Paleozoic suture zone in northwest Africa. North America stayed mainly in low latitudes during its continental migration in the Paleozoic, thereby favoring the formation of vast carbonate platforms. In contrast, Africa stayed mainly in the mid to high southerly latitudes in the Early Paleozoic and developed extensive siliclastic sequences, but few carbonate rocks. The rapid migration northward of Africa culminated with its collision with North America (Laurentia) in the Late Paleozoic. Therefore, the collision of "carbonate platform-rich" North America with "carbonate platform-poor" West Africa mainly explains the absence of MVT deposits in Paleozoic rocks in West Africa. This relatively obvious connection between MVT ore genesis and the low latitudes that form carbonate platforms is important.

Meteoric recharge for topography-driven systems

As discussed previously, the age dates for MVT deposits (Table 1) show that although several fluid-drive mechanisms are possible for MVT ore-forming systems, the most widely applicable model for many MVT deposits is the topographic or gravity-driven model (Garven 1985). An adequate supply of precipitation in the recharge area to the hydrological system is implicitly required for a topographic or gravity-driven model. Rapidly uplifted mountains along an orogenic belt provide excellent sites to generate adequate precipitation and for hydraulic head to drive the long-distance migration of MVT fluids.

It seems unlikely that a topographic recharge system for the ore-forming hydrological system could be effective if the orogenic highlands were located in arid climatic zones, or for that matter, in high latitudes that typically receive small amounts of precipitation. Conversely, the location of orogenic highlands in areas of extreme precipitation may be detrimental to the formation and/or preservation of the highly saline brines required for the transport of MVT metals. Furthermore, it seems reasonable to expect that the highest potential for a topographically-driven MVT system would occur along the windward slopes of mountain belts, located between equatorial and temperate latitudes, especially in climatic zones that have high evaporation rates and moderate amounts of precipitation. Conversely, the lowest potential would occur in dry climates (generally higher latitudes) and along the leeward side of mountain ranges.

Brines and paleoclimate

An essential requirement for the genesis of MVT deposits is the availability of brines to leach metals from crustal sources (i.e., aquifers) and to transport these metals to depositional sites. Salinities much higher than seawater in sediments can have at least four potential origins: (1) infiltration of evaporated seawater or continental runoff water that evaporates and accumulates in endorheic playas; (2) dissolution by circulating groundwater of evaporites already deposited within the sediments; (3) upward migration of brines from the deep crust, the origin of the salt most likely being the dissolution of minerals in the crystalline bedrock; and (4) brines associated with magmatic intrusions. There is no evidence of magmatic intrusion associated with MVT lead–zinc deposits, therefore derivation of salinity through magmatic activity can be ignored. Similarly, the occurrence of brines in deep crystalline rocks has recently been observed in drill holes in granitic bedrock (e.g., in Canada, Sweden, France, Switzerland; e.g., Savoye et al. 1997). However, these waters are moving very slowly and are, therefore, unable to provide the large amounts of fluids required to precipitate the mass of metals in most MVT deposits. The two most likely assumptions are therefore evaporite dissolution and evaporated water infiltration.

Dissolution of evaporites along the ore fluid's flowpath is a widely invoked mechanism to explain the salinity of the brines. However, evidence for evaporites is commonly lacking in potential flow for many MVT districts. The absence of remnant evaporites, which could support this model, can be interpreted as the result of their having been completely dissolved. However, the most compelling evidence for the origin of the salinity comes from recent studies of fluid inclusion compositions.

Studies of the composition of fluid inclusions in samples from many MVT districts (e.g., Kesler et al. 1995; Viets et al. 1996) show that the evaporation of seawater, past halite precipitation, is the most likely process for achieving the high salinity of most MVT ore fluids. These conclusions are based mainly on Cl–Br systematics during the evaporation of seawater and the assumption that there has been no gain or loss during fluid–rock reactions (e.g., Walter et al. 1990, 1993). These relationships have been used to distinguish between brines that formed from the dissolution of halite and those that formed during seawater evaporation. However, Chi and Savard (1997) have shown that some mixtures of brines from evaporite dissolution and brines from evaporated seawater plot on the evaporation line for seawater, thus complicating the discrimination of brines derived solely from halite dissolution or evaporation of seawater. Such mixtures of brine sources were detected by Viets et al. (1996) for the ore fluids of the Viburnum Trend. They showed that the ore fluids must have been a mixture of evaporated seawater containing about 10% halite-dissolution fluids. Despite the complications pointed out by Chi and Savard (1997), Cl/Br data from fluid inclusions do provide an excellent tracer for the source of the salinity.

Modern evaporites formed from evaporation of seawater are largely confined to latitudes 8–45°N and 5–27°S (Witzke 1990) whereas Cenozoic–Mesozoic evaporites are confined between 50°N and 50°S (Parrish et al. 1982). Thus, the presence of evaporites and evaporated concentrated seawater compositions in the MVT ore-forming brines suggests that the ore fluids acquired their salinity through the evaporation of seawater at low latitudes. The apparent paleogeographic position of most MVT deposits in relatively low latitudes during ore deposition is consistent with the concurrent evaporation of seawater during the migration of the ore-forming brines. The migration of MVT ore fluids concurrent with the evaporation of seawater to generate the MVT brines was suggested by Rowan (1998) for the Upper Mississippi Valley district (discussed in more detail below). However, the ore-forming brines could have been derived from connate brines that formed at some time before the MVT ores were deposited. For this latter scenario, there would be less correspondence between low paleolatitudes of the deposits at the time of ore deposition. Thus, MVT deposits that formed at high paleolatitudes (e.g., Nanisivik and those in the Western Canada Sedimentary Basin) probably formed from connate brines that formed well before the time of MVT deposition.

Given that the evaporative concentration of seawater best explains the salinity of the ore fluids, there are critical constraints placed on the volume of evaporative brines available to account for the temperatures recorded by fluid inclusions in some districts. For example, Bethke (1986) recognized that, for the Upper Mississippi Valley district at the northern limit of the Illinois Basin, massive volumes of brines must have infiltrated in the recharge area to account for the temperature of ore deposition. Bethke et al. (1988) also made the same observation for the important MVT deposits in the Ozark region of the US mid-continent. Rowan (1998) and Rowan and Marsily (2001) discussed the possibility that the evaporative concentrated brines were initially present in the Illinois basin and were simply flushed out by the infiltrating freshwater. The dissolved salts would then have been in the connate water, or in infiltrated evaporated seawater that preceded the uplift of the orogenic flank of the basin margin, south of the Upper Mississippi Valley district. In this model, the brine flux would have stopped once this initial brine reserve was depleted. However, the fluid inclusion temperatures are not consistent with a "one-basin volume" scenario. Many basin-volumes of fluids (residing in available porosity in the basin aquifers) are necessary to transport the heat, available in the deeper part of the basin, to the distant position of the MVT, and explain the high temperature observed in the fluid inclusions. Bethke (1986) reached the same conclusion with respect to available heat; however, he did not consider the salinity constraint.

A model presented by Rowan (1998) and Rowan and Marsily (2001) provides a potential explanation for this apparent enigma, and was shown to be consistent with the information available in the Upper Mississippi Valley district. This model assumes that evaporative concentrated brines were forming in the center of the Illinois basin at the time the southern flank of the basin was uplifted during the Ouachita orogeny. The uplift of the basin margin created a topographic drive for a regional fluid migration through permeable aquifers at the base of the basin. The evaporative concentrated brine infiltrated through faults into the deep sandstone aquifers at the base of the basin. Mixing of the evaporative concentrated brine with the regional flow system adequately accounted for the temperatures and salinities observed from fluid inclusions in ores of the Upper Mississippi Valley district. Because there is continued brine recharge, this model can operate throughout the period of MVT mineralization, contrary to the "one-basin volume" model. This model is also consistent with the electrolyte composition of the fluid inclusions that show the salinity of the ore fluid was derived from the evaporative concentration of seawater past halite precipitation. Although this model was applied specifically to the Upper Mississippi Valley district, it may well be applicable to a number of other MVT districts. Furthermore, this model requires climatic conditions that favor evaporative concentration of seawater, and a tectonic setting that includes topography at the basin margin.

Exploration implications

The observations and conclusions presented in this paper have important genetic implications for MVT deposits. However, exporting genetic concepts into exploration programs has always been somewhat esoteric, despite the fact that genetic concepts underpin most exploration programs. In order to appreciate how information and conclusions from the age-dating studies can be applied to exploration programs, it is important to address the importance of "scale" to the exploration objectives (Leach 1997). The identification of a universally applicable list of geological features useful for exploration in frontier areas is probably impossible because of the diversity in local and regional controls on MVT mineralization. However, within a given MVT district, empirically observed features that controlled ore deposition (i.e., basement topography, facies changes, faults, etc.) can be used effectively for exploration in and near the district. As the scale of exploration increases, knowledge of the fundamental MVT ore-forming processes becomes increasingly valuable. Therefore, the more favorable factors for MVT ore formation that can be identified for a region, the greater the potential for exploration success. To the list of favorable geological and geochemical controls or factors for MVT exploration given by Leach and Sangster (1993), we can now add the increased potential based on global-scale orogenic events that clearly are responsible for most of the MVT districts in the world. The observations and conclusions presented here underscore the direct connection between the formation of MVT districts and large tectonic events that affected carbonate platforms sequences. These orogenic events established large-scale migration of basinal fluids and created far-field structural deformation of the forelands that that focused the ore-forming fluids into sites where fluid mixing or fluid–rock interaction precipitated ore. The new data also show that the formation of MVT districts is not necessarily part of the "normal geologic evolution" of sedimentary basins. If this were the case, most sedimentary basins containing carbonate sequences would have MVT deposits. Rather, most MVT districts are related to carbonate platform sequences that have some hydrological connection to basins affected by the development of orogenic belts.

Furthermore, paleoclimate may have played an important role in the formation of MVT deposits. The most obvious and important paleoclimate factors in the formation of MVT deposits are the paleoenvironmental conditions that lead to the formation and the preservation of carbonate platform sequences. The possible interplay between the climatic conditions, that allow the formation and preservation of carbonate platforms, with orogenic deformation of these carbonate platforms in restricted paleoclimates may explain why Pangea was so endowed with MVT deposits. Not only does this suggest a possible explanation for the abundance of MVT deposits in North America, but it may offer insights into the exploration for undiscovered MVT deposits in other parts of the Earth. Therefore, exploration programs for MVT ore districts in frontier areas perhaps should include evaluations of paleogeographical and paleoclimate history of the areas of interest. For example, carbonate platforms sequences that experienced orogenic events in paleoclimatic zones that had evaporative conditions will likely have a higher probability for MVT ore formation than carbonate sequences that were affected by orogenic events in extremely arid conditions or arctic environments.

Perhaps the most fundamental insight provided by the age dating efforts is the reaffirmation of the diversity in ore-forming processes for MVT ores. Although the age dates show a clear preference for MVT formation in contractional orogenic events and for fluid drive by topographic- or gravity-driven pressure, the age dates show that no single broad tectonic or hydrological model can be applied to the family of MVT deposits. Establishing the time of MVT ore formation in a region is, without doubt, the most critical piece of information that can guide the exploration for undiscovered ore.

Summary

The principal conclusions of this analysis are:

1. The compilation of the age dates for MVT deposits demonstrates a broad agreement between ages obtained by paleomagnetic and radiometric methods. For deposits that have been dated by both radiometric and paleomagnetic methods, eight are in agreement whereas only two differ. We believe it is reasonable to exclude the K–Ar date for illite in the Cévennes in light of the new radiometric date for fluorite associated with the Cévennes ores, which are in agreement with paleomagnetic ages and the radiometric date for the MVT deposit located on the southern side of the Pyrénées. Therefore, only the age dates for Pine Point and East Tennessee districts remain controversial. There are three districts with only radiometric dates and four that have only paleomagnetic dates. For these seven districts, we see no compelling reason to believe that they have not dated the ore-forming event. Thus, the new dates have probably provided accurate ore-forming ages for most of the world's MVT districts. Prior to these dates, MVT deposits were generally considered unsuitable for dating.
2. For many years, MVT deposits were considered to have little relationship to tectonic processes. However, the revolution in dating MVT lead–zinc deposits has provided strong proof for the direct connection between the genesis of MVT lead–zinc deposits and global scale tectonic events. The dates show that MVT deposits typically formed during large contractional tectonic events at restricted times in the geologic history of the Earth. The series of intense tectonic events associated with the assimilation of Pangea in Devonian to Permian time was the most important period for MVT formation in the history of the Earth. Of the MVT lead–zinc deposits that have been dated, 75% of the combined metal formed during this period of Pangean assembly. The second most important time for MVT genesis was the Cretaceous–Tertiary period when a collage of microplate assimilation affected the western margin of North America and Tethyian Eurasia.
3. Remarkably, there was an absence of MVT lead–zinc ore genesis during the periods of major plate dispersal represented by the Late Proterozoic–Early Paleozoic and the rapid breakup of Pangea in Triassic through Jurassic time. Perhaps the most perplexing observation of the distribution of MVT deposits through geologic time is that there are very few MVT deposits in Proterozoic rocks relative to the abundance of SEDEX lead–zinc deposits in rocks of this time. Only five MVT lead–zinc deposits are known in Proterozoic rocks and only the Nanisivik deposit has been dated as Proterozoic in age. Not included in this count are a few small, low grade MVT lead–zinc deposits in Proterozoic rocks in Canada and the willemite deposit of Vazante, Brazil which may not be a MVT deposit (M. Hitzman, personal communication 2001). Even if we included these other Proterozoic occurrence, there remains a striking contrast in abundance between SEDEX and MVT deposits in the Proterozoic. If MVT and SEDEX lead–zinc deposits shared similar genetic processes, it seems reasonable that there should be a better correlation of ages. We suggest that this poor correspondence between MVT and SEDEX lead–zinc deposits in the Proterozoic challenges the widely suggested notion (e.g., Hutchinson 1980; Goodfellow et al. 1993, p. 242) that the two classes of deposits share similar genetic pathways.
4. The age dates reaffirm that diversity is a key characteristic of MVT ore genesis. Despite the fact that the formation of MVT ores has a clear affinity for contractional tectonic events, some deposits formed during continental extension. The clearest examples related to continental extension are the deposits of the Lennard Shelf in Australia and possibly the Nanisivik deposit in the Canadian Arctic. Diversity of MVT ore-forming processes is also shown by the observations presented here that suggest no single hydrological model can be broadly applied to all MVT deposits. A topographically-driven (i.e., gravity-driven) hydrological model best explains the hydrological system for the MVT deposits in the Ozark region of the US mid-continent, central Tennessee, Polaris, Cévennes district of France, and probably the deposits of the Western Canada Sedimentary Basin, and Poland. However, the topographic model does not appear applicable to the Newfoundland Zinc district and is uncertain for other MVT deposits in the Appalachians orogen. Fluid expulsion during sediment compaction appears to be the best explanation for the migration of the fluids in the Lennard Shelf.
5. Most MVT deposits cannot be considered the products of the normal evolution of sedimentary basins; rather, they are the products of global-scale orogenesis. The ore fluids for most of these deposits were derived from sedimentary basins that had some hydrological connection to orogenic belts.
6. Paleoclimate may be an important factor for the formation of some MVT deposits. The most important paleoclimate factor is the obvious need for the paleoclimatic conditions that form and preserve carbonate platform sequences. Other than these basic relationships, there are other observations that suggest paleoclimate may have played a direct role in the formation of some MVT ores. These include (1) the Cl/Br data from fluid inclusions that indicate most of the salinity was derived from evaporated seawater rather than dissolution of evaporites; (2) the apparent requirement that adequate precipitation in mountain belts is necessary to provide sufficient hydrologic head to drive a topographically-driven (i.e., gravity-driven) fluid systems, common for many

MVT districts; (3) the apparent need for some MVT districts to have formed from multiple basin-volumes of fluids in order to account for the mass of metal deposited and thermal conditions present during ore formation; which is consistent with infiltration of evaporative concentrated waters into the deep pathways for the ore fluid. These possibilities are consistent with the formation of some MVT deposits at climatic conditions that are common in latitudes less than about 50°. However, the possible paleoclimate relationships described above cannot be applied to districts that formed at high paleolatitudes such as Nanisivik and the deposits in the Western Canada Sedimentary Basin, despite the fact that the Cl/Br content of fluid inclusions for Pine Point (Viets et al. 1996) indicate the ore fluids likely formed from the evaporation of seawater. The preference for MVT ore deposition to have occurred mainly at low paleolatitudes, may simply reflect the fact that most of the Earth's surface occurs at the low latitudes. Nevertheless, the consistent presence of evaporated seawater, as the primary source of salinity, together with basic hydrological considerations, is at least suggestive of a paleoclimate factor for MVT genesis. The factors that led to the extraordinary endowment of Pangea and North America with MVT deposits may be explained by the following: (1) Laurentia, which formed a large part of Pangea, stayed in low latitudes during most of the Paleozoic. This allowed for the extensive development of carbonate platforms. (2) Intense orogenic activity during the final assembly of Pangea created far-field deformation of the continental interiors, which provided ground preparation and local areas for fluid focusing (drain) into favorable areas for precipitation of the ores. Many MVT districts are located in zones of crustal extension produced within large-scale tectonic contractional regimes. (3) Intense contractional orogenic events along Pangean suture zones led to the development of extensive mountain ranges that may have established large-scale, topographic-driven fluid migration into the continental interiors. (4) The location of Pangea in low latitudes and in paleoclimates with high evaporation rates, during protracted and intense orogenic events, led to the formation and infiltration of evaporated seawater into deep basin aquifers.

Concluding remarks

The remarkable advances in dating MVT deposits ushered in a new level of understanding for this important class of ore deposits. For many years, these seemingly simple deposits appeared to be unrelated to tectonic events and were long regarded as simply "product of the normal evolution" of sedimentary basins. Now, it is clear that these deposits formed as a consequence of dynamic fluid events driven by global scale tectonic processes at restricted windows of time in the Earth's history. Despite the advances in dating these deposits, many questions remain to be addressed before we can evaluate the large "blank spaces" in the distribution of MVT deposits in the world (Fig. 1). Are these blank areas where MVT deposits have been misclassified, undiscovered, or simply never formed?

Research needs to continue to focus on dating deposits that have not been dated. Fundamental questions about why radiometric and paleomagnetic dates disagree for Pine Point and East Tennessee districts must be resolved. The duration of MVT events continues to be an area that is poorly understood. Finally, the possible relationship between MVT ore genesis and paloeclimate should be investigated.

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References

Anderson DL (1982) Hotspots, polar wander, Mesozoic convection, and the geoid. Nature 297:391–393

Appold MS, Garven G (1999) The hydrology of ore-formation in the southeast Missouri district: numerical models of topography-driven fluid flow during Ouachita orogeny. Geology 94:913–935

Arne DC (1991) Regional thermal history of the Pine Point area, Northwest Territories, Canada, from fission track analysis. Geology 86:428–435

Arne DC (1992) Evidence from apatite fission-track analysis for regional Cretaceous cooling in the Ouachita mountain fold belt and Arkoma basin of Arkansas. Am Assoc Petrol Geol Bull 76:392–402

Arne DC, Duddy IR, Sangster DF (1990) Thermochronologic constraints on ore formation at the Gays River Pb–Zn deposit Nova Scotia, Canada, from apatite fission track analysis. Can J Earth Sci 27:1013–1022

Bachtadse V, Van der Voo R, Haynes FM, Kesler SE (1987) Late Paleozoic magnetism of mineralized and unmineralized Ordovician carbonates from East Tennessee: evidence for post-ore chemical event. J Geophys Res 92:14165–14176

Bastin ES (1939) Contributions to a knowledge of the lead and zinc deposits of the Mississippi Valley region. Geol Soc Am Spec Pap 24:156

Baubron JC, Jébrak M, Joannes C, Lhegu J, Touray JC, Ziserman A (1980) Nouvelles datations K–Ar sur des filons à quartz et fluorine du Massif central français. C R Acad Paris 290:951–953

Bethke C (1986) Hydrologic constraints on the genesis of the Upper Mississippi Valley mineral district from Illinois basin brines. Geology 81:233–249

Bethke CM, Harrison WJ, Upson C, Altaner SP (1988) Supercomputer analysis of sedimentary basins. Science 239:261–267
Bethke CM, Marshak S (1990) Brine migration across North America – the plate tectonics of groundwater. Annu Rev Earth Planet Sci 18:228–315
Bjørlykke A, Sangster DF, Fehn U (1991) Relationship between high heat producing (HHP) granites and stratabound lead–zinc deposits. In: Pagel M, Leroy M (eds) Source, transport, and deposition of metals. Balkema, Rotterdam, pp 257–260
Bjornerud MG, Bradley DC (1994) Silurian foredeep and accretionary prism in northern Ellesmere Island: implications for the nature of the Ellesmerian orogeny. In: Thurston F (ed) 1992 Proceedings International Conference on Arctic Margins. United States Minerals Management Service Outer Continental Shelf Study MMS 94-0040. Anchorage, Alaska, pp 129–133
Bouabdellah M, Brown AC, Sangster DF (1995) Geology of the Beddiane Mississippi Valley-type Pb–Zn deposit, Touissit-Bou Beker mining district, Morocco. In: Leach DL, Goldhaber M (eds) Extended abstracts. International Field Conference on Carbonate-Hosted Lead–Zinc Deposits. St. Louis, Missouri, pp 23–25
Bradley DC (1984) Late Paleozoic strike-slip tectonics of the northern Appalachians. PhD Thesis, State University of New York at Albany, Albany, NY
Bradley DC (1993) Role of lithospheric flexure and plate convergence in the genesis of some Appalachian zinc deposits. US Geol Surv Bull 2039:35–43
Bradley DC, Kidd WSF (1991) Flexural extension of the upper crust in collisional foredeeps. Geol Soc Am Bull 103:1416–1438
Brannon JC, Podosek FA, Viets JG, Leach DL, Goldhaber MG (1991) Strontium isotopic constraints on the origin of the ore-forming fluids of the Viburnum Trend, southeast Missouri. Geochim Cosmochim Acta 55:1407–1419
Brannon JC, Podosek FA, McLimans RK (1992a) A Permian Rb–Sr age for sphalerite from the Upper Mississippi Valley zinc–lead district, Wisconsin. Nature 356:509–511
Brannon JC, Podosek FA, McLimans RK (1992b) A clue to the origin of dark and light bands in the 270 Ma Upper Mississippi Valley zinc–lead district, southwest Wisconsin. Geol Soc Am Abstr Program S24:A353
Brannon JC, Cole SC, Podosek FA, Misra KC (1995) Radiometric dating of ancient calcite: Th–Pb and U–Pb isochrons for ore-stage and late-stage calcite from central Tennessee zinc district, an Appalachian–Ouachita age MVT deposit. Geol Soc Am Abstr Program 27:118
Brannon JC, Cole SC, Podosek FA, Ragan VM, Coveney RMJ, Wallace MW, Bradley AJ (1996a) Th–Pb and U–Pb dating of ore-stage calcite and Paleozoic fluid flow. Science 271:491–493
Brannon JC, Podosek FA, Cole SC (1996b) Radiometric dating of Mississippi Valley-type ore deposits. Lead-zinc. In: Sangster DF (ed) Carbonate-hosted lead–zinc deposit. Soc Econ Geol Spec Publ 4:546–554
Brannon JC, Leach DL, Goldhaber MG, Taylor CD, Livington E (1997) Radiometric dating of ore-stage calcite from Knight Vein, Il-KT fluorospar district, yields 195 Ma for both U–Pb and Th–Pb systems. Geol Soc Am Meeting Abstr Programs 29:A209
Burchfiel BC (1990) Eastern European Alpine system and the Carpathian orocline as an example of collisional tectonics. Tectonophysics 63:31–61
Chesley JT, Halliday AN, Kyser KT, Spry PG (1994) Direct dating of Mississippi Valley-type mineralization: use of Sm–Nd in fluorite. Geology 89:1192–1199
Chi G, Savard MM (1997) Sources of basinal and Mississippi Valley-type mineralizing brines: mixtures of evaporated seawater and halite dissolution brines. Chem Geol 143:121–125
Christensen JN, Halliday AN, Kesler SE, Sangster DF (1993) Further evaluation of the Rb–Sr dating sphalerite: the Nanisivik Precambrian MVT deposit, Baffin Island, Canada. Geol Soc Am Abstr Program S25:471
Christensen JN, Halliday AN, Leigh KH, Randell RN, Kesler SE (1995a) Direct dating of sulfides – a critical test using Polaris Mississippi Valley-type Zn–Pb deposits. Geochim Cosmochim Acta 59:5191–5197
Christensen JN, Halliday AN, Vearncombe J, Kesler SE (1995b) Testing models of large-scale crustal fluid flow using direct dating sulfides: Rb–Sr evidence for early dewatering and formation of MVT deposits, Canning Basin, Australia. Geology 90:877–884
Cioppa MT, Symons DTA (2000) Timing of hydrocarbon generation and migration: paleomagnetic and rock magnetic analysis of the Devonian Duvernay Formation, Alberta, Canada. J Geochem Explor 68–70:387–390
Cioppa MT, Al-Aasm IS, Symons DTA, Lewchuk MT, Gillen KP (2000) Correlating paleomagnetic, geochemical and petrographic evidence to date diagenetic and fluid flow events in the Mississippian Turner Valley Formation, Moose Field, Alberta, Canada. Sediment Geol 131:109–129
Clauer N, Chaudhuri S (1995) Clays in crustal environments: isotope tracing and dating. Springer-Verlag Berlin Heidelberg New York
Clauer N, Zwingmann H, Chaudhuri S (1996) Isotopic (K–Ar, and Oxygen) constraints on the extent and importance of Liassic hydrothermal activity in Western Europe. Clay Miner 31:301–318
Clauer N, Weber F, Gauthier-Lafaye F, Toulkeridis T, Sizun J-P (1997) Mineralogical, geochemical (REE), and isotopic (K–Ar, Rb–Sr, ^{18}O) evolution of the clay minerals from faulted, carbonate-rich, passive paleomargin of the southeastern Massif Central, France. J Sediment Res 67:923–934
Crawford J, Hoagland AD (1968) The Mascot-Jefferson City zinc district, Tennessee. In: Ridge JD (ed) Ore deposits of the United States 1933–1967 (Graton-Sales Volume). Am Inst Mining Metall Petrol Eng, New York, pp 242–256
Duane MJ, de Witt MJ (1988) Pb–Zn ore deposits of the northern Caledonides: products of continental scale fluid mixing and tectonic expulsion during continental collision. Geology 16:999–1002
Elliot WC, Aronson JJ (1987) Alleghenian episode of K-bentonite illitization in the southern Appalachian Basin. Geology 15:735–739
Freytet P (1970) Les dépots continentaux et marins du Crétacé supérieur et des couches de passage à l'Eocène en Languedoc. Thesis, University of Orsay, France
Fulweiler RE, McDougal WT (1971) Bedded-ore structures, Jefferson City mine, Jefferson City, Tennessee. Geology 66:763–769
Garven G (1985) The role of regional fluid flow in the genesis of the Pine Point deposit, Western Canada sedimentary basin. Geology 80:307–324
Garven G, Raffensperger JP (1997) Hydrogeology and geochemistry of ore genesis in sedimentary basins. In: Barnes HL (ed) Geochemistry of hydrothermal ore deposits. Wiley, New York, pp 125–189
Garven G, Ge S, Person MA, Sverjensky DA (1993) Genesis of stratabound ore deposits in the Mid-continent Basins of North America. 1. The role of regional groundwater flow. Am J Sci 293:497–568
Ge S, Garven G (1989) Tectonically induced transient groundwater flow in the foreland basins. In: Price RA (ed) Origin and evolution of sedimentary basins and their energy and mineral resources. American Geophysical Union Monograph, pp 145–157
Ge S, Garven G (1992) Hydromechanical modeling of tectonically-driven groundwater flow with application to the Arkoma basin. J Geophys Res 97:9119–9114
Goldhaber M, Church SE, Doe BR, Aleinikoff JN, Brannon JC, Podosek FA, Mosier EL, Taylor CD, Gent CA (1995) Lead- and sulfur-isotope investigations of Paleozoic sedimentary rocks from the southern mid-continent of the United States: implications for the paleohydrology and ore genesis of the southeast Missouri lead-belt. Economic Geology 90:1875–1910
Goodfellow WD, Lydon JW, Turner RJW (1993) Geology and genesis of stratiform sediment-hosted (Sedex) zinc–lead–silver

sulfide deposits. In: Kirkham RV, Sinclair WD, Thorp RI, Duke JM (eds) Mineral deposit modeling. Geol Assoc Can Spec Pap 40:201–251

Gorecka E (1993) Geological setting of the Silesian–Cracow Zn–Pb deposits. Polish Inst Geol Q 37:27–146

Grandia F, Asmerom Y, Getty S, Cardellach E, Canals A (2000) U–Pb dating of MVT ore-stage calcite: implications for fluid flow in a Mesozoic extensional basin from Iberian Peninsula. J Geochem Explor 69–70:377–380

Grant NK, Laskowski TE, Foland KA (1984) Rb–Sr and K–Ar ages of Paleozoic glauconites from Ohio and Missouri, USA. Isotop Geosci 2:217–239

Hall CM, York D, Saunders CM, Strong DF (1989) Laser (super 40) Ar/ (super 39) Ar dating of Mississippi Valley type mineralization from western Newfoundland. Int Geol Congr Abstr Congr Geol Int 28:2.10–2.11

Hatcher RD, Thomas WA, Geiser PA, Snoke AW, Mosher S, Witschko, DV (1989) Alleghanian Orogen. In: Hatcher RD, Thomas A, Viele GW (eds) The Appalachian–Ouachita Orogen in the United States. DNAG F-2:233–318

Hay RL, Liu J, Barnstable DC, Deino A, Kyser TK, Childers GA, Walker WT (1995) Dates and mineralogic results from clay pods of Mine 29 and Sweetwater Mine, Vibrurnum Trend, Missouri. In: Leach DL, Goldhaber MJ (eds) Extended abstracts. International Field Conference on Carbonate-Hosted Lead–Zinc Deposits. St. Louis, Missouri, pp 124–126

Hazlett TJ (1997) A hydrogeologic analysis of the Irish carbonate-hosted lead–zinc ore deposits. PhD Thesis, Johns Hopkins University, Baltimore, Maryland

Hazlett TJ, Garven G (1995) A hydrologic analysis of the role of faults in the genesis of carbonate-hosted Pb–Zn deposits, Midlands Basin, Ireland. In: Leach DL, Goldhaber M (eds) Extended abstracts. International Field Conference on Carbonate-Hosted Lead–Zinc Deposits. St. Louis, Missouri, pp 127–130

Hearn PP, Sutter JF, Belkin HE (1987) Evidence for Late Paleozoic brine migration in Cambrian carbonate rocks of the central and southern Appalachians: implications for Mississippi Valley-type sulfide mineralization. Geochim Cosmochim Acta 51:1323–1334

Henry B, Rouvier H, Le Goff M, Leach D, Macquar J-C, Thibieroz J, Lewchuk MT (2001) Paleomagnetic dating of widespread remagnetization on the southeastern border of the French Massif Central and implications for fluid-flow and Mississippi Valley-type mineralization. Geophysical Journal International 145:368–380

Hill WT, McCormick JE, Wedlow H (1971a) Problems on the origin of ore deposits in the Lower Ordovician formations of East Tennessee. Geology 66:799–804

Hill WT, Morris RG, Hagegeorge CG (1971b) Ore controls and related sedimentary features at the Flat Gap mine, Treadway, Tennessee. Geology 66:748–756

Hitzman MW (1994) Argon–argon step heating studies of muscovite in the upper Devonian old red sandstone: the first absolute dates for the age of Irish zinc–lead mineralization. Geol Soc Am Abstr Programs 26:A-381

Hitzman MW (1999) Extensional faults that localized syndiagenetic Zn–Pb deposits and their reactivation during Variscan compression. In: McCaffrey KJW, Lonergan L, Wilkinson JJ (eds) Fractures, fluid flow and mineralization. Geol Soc Lond Spec Publ 155:233–245

Hitzman MW, Large D (1986) A review and classification of the Irish carbonate-hosted base metal deposits. In: Andrew CJ, Crowe RWA, Finley S, Pennell WA, Pyne JF (eds) Geology and genesis of mineral deposits in Ireland. Irish Association of Economic Geologists, Dublin, pp 217–238

Hoffman PF (1989) Precambrian geology and tectonic history of North America. In: Bally AW, Palmer AR (eds) The geology of North America; an overview. DNAG. Geological Society of America, Boulder, Colorado, pp 447–510

Horrall KB, Farr MR, Hagni RD (1996) Evidence for focusing of Mississippi Valley-type ore fluids along the Bloomfield Lineament zone, southeast Missouri. In: Sangster DF (ed) Carbonate-hosted lead–zinc deposits. Soc Econ Geol Spec Publ 4:400–412

Hudson MR (2000) Coordinated strike-slip and normal faulting in the southern Ozark dome of northern Arkansas: deformation in a late Paleozoic foreland. Geology 28:511–514

Hutchinson RW (1980) Massive base metal sulfide deposits as a guide to tectonic evolution. In: The continental crust and its mineral deposits. Geol Assoc Can Spec Pap 20:659–684

Joseph D, Bellon H, Derré C, Touray JC (1973) Fluorite veins dated in the200 million year range at La Petite Verrière and Chavaniac, France. Geology 68:707–708

Kesler SE, Jones LM, Ruiz J (1988) Strontium isotopic geochemistry of Mississippi Valley-type deposits, East Tennessee: implications for age and source of mineralizing brines. Geol Soc Am Bull 100:1300–1307

Kesler SE, Appold MS, Martini AM, Walter LM, Huston TJ, Kyle JR (1995) Na–Cl–Br systematics of mineralizing brines in Mississippi Valley-type deposits. Geology 23:641–644

Kibitlewski S (1991) Tectonic control of the origin of the Zn–Pb deposits in the Chrzanow region, Poland. Geol Quart 37:229–240

Kontak DJ, McBride S, Farrer E (1994) 40Ar/39Ar dating of fluid migration in a Mississippi Valley-type deposit: Gays River Zn–Pb deposit, Nova Scotia. Econ Geol 89:1501–1517

Lancelot J, Briqueu L, Respaut J-P, Clauer N (1995) Géochimie isotopique des systémes U–Pb/Pb–Pb et évolution polyphasée des gîtes d'uranium du lodevois et du sud Massif central. Choronique Recherche Miniére 521:3–17

Lange S, Chaudhuri S, Clauer N (1983) Strontium isotopic evidence for the origin of barites and sulfides from the Mississippi Valley-type ore deposits in southeast Missouri. Econ Geol 78:1255–1261

Lange S, Chaudhuri S, Clauer N (1985) Strontium isotopic evidence for the origin of barites and sulfides from the Mississippi Valley-type ore deposits in southeast Missouri – a reply. Econ Geol 80:778–780

Lavery NG, Barnes HI (1971) Zinc dispersion in the Wisconsin zinc–lead district. Econ Geol 66:226–242

Le Guen M, Orgeval JJ, Lancelot J (1991) Lead isotope behavior in a polyphased Pb–Zn ore deposit: Les Malines (Cévennes, France). Miner Deposita 26:180–188

Leach DL (1973) Possible relationship of Pb–Zn mineralization in the Ozarks to Ouachita orogeny. Geol Soc Am Program Abstr 5:269

Leach DL (1994) Genesis of the Ozark Mississippi Valley-type metallogenic province. In: Fontboté L, Boni M (eds) Sediment hosted Zn–Pb ores. Springer, Berlin Heidelberg New York, pp 104–138

Leach DL (1997) Genetic studies of Mississippi Valley-type deposits in the United States mid-continent: implications for the exploration for undiscovered MVT deposits. Proceedings of Table Ronde sur les Minéralisations Pb-Zn du district de Touissit, Comparison avec d'autres districts MVT. Notes ét Mem Serv Geol Maroc 388:99–112

Leach DL, Rowan EL (1986) Genetic link between Ouachita fold belt tectonism and the Mississippi Valley-type deposits of the Ozarks. Geology 14:931–935

Leach DL, Sangster DF (1993) Mississippi Valley-type lead–zinc deposits. In: Kirkham RV, Sinclair WD, Thorpe RI, Duke JM (eds) Mineral deposit modeling. Geol Assoc Can Spec Pap 40:289–314

Leach DL, Viets JG, Kozlowski A, Kibletski S (1996) Geology, geochemistry, and genesis of the Cracow-Silesia zinc–lead district, southern Poland. In: Sangster DF (ed) Carbonate-hosted lead–zinc deposits. Soc Econ Geol Spec Publ 4:144–170

Leach DL, Premo W, Lewchuk M, Henry B, LeGoff M, Rouvier H, Macquar J-C, Thibieroz J (2001) Evidence for Mississippi Valley-type lead–zinc mineralization in the Cévenne region, southern France, during Pyrénées orogeny. In: Mineral Desposits at the Beginning of the 21st Century. Balkema, Rotterdam. 157–160

Lewchuk MT, Symons DTA (1995) Age and duration of Mississippi Valley-type (MVT) Pb–Zn–Ba–F mineralizing events. Geology 23:233–236

Lewchuk MT, Symons DTA (1996) Paleomagnetism and Mississippi Valley-type ore genesis in the Ordovician Knox Supergroup of Central Tennessee. In: Sangster DF (ed) Carbonate-hosted lead–zinc deposits. Soc Econ Geol Spec Publ 4:567–576

Lewchuk MT, Al-Aasm IS, Symons DTA, Gillen KP (1998a) Dolomitization of Mississippian carbonates in the Shell Waterton gas field, southwestern Alberta: insights from paleomagnetism, petrography, and geochemistry. Can Soc Petrol Geol Bull 46:387–410

Lewchuk MT, Rouvier H, Henry B, LeGoff M, Leach D (1998b) Paleomagnetism of carbonates and lead–zinc mineralization inn Southern France. Abstract, IUGG, Birmingham, UK

Lewchuk MT, Rouvier H, Henry B, Macquar J-C, Leach D (1998c) Paleomagnetism of Mississippi Valley-Type mineralization in southern France and Cenozoic orogenesis. European Geophysical Society XXIII General Assembly, Nice, France, 20–24 April

Lewchuk M, Henry B, Rouvier H, Macquar J, Leach D (1998d) Paleomagnetism of Mississippi Valley-type mineralization in southern France and Cenozoic orogenesis. Ann Geophys 16:53

Macquar JC (1973) Evolution tectonique post-hercynienne du domaine péricévenol. Incidences sur les filons de couverture. Exemple des bordures ouest et sud des Cévennes. Bull BRGM 1:45–68

Macquar JC, Leach DL (1995) Geology and geochemistry of the Treves lead–zinc deposit-an example of the Mississippi Valley-type mineralization bordering the Cévennes horst in southern France. In: Leach DL, Goldhaber M (eds) Extended abstracts. International Field Conference on Carbonate-Hosted Lead–Zinc Deposits. St, Louis, Missouri, pp 23–25

Macquar JC, Rouvier H, Thibieroz J (1990) Les mineralizations Zn, Pb, Fe, Ba, F péri-cévenoles: cadre structuro-sedimentaire et distribution spatio-temporelle. Doc BRGM 183:143–158

Marcoux E, Pelisson P, Baubron J-C, Lhegu J, Touray J-C (1990) Ages des formatons filoniennes a fluorine–barytine–quartz du district de Paulhaguet (Haute-Loire, Massif central francais). C R Acad Sci, Ser 2, Mecaniq, Phys, Chim, Sci Univers, Sci Terre 311:829–835

Matlock JF, Misra KC (1993) Sphalerite-bearing detrital "sand" bodies in Mississippi Valley-type zinc deposits, Mascot-Jefferson City district, Tennessee: implications for the age of mineralization. Miner Deposita 28:344–353

Mattauer M, Proust F (1967) L'évolution structurale de la partie Est du domaine pyrénéo-provencal au Crétacé et au Paléogène. Compt Rend Coll Biogéographie du Crétacé-Eocène de la France méridionale. Travaux Lab.. Géoch Biosphère Ecole Prat Hautes Etudes, Paris, pp 9–20

McCabe C, Elmore RD (1989) The occurrence and origin of late Paleozoic remagnetization in the sedimentary rocks of North America. Rev Geophys 27:471–494

McCormick JE, Evans LL, Palmer RA, Rasnick FD (1971) Environment of the zinc deposits of Mascot–Jefferson City district, Tennessee. Geology 66:757–762

McKibbon MA, Eldridge CS (1995) Microscopic sulfur isotope variations in ore minerals from the Viburnum Trend, southeast Missouri: a SHRIMP. Econ Geol 90:228–245

McMechan ME, Thompson RI (1993) The Canadian Cordilleran fold and thrust belt south of 66 degrees N and its influence on the Western Interior Basin. In: Caldwell WGE, Kauffman EG (eds) Geol Assoc Can Spec Pap 39:73–90

Meurisse M (1975) Données nouvelles sur les brèches rouges éocènes et la tectogenèse de la zone nord-pyrénéenne orientale. Datation et conséquences. Arch Sci 28:67–79

Mitchell AHG (1985) Mineral deposits related to tectonic events accompanying arc-continent collision. Trans Mining Metall Sect B 94:B115–B125

Mitchell JG, Halliday AN (1976) Extent of Triassic/Jurassic hydrothermal ore deposits on the North Atlantic margin. Trans Mining Metall Sect B 85:B85–B169

Nakai S, Halliday AN, Kesler SF, Jones HD (1990) Rb–Sr dating of sphalerites from Tennessee and the genesis of Mississippi Valley-type ore deposits. Nature 346:354–357

Nakai S, Halliday AN, Kesler SF, Jones HD, Kyle JR, Lane TE (1993) Rb–Sr dating of sphalerites from Mississippi Valley-type (MVT) ore deposits. Geochim Cosmochim Acta 57:417–427

Nesbitt BE, Muehlenbachs K (1993) Synorogenic fluids of the Rockies and their impact on paleohydrology and resources of the Western Canada Sedimentary Basin. Lithoprobe Rep 31:60–62

Nesbitt BE, Muehlenbachs K (1994) Paleohydrology of the Canadian Rockies and origins of brines, Pb–Zn deposits and dolomitization in the Western Canada Sedimentary Basin. Geology 22:243–246

Nesbitt BE, Muehlenbachs K (1995a) Importance of paleo-fluid systems in the southern Canadian Rockies in the genesis of mineral deposits in the Rockies and the Western Canada Sedimentary Basin. Lithoprobe Rep 47:250–253

Nesbitt BE, Muehlenbachs K (1995b) Paleohydrology of the Canadian Rockies and origins of brines, Pb–Zn deposits and dolomitization in the Western Canada Sedimentary Basin: reply. Geology 23:190

Ohle EL (1980) Some considerations in determining the origin of ore deposits of the Mississippi Valley-type, part II. Geology 75:161–172

Oliver J (1986) Fluids expelled tectonically from orogenic belts: their role in hydrocarbon migration and other geologic phenomena. Geology 14:99–102

Oliver J (1992) The spots and stains of plate tectonics. Earth Sci Rev 32:77–106

Osberg PH, Tull JF, Robinson P, Hon R, Butler JR (1989) The Acadian orogen. In: Hatcher RDJ, Thomas WA, Viele GW (eds) The Appalachian–Ouachita Orogen in the United States. Geological Society of America, Boulder, 139–232

Pagel M, Braun JJ, Disnar JR, Martinez L, Renac C, Vasseur G (1997) Thermal history constraints from studies of organic matter, clay minerals, fluid inclusions, and apatite fission tracks at the Ardeche paleo-margin (BA1 Drill Hole, GPF Program), France. J Sediment Res 67:235–245

Pan H, Symons DTA (1993) Paleomagnetism of the Mississippi Valley-type Newfoundland zinc deposits: evidence for Devonian mineralization in the northern Appalachians. Geophys Res Lett 98:22415–22427

Pan H, Symons DTA, Sangster DF (1990) Paleomagnetism of Mississippi Valley-type ore and host rocks in the northern Arkansas and Tri-State districts. Can J Earth Sci 27:923–931

Pan H, Symons DTA, Sangster DF (1993) Paleomagnetism of the Gays River zinc–lead deposit, Nova Scotia: Pennsylvanian ore genesis. Geophys Res Lett 20:1159–1162

Parrish JT, Barron EJ (1986) Paleoclimates and economic geology. SEPM Short Course no 18

Parrish JT, Ziegler AM, Scoteese CR (1982) Rainfall patterns and the distribution of coals and evaporites in the Mesozoic and Cenozoic. Palaeogeog Palaeoclimatol Palaeoecol 36:67–101

Person MA, Garven G (1992) Hydrological constraints on petroleum generation within continental rift basins: theory and application to the Rhine Graben. Am Assoc Petrol Geol 76:468–488

Posey HH, Stein HJ, Fullagar PD, Kish SA (1983) Rb–Sr isotopic analysis of Upper Cambrian glauconites, southern Missouri: implications for movement of Mississippi Valley-type ore-fluids in the Ozark region. In: Kisvarsanyi G, Grant SK, Pratt WP, Koenig JW (eds) International conference on Mississippi Valley-type lead–zinc deposits. Proceedings volume, University of Missouri, Rolla, pp 166–173

Qing H, Mountjoy EW (1990) Petrography and diagenesis of Middle Devonian Presqu'ile barrier: implications on formation of dissolution vugs and breccias at Pine Point and adjacent subsurface, district of Mackenzie. Can Geol Surv Curr Res Pap 90-1D:37–45

Qing H, Mountjoy EW (1992) Large scale fluid flow in the Middle Devonian Presqu'ile barrier, Western Canada Sedimentary Basin. Geology 20:903–906

Qing H, Mountjoy EW (1994) Formation of coarsely crystalline, hydrothermal dolomite reservoirs in the Presqu'ile barrier, Western Canada Sedimentary Basin. Am Assoc Petrol Geol Bull 78:55–77

Qing H, Mountjoy EW (1995) Paleohydrology of the Canadian Rockies and origins of brines, Pb–Zn deposits and dolomitization in the Western Canada Sedimentary Basin: comment. Geology 23:189–190

Ravenhurst CE (1987) An isotopic and thermochronological constrained model for lead–zinc and barium mineralization related to Carboniferous basin evolution in Nova Scotia, Canada. PhD Thesis, Dalhouse University, Halifax, Nova Scotia

Ravenhurst CE, Reynolds PH, Zentilli M, Krueger HW, Blenkinsop J (1989) Formation of Carboniferous Pb–Zn and barite mineralization from basin-derived fluids, Nova Scotia, Canada. Econ Geol 84:1471–1488

Ravenhurst CE, Willett SD, Donelick RA, Beaumont C (1994) Apatite fission track thermochronometry from central Alberta: implications for the thermal history of the western Canadian sedimentary basin. J Geophys Res 99:20023–20041

Repetski JE, Narkiewicz M (1996) Conodont color and surface textural alteration in the Muschelkalk (Triassic) of the Silesian–Cracow Zn–Pb district, Poland. In: Górecka E, Leach DL, Kozlowski A (eds) Carbonate-hosted zinc–lead deposits in the Silesian–Cracow area Poland. Polish Geological Institute, Warsaw, 113–120

Rickard DT, Willden MY, Marinder N-E, Donnelly TH (1979) Studies on the genesis of the Laisvall sandstone lead–zinc deposit, Sweden. Econ Geol 74:1235–1285

Rouvier H, Henry B, Le Goff M (1995) Regional remagnetization and Mesozoic levels containing "Mississippi Valley Type" deposits: the southern border of the French Massif Central. Abstract, XXI UGGI General Assembly, Boulder

Rouvier H, Henry B, Macquar J-C, Leach DL, Le Goff M, Thibiéroz J, Lewchuk M (2001) Réaimantation régionale éocène, migration de fluides et minéralisations sur la bordure cévenole (France). Bull Soc Géol France 4:503–516

Rowan EL (1998) Thermal and hydrogeologic history of a sedimentary basin: case studies in the Illinois basin, USA, and the Albigeois district, France. unpublished doctoral Thesis, University of Paris

Rowan EL, de Marsily G (2001) Infiltration of Late Paleozoic evaporative brines in the Reelfoot rift: a possible salt source for Illinois basin formation waters and MVT mineralizing fluids. Soc Geol Fr 172(4):321–348

Rowan EL, Goldhaber MB (1995) Duration of mineralization and fluid-flow history of the Upper Mississippi Valley zinc–lead district. Geology 23:609–612

Ruiz J, Kelly WC, Kaiser CJ (1985) Strontium isotopic evidence for the origin of barites and sulfides from the Mississippi Valley-type ore deposits in southeast Missouri – a discussion. Econ Geol 80:773–778

Sangster DF (1983) Mississippi Valley-type deposits: a geological melange. In: Kisvarsanyi G, Grant SK, Pratt WP, Koenig JW (eds) International conference on Mississippi Valley type lead–zinc deposits. University of Missouri Press, Rolla, Missouri, 7–19

Sangster DF (1986) Age of mineralization in Mississippi Valley-type (MVT) deposits: a critical requirement for genetic modeling. In: Andrew JC (ed) Geology and genesis of mineral deposits in Ireland. Irish Association of Economic Geologists, Dublin, pp 625–633

Sangster DF (1990) Mississippi Valley-type and SEDEX lead–zinc deposits: a comparative examination. Trans Inst Mining Metall B:B21–B42

Sass-Gustkiewicz M, Kwiecinska (1999) Organic matter in the Upper Silesian (Mississippi Valley-type) Zn–Pb deposits, Poland. Econ Geol 94:981–992

Sass-Gustkiewicz M, Dzulynski S, Ridge JD (1982) The emplacement of zinc–lead sulfide ores in the Upper Silesian district – a contribution to the understanding of Mississippi Valley-deposits. Econ Geol 77:392–412

Savoye S, Aranyossi JF, Beaucaire C, Louvat D, Michelot JL (1997) The relationship between chloride and bromide concentrations in fluid and associated crystalline rocks: constraints on the origin of salinity. Terra Nova 9:647

Schneider J, Haack U, Hein UF, Germann A (1999) Direct Rb–Sr dating of sandstone-hosted sphalerite from stratabound Pb–Zn deposits in the northern Eifel, NW Rhenish Massif, Germany. In: Stanley CJ (ed) Mineral deposits: process to processing. Balkema, Rotterdam, pp 287–1290

Scotese CR (2000) Atlas of Earth history, vol 1. In: Paleogeography, PALEOMAP Project. Arlington, Texas

Sedivy RA, Wampler JM, Weaver CE (1984) Potassium-argon. In: Weaver CE (ed) Shale–slate metamorphism in southern Appalachians. Developments in petrology, vol 10. Elsevier, Amsterdam, 153–183

Sinclair WD, Chorlton LB, Laramee RM, Eckstrand OR, Kirkham RV, Dunne KPE, Good DJ (1999) World minerals geoscience databaseproject: digital databases of generalized world geology and mineral deposits for mineral exploration and research. In: Stanley CL (ed) Mineral deposits: processes to processing. Proceedings, Fifth Biennial SGA Meeting and the Tenth Quadrennial IAGOD Meeting. Balkema, Rotterdam, pp 1435–1437

Smethurst MT, Symons DTA, Lewchuk MT, Ashton JH (1998) Hercynian neomorphism and genesis of the Navan Pb–Zn deposit, Ireland, from paleomagnetism. In: Society Symposia, solid Earth geophysics and geodesy. 23rd General Assembly of the European Geophysical Society, part 1. Nice

Smethurst MT, Symons DTA, Sangster DF, Lewchuk MT (1999) Paleomagnetic age for the Zn–Pb mineralization at Robb Lake, northeastern British Columbia. Bull Can Petrol Geol 47:548–555

Smith MT, Dickinson WR, Gehrels GE (1993) Contractional nature of Devonian–Mississippian Antler tectonism along the North American continental margin. Geology 21:21–24

Stein HJ, Kish SA (1985) The timing of ore formation in southeast Missouri: Rb–Sr glauconite dating at the Magmont Mine, Viburnum Trend. Econ Geol 80:739–753

Stein HJ, Kish SA (1991) The significance of Rb–Sr glauconite ages, Bonneterre Formation Missouri: Late Devonian–Early Mississippian brine migration in the mid-continent, USA. J Geol 99:1468–1481

Sverjensky DA, Rye DM, Doe BR (1979) The lead and sulfur isotopic compositions of galena from a Mississippi Valley-type deposit in the New Lead Belt, southeast Missouri. Econ Geol 74:149–153

Symons DTA (1994) Paleomagnetism and the Late Jurassic genesis of the Illinois–Kentucky fluorite deposits. Geology 89:438–449

Symons DTA, Sangster DF (1991) Paleomagnetic age of the Central Missouri barite deposits and its genetic implications. Econ Geol 86:1–12

Symons DTA, Sangster DF (1992) Late Devonian paleomagnetic age for the Polaris Mississippi Valley-type Zn–Pb deposit, Canadian Arctic Archipelago. Can J Earth Sci 29:15–25

Symons DTA, Stratakos (2000) Palaeomagnetic dating of dolomitization and Mississippi Valley-type zinc mineralization in the Mascot-Jefferson City district of eastern Tennessee: a preliminary analysis. In: Pueyo JJ, Cardellach E, Bitzer K, Taberner C (eds) Proceedings of geofluids III; third international conference on fluid evolution, migration and interaction in sedimentary basins and orogenic belts. J Geochem Explor 69–70:373–376

Symons DTA, Pan H, Sangster DF, Jowett EC (1993) Paleomagnetism of the Pine Point Zn–Pb deposits. Can J Earth Sci 30:1028–1036

Symons DTA, Sangster DF, Leach DL (1995) A Tertiary age from paleomagnetism for Mississippi Valley-type zinc–lead mineralization in Upper Silesia, Poland. Econ Geol 90:782–794

Symons DTA, MacDonald M, Lewchuk MT, Sangster DF (1996a) Late Cretaceous age for the Monarch-Kicking Horse Mississippi Valley-Type deposit in the southern Rocky Mountains of Canada from paleomagnetism. EOS 77:160

Symons DTA, Sangster DF, Leach DL (1996b) Paleomagnetic dating of Mississippi Valley-type Pb–Zn–Ba deposits. In: Sangster DF (ed) Carbonate-hosted lead–zinc deposits. Soc Econ Geol Spec Publ 4:515–526

Symons DTA, Lewchuk M, Leach DL (1998a) Age and duration of the Mississippi Valley-type mineralizing fluid flow events in the Viburnum Trend, southeast Missouri, USA, from paleomagnetism. J Geol Soc Spec Publ 144:27–39

Symons DTA, Lewchuk M, Sangster DF (1998b) Laramide orogenic fluid flow into the Western Canada Sedimentary Basin: evidence from paleomagnetic dating of the Kicking Horse Mississippi Valley-type ore deposit. Econ Geol 93:68–83

Symons DTA, Enkin R, Cioppa MT (1999a) Paleomagnetism in the Western Canada Sedimentary Basin: dating fluid flow and deformation events. Bull Can Petrol Geol 47:534–547

Symons DTA, Smethurst MT, Sangster DF, Lewchuk MT (1999b) Paleomagnetic dating of the Robb Lake Mississippi Valley-type mineralization, northern Rocky Mountains, British Columbia. Abstracts, Geological Association of Canada Annual Spring Meeting, Sudbury, Ontario, May 1999

Symons DTA, Symons TB, Sangster DF (2001) Paleomagnetism of the Society Cliffs dolostone and the age of the Nanisivik zinc deposits, Baffin Island, Canada. Miner Deposita 36:412–459

Taylor M, Kesler SE, Cloke PL, Kelly WC (1983) Fluid inclusion evidence for fluid mixing, Mascot-Jefferson City zinc district, Tennessee. Econ Geol 78:1425–1439

Thomas WA (1966), Late Mississippian folding of a syncline in the western Appalachians, West Virginia and Virginia. Geol Soc Am Bull 77:473–494

Toulkeridis T, Clauer N, Stille P (1993) Pb-isotopic composition and dating of clay minerals associated with the Pb–Zn ores of Les Malines (Cévennes, France). Terra Abstr 5:346

Trettin HP, Mayr U, Long GDF, Pakard JJ (1991) Cambrian to Early Devonian basin development, sedimentation, and volcanism, Arctic Islands. In: Trettin HP (ed) Geology of the Innuitian Orogen and Arctic Platform of Canada and Greenland. Geological Survey of Canada, Ottawa, Ontario, pp 163–238

Unrug R (1996) Geodynamics map of Gondwana Supercontinent assembly. Bureau des Recherches Géologiques et Minières, Orléans, France

Verncombe JR, Dorling SL, Reed A, Cooper R, Hart J, Muhling P, Windrim D, Woad G (1995) Regional- and prospect-scale fault controls on Mississippi Valley-type Zn–Pb mineralization at Blendvale, Canning Basin, Western Australia. Econ Geol 90:181–186

Viets JG, Hofstra AH, Emsbo P (1996) Solute compositions of fluid inclusions in sphalerite from North America and European Mississippi valley-type ore deposits: ore fluids derived from evaporated seawater. In: Sangster DF (ed) Carbonate-hosted lead–zinc deposits. Soc Econ Geol Spec Publ 4:465–482

Walter LM, Stueber AM, Huston TJ (1990) Br–Cl–Na systematics in Illinois Basin fluids: constraints on fluid origin and evolution. Geology 18:315–318

Walter LM, Martini A, Stueber AM, Moldovanyi EP (1993) Saline formational waters: new constraints on origin and migration from comparisons at the basin scale. Geol Soc Am Abstr Programs 25:A-23

Weil AB, Van der Voo R, Niocaill CM, Meert JG (1998) The Proterozoic supercontinent Rodinia: paleomagnetically derived reconstructions for 1,100 to 800 Ma. Earth Planet Sci Lett 154:13–154

Wisniowiecki MJ, Van der Voo R, McCabe C, Kelly WC (1983) A Pennsylvanian paleomagnetic pole from the mineralized Late Cambrian Bonneterre Formation, southeast Missouri. J Geophys Res 88:6540–6548

Witzke BJ (1990) Palaeoclimatic constraints for Paleozoic palaeolatitudes of Laurentia and Euramerica. In: McKerrow WS, Scotese CR (eds) Palaeogeography and biogeography. Geol Soc Mem 12:57–73

York DA, Masliwec A, Hall CM, Kuybida P, Kenyon WJ, Spooner ETC, Scott SD (1981) The direct dating of ore minerals. Ontario Geol Surv Misc Pap 98:334–340

Ziegler PA (1992) Plate tectonics, plate moving mechanisms and rifting. Tectonophysics 215:9–34

Ziegler PA, Hulver ML, Lottes AL, Schmachtenberg WF (1984) Uniformitarianism and paleoclimate: inferences from the distribution of carbonate rocks. In: Brenchley P (ed) Fossils and climate. Wiley, New York, pp 3–25

Christensen JN, Halliday AL, Kesler SE (1996) Rb-Sr dating of sphalerite and the age of Mississippi valley-type Pb-Zn deposits. In: Sangster DF (ed) Carbonate-hosted lead-zinc deposits. Society of Economic Geologists Special Publication Number 4:307–319