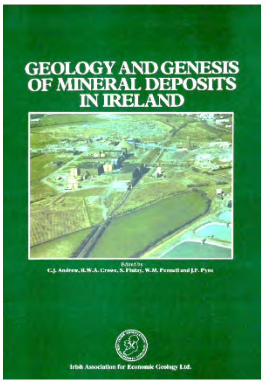

Age of mineralization in Mississippi Valley-type (MVT) deposits: a critical requirement for genetic modelling.

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Age of mineralization in Mississippi Valley-type (MVT) deposits: a critical requirement for genetic modelling.

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Abstract

Evaluation of current and future genetic models for MVT deposits depends first and foremost on reliable determinations of the absolute age of ore emplacement. For example, a 1968 proposal that ores in the Upper Mississippi Valley district were produced as a result of Pleistocene glaciation has never been challenged or refuted. Even today, the theory cannot be dismissed on age dating grounds alone.

A review of the literature regarding absolute dating of MVT ores reveals two main techniques have been used, palaeomagnetic and isotopic. Results of these studies have shown that age mineralization (T_m) and age of host rock (T_r) differ anywhere from zero to more than 650 Ma ($\triangle T$). Within the SE Missouri district alone, determinations of $\triangle T$ range from 0-265 Ma.

Attempts to date accurately the age of mineralization in MVT districts is hindered by two common characteristics of these ores: (1) the generally stable tectonic environment in which they occur precludes the presence of datable post-ore events with which to bracket age of mineralization; (2) their simple mineralogy and absence of wall-rock alteration precludes normal age dating procedures.

Introduction

Although MVT deposits have been recognized as a distinct deposit-type for about a hundred years, no unifying descriptive or genetic model for them has emerged. This situation is in marked contrast to other major ore types such as porphyry copper and exhalative deposits. For each of these, much greater progress has been made in the recognition of their common parameters and the subsequent erection of unifying descriptive and genetic theories.

At least one lead-zinc deposit in Ireland has been interpreted as having MVT characteristics (i.e. Harberton Bridge, see paper by Emo, this vol.) and several other Irish deposits have several features in common with MVT deposits, notably that of open space filling. Textural relations in several deposits indicate a syndiagenetic origin. Available absolute dating (K-Ar method; Halliday and Mitchell, 1983), however, indicates mineralization post-dated deposition of host sediments by up to 100Ma, an age difference more compatible with an MVT model of ore genesis than a synsedimentary one.

Before examining the causes of this inability to find an MVT model, perhaps it is pertinent to ask the question "Why is it important to find an MVT model in the first place?" One answer to this question obviously relates to improved efficiency in exploration for deposits of this type. For example, in 1964, when New Jersey Zinc Company set out to find a new zinc district in central Tennessee, management of the company was told that "no acceptable hypothesis was available as to why MVT districts are located where they are" (Callahan, 1977, p. 1387). Consequently, the exploration approach used by this company was the "random walk" method whereby drill sites were selected at random in the Nashville Dome area. Drilling began in May 1964 and, in Feb. 1967, hole # 79 hit five feet of 16.5% Zn. After follow-up drilling, a commercial deposit was located about a mile west of the "discovery" hole. This "random walk" method of exploration for MVT deposits, although obviously effective in this case, is one which is unlikely to be regarded as efficient by most exploration companies. Even as late as 1980, after much more research had been accomplished on MVT deposits, Ohle (1980, p. 163) conceded that "no general consensus has been reached" on a number of basic parameters of these amazing deposits.

The situation is similar in Ireland where previous exploration seemed to indicate that mineralization was confined to specific time intervals, viz. the Navan Beds and the base of the Waulsortian reef, both Courceyan. If, however, mineralization extends beyond Courceyan time, as indicated by deposits in post-Courceyan rocks (e.g. Navan, see Ashton et al., this vol., and Harberton Bridge, see Emo, this vol.), then the stratigraphic range of exploration, as well as ore genesis models as applied in the Irish Carboniferous basin, must be expanded.

This apparent inability of economic geologists to understand or even to recognize some of the more basic features of MVT deposits has been discussed previously (Sangster, 1983). Two main barriers to development of an MVT descriptive or genetic model were recognized: 1. differences in geological parameters between deposits outweigh, both in number and significance, the similarities; 2. lack of knowledge regarding age of mineralization.

The first barrier, geological differences between deposits, is summarized in Table 1. Here, the profound range in parameters such as regional tectonic settings, host rock lithologies, metal ratios, nature of the associated erosion surfaces, lateral facies changes, and ore-host relations, can be appreciated. When these differences are taken into account, perhaps finding a common genetic model is akin to searching for a common tree that will grow apples, oranges, and peaches.

The second barrier to erecting a general MVT model is our lack of knowledge regarding time of ore emplacement. This permits numerous models to be erected, each of which is capable of embracing a variety of geological and geochemical observations. The author is convinced that signifi-

Table 1.

Summary of selected attributes of MVT deposits (from Sangster, 1983).

1. *Regional tectonic setting*
   —stable, interior platform resting on craton (SE Missouri) to mobile shelf adjacent to active rift zone (E Alpine);
2. *Host rock lithology*
   —limestone with minor dolostone (Tri-State) to entirely dolostone (Pine Point, Upper Silesia, etc.);
3. *Metal ratios*
   —two populations of Zn/(Zn+Pb) ratios; one with ratios greater than 0.7 (includes a majority of the districts), and the other, consisting of one district (SE Missouri), which is unique in having ratios less than 0.2.
4. *Erosion surfaces*
   —all districts except SE Missouri occur *below* an erosion surface; the SE Missouri deposits lie *above* a major unconformity. In the former, the hiatus represented by the erosion surface ranges in length from a diastem (e.g. Upper Mississippi Valley) to a major angular unconformity (Polaris).
5. *Sedimentary facies changes*
   —range from virtually nil (e.g. E Tennessee) to highly complex (E Alpine; Pine Point). Where facies changes occur, ores show no consistent position relative to facies from one district to the next.
6. *Relation of orebodies to host rock*
   —ranges from highly concordant (e.g. blanket orebodies in Tri-State; "U-bed" ore in E Tennessee) to highly discordant in syn-sedimentary faults (Raibl and Mezica) and "breccia domes" in Tennessee and Poland.

cant advances in understanding MVT deposits are precluded until accurate methods are developed for measuring the time of ore emplacement. This was recognized by Ohle (1980, p.165) when he stated: ". . . if by some means the . . . age of ore deposition could be determined, it would have a needed, guiding effect on theories of Mississippi Valley-type ore formation".

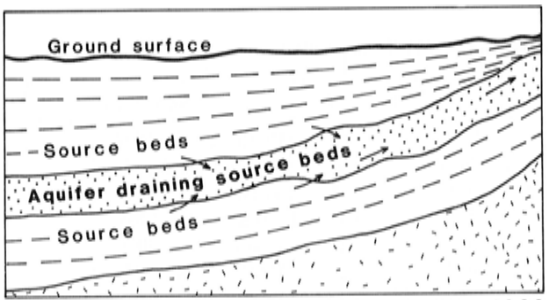
Genetic model for MVT deposits

Probably the most popular model for MVT deposits is the so-called "basin expulsion" or "basin compaction" model wherein ore-bearing brines are expelled, by compaction, from the deeper parts of a basin to its periphery, at which point the ore is deposited. The model has been popular for over twenty years (Fig. 1) and received a great boost when it was applied to the Pine Point district by Jackson and Beales (1967). The model is exceedingly popular in spite of the fact that it has never been tested, let alone proven (as emphasized by Ohle, 1980). For example it has never been demonstrated that metals in a particular deposit or district came from a specified basin and no other. Nor have the channelways through which ore fluids migrated from source to deposition site ever been identified, although recent studies in SE Missouri seem to indicate a sandstone aquifer for that region (Sverjensky, 1981). Again, quoting from Ohle (1980. p. 170), "the basinal brine hypothesis . . . . has been accepted as the final answer too quickly considering the vagueness of our understanding of how it works".

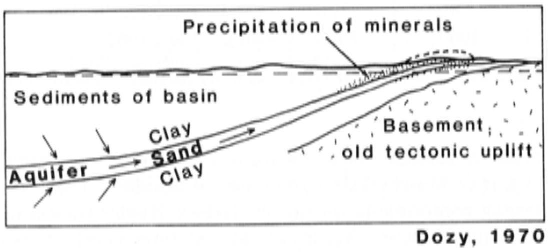
The chemical and physical changes that take place in sediments and pore fluids during compaction, and their relevance to generating ore fluids, have recently been discussed and summarized by Lydon (1983). Leaching of ore elements (for example, base metals) in the compacting sedimentary pile occurs most effectively only during transformation of expandable to non-expandable clays. This transformation is temperature-dependent and begins to take place in the range 90° to 130°C (Lydon, 1983, Fig. 6.12). In basins with normal sediment deposition rates and geothermal gradients, metal leaching by this process would occur at depths of about 3km. In basins with unusually high heat flow provided by crustal thinning (rifting) and/or volcanism, such as the Irish Basin (Russell, 1968 and 1971), these depths and times can be significantly decreased.

In a recent landmark paper, Cathles and Smith (1983) examined the effects of basin compaction in the classic MVT districts of the United States. Among the several conclusions arising from this study was that maximum expulsion rates of pore water out of the basin coincides roughly with the depth of burial necessary to generate temperatures compatible with those found in MVT deposits (i.e. approximately 100°C). Furthermore, they calculated at what point in the depositional history of this ideal basin the maximum rate of fluid expulsion took place and found it to be 40Ma. That is to say, about 40 Ma after burial, a sediment has reached temperatures greater than approximately 130°C, maximum metal leaching is taking place, and maximum water flow out of the basin is occurring. Should these fluids reach the top of the sedimentary pile (the sea floor), they will form a sedimentary-exhalative (SEDEX) deposit. If the fluids reach a trap somewhere within the sedimentary sequence, they could form an MVT deposit. Thus the same "basin compaction" model has been proposed for both SEDEX (Lydon, 1983) and MVT (Cathles and Smith, 1983) deposits.

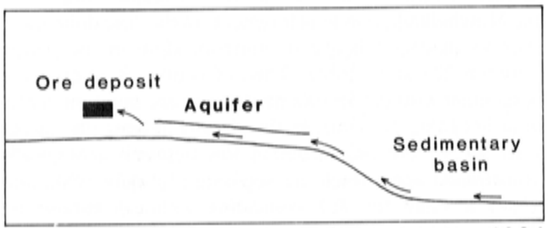
A common genetic model for both SEDEX and MVT deposits, as a first approximation, may have some merit. Both deposit-types have similar Zn/(Zn + Pb) ratios and highly variable Fe/(Zn + Pb) ratios. Furthermore, many examples exist of basins having SEDEX deposits in the central portion of the basin and MVT deposits at the



Noble, 1963



Dozy, 1970



Sverjensky, 1984

Figure 1. Schematic representation of the "basin compaction" genetic model for Mississippi Valley-type deposits illustrating how little it has changed over the past twenty years.

margin. For example, the Carboniferous Fundy Basin of eastern Canada contains the Walton and Smithfield SEDEX deposits associated with a bounding fault of a graben within the Fundy Basin (Chatterjee, 1983). The Gays River MVT deposit occurs in essentially the same age rocks in a smaller, shallow water basin peripheral to the Fundy Basin (Akande and Zentilli, 1984). The Selwyn Basin of northern Canada contains the Anvil Range, Mac Pass, and Howard's Pass SEDEX deposits, while the shelf carbonates to the east host a plethora of MVT deposits, the largest of which are Gayna River and Bear-Twit. The southern extension of the Selwyn Basin into northern British Columbia, the Gataga Lakes area, contains the important Cirque and Driftpile SEDEX deposits; only 60km to the SE the Robb Lake MVT deposit lies in the bordering shelf carbonates (MacIntyre, 1982).

One of the major differences in all these examples of basin-generated lead-zinc deposits, is that the SEDEX and volcanogenic deposits are coeval with their host rocks, whereas the MVT deposits are clearly epigenetic i.e. time of ore emplacement relative to host rock is one of several factors distinguishing the two deposit-types although they appear to share a common genetic heritage.

At this point in the discussion, some of the attributes of basin compaction relative to formation of lead-zinc deposits have been examined and, following Cathles and Smith (1983), some of these phenomena have been related to time, thereby setting up a situation whereby the basin compaction model can be tested directly by age dating.

Age constraints for MVT deposits

This brings the discussion back to the original point concerning the profound lack of knowledge regarding age of deposition of MVT ores. To illustrate how little is known of this topic, a proposal by McGinnis (1968), relating MVT ore districts in the United States to maximum extent of Wisconsin continental glaciation, has never been subsequently challenged in print since it was first proposed. According to the basin compaction model and the data of Cathles and Smith (1983), these ores should have formed in the early Palaeozoic about 40Ma after deposition of their carbonate host rocks. McGinnis's model, however, would emplace the ores 400-500Ma later than the carbonate hosts. The two models should be easily testable simply by dating the time of ore emplacement. However, there are no geochronological data which would permit acceptance of one model over the other in spite of the startling disparity in the suggested time of ore deposition. Such is the sorry state of age dating of MVT ores, a situation which can obviously permit a wide range of genetic models to be proposed but with little means by which to choose between them. In an attempt to evaluate the current state of knowledge regarding ages of MVT ores, results of direct dating of these deposits have been compiled from the literature (Table 2). In this table, T_r=age of host rock, and T_m=age of mineralization, as determined by the technique indicated. The factor $\triangle T=(T_r-T_m)$ represents the age difference between host and ore and should be compared with estimates of maximum basinal brine expulsion as calculated by Cathles and Smith (Table 3). Note the extreme range in $\triangle T$, not only between districts, but also for the same district such as SE Missouri. If one accepts that the two Rb-Sr dates in Table 2 (392 v 358Ma) are in reasonable agreement for this district, these yield $\triangle T$s of 125 and 155Ma, respectively. These dates are obviously at high variance with Cathles and Smith's estimates for basin dewatering, even though the SE Missouri district lies within their "type" study area. This dichotomy raises the obvious question — are the dates right and the model wrong or vice versa? The Rb-Sr dates were derived from two different materials (galena v glauconite) and yield ages which could be argued to be in reasonable agreement. If these dates are accepted as the age of mineralization for SE Missouri ores, then the popular basin compaction model based on the "normal" basin of Cathles and Smith (1983) would obviously fail the test.

Preliminary dating of SE Missouri and Newfoundland zinc ores by palaeomagnetic methods (Beales et al., 1974) detected no difference between T_m and T_r, hence $\triangle T=0$ in both districts. Unless the error limits on this method of dating are very much greater than 40Ma, these results could be taken as support for the basin expulsion model.

Later palaeomagnetic studies by Wu and Beales (1981), however, on SE Missouri ores yielded a Pennsylvanian age for mineralization and therefore $\triangle T$=265Ma. Similarly, determination of T_m, by palaeomagnetic methods, at Pine Point gave $\triangle T$=133Ma. Pelitic rocks buried as long as these $\triangle T$ values suggest should not have retained sufficient

Table 2.
Results of direct dating of minerals in MVT deposits

District	Method	Material	T_m(Ma)	T_r (Ma)	ΔT	References
SE Missouri	palaeomag.	ore	515–500	515	0	Beales et al., 1974
SE Missouri	palaeomag.	ore	290–250	515	+265	Wu and Beales, 1981
SE Missouri	K-Ar	pyrite	549±20	515	-34	York et al., 1983
SE Missouri	Rb-Sr	galena	392±21	515	+125	Lange et al., 1983
SE Missouri	Rb-Sr	glauconite	358±6	515	+155	Posey et al., 1983
Newfoundland Zinc	palaeomag.	ore	485	485	0	Beales et al., 1974
Pine Point	palaeomag.	ore	280–232	365	+133	Beales and Jackson, 1982
Pine Point	Pb-Pb	galena	285	365	+80	Sangster (unpub. data)
Silesia	Pb-Pb	galena	184	225-220	+40	Ridge and Smolarska, 1972
E Alpine	Pb-Pb	galena	345	218-212	-130	Brigo et al., 1977
Gays River	Pb-Pb	galena	456	330	-126	Akande and Zentilli, 1984
Coxco	Pb-Pb	galena	1580	1680	+126	Walker et al., 1983
Nanisivik	Pb-Pb	galena	550	1220–1202	+670	Sangster (unpub. data)

porosity or pore fluids to serve as source beds or conduits for ore fluids.

Many Mississippi Valley-type deposits display very radiogenic lead isotopes indicating a multi-stage history. Lead isotope abundances in districts such as SE Missouri, Upper Mississippi Valley, and Tri-State, define linear trends in which age of mineralization cannot be calculated unless age of source is known. Because the source of lead in these and other MVT districts remains unknown, age of mineralization cannot be calculated. In other districts, the lead isotope ratios are much more homogeneous and fall close to the average growth curve (Fig. 3) and, for these districts, model lead ages can be calculated. The East Alpine region contains so-called "B-leads" which yield ages older than the host rock and hence are unacceptable on geological grounds. The remainder, however, yield model ages which do not contradict known geological evidence and hence must be examined.

First, it should be noted that deposits in the Silesia district of Poland give a model age of 184Ma (using the Stacey-Kramers model) yielding ΔT=40Ma, coinciding with the time of maximum fluid expulsion from sedimentary basins as calculated by Cathles and Smith (1983). Furthermore, this age for the Polish ores is supported by geological evidence summarized in Figure 2. The deposits are hosted in Lower Muschelkalk carbonates of Middle Triassic age resting conformably on Lower Triassic Bunter sandstone (Sliwinski, 1969). According to the time chart of van Eysinga (1975), this boundary occurs at approximately 225Ma. Bogacz et al. (1970) have recorded that a conglomerate of Middle Jurassic age, resting unconformably on the Muschelkalk, contains fragments of the "ore dolomite", thereby placing the age of mineralization in the period between 225 and 176Ma. This, of course, is in excellent agreement with the 184Ma model lead age mentioned previously (Table 2). Thus, in this district at least, the model lead age of ore emplacement lies between geologically constrained ages which are separated by only 19Ma and yields a value for ΔT coinciding with calculations by Cathles and Smith (1983).

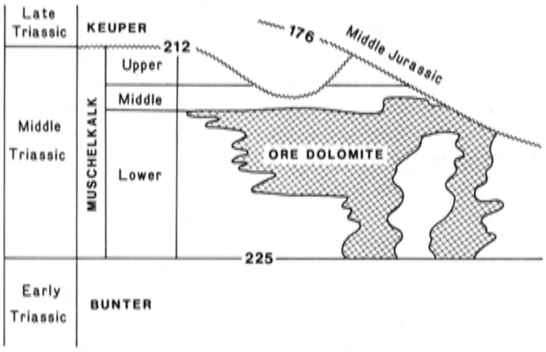


Figure 2. Stratigraphic position of the Silesian lead-zinc district (Poland)relative to known time-lines. Numbers are absolute ages in million years (drawn by the author from descriptions in Sliwinski (1969) and Bogacz et al. (1970); time boundaries from van Eysinga (1975))

At Pine Point, the model lead age of 285Ma is not contradicted by any known geological evidence, but neither is it confirmed by such evidence as was the case in Poland. In fact, the only "hard" constraints on the age of mineralization at Pine Point are that the maximum age is defined by the Middle Devonian age of the host rocks; minimum age is constrained by the fact that the deposit was shown to prospectors by the local Indians in 1898! (This is a slight exaggeration; ore boulders in the overlying till and glacially striated ore surfaces indicate a pre-glacial age for the deposit; Rhodes et al., 1984). Barring further evidence, however, the 285Ma model lead age must be tentatively accepted for Pine Point. A ΔT=80Ma (Table 2) would be at the extreme limit of Cathles and Smith's (1983) dewatering event. Thus, in contrast to SE Missouri, model lead ages for Silesia and Pine Point appear to support the basin dewatering model.

Several other model lead ages summarized in Table 2 and displayed in Figure 3 can be examined relative to local geology. Gays River galenas are of the B-lead type, yielding an Ordovician age for ores in Carboniferous carbonates. The Nanisivik deposit, located in Upper Proterozoic dolomites of northern Baffin Island, contains galena of relatively homogeneous Pb-isotope composition yielding a model lead age of about 550 Ma. Host rock age has been estimated to be in the range 1220-1202Ma, based on palaeomagnetic methods (Fahrig et al., 1981). The deposit is cut by a diabase dyke of the Franklin swarm, the age of which ranges from 463 to 786Ma as determined by K-Ar (Jackson and Iannelli, 1981). Two samples from the mine dyke itself gave K-Ar ages of 531 and 463Ma (Olson, 1977). A small

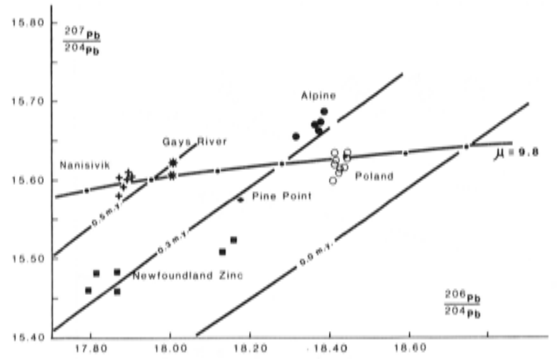


Figure 3. Pb-isotope compositions of galenas from several MVT deposits or districts plotted relative to the Stacey-Kramers (1975) growth curve. In this diagram, Gays River and Alpine galenas, although relatively homogeneous, are of the "B-lead" type and yield geologically unacceptable model lead ages. Data for Nanisivik, Pine Point, and Poland (Silesia) are equally homogeneous in composition and give model lead ages not contradicted by local geology in these districts. The reason for the apparent two populations in Pb-isotopic compositions at Newfoundland Zinc is not known. Data sources are given in caption for Figure 6.

trachyte dyke, also post-ore, yields a Rb-Sr age of 485Ma with an initial intercept of 0.70966±0.00043. Because both the K-Ar and Rb-Sr ages are younger than the model lead age of ore, which itself is younger than the best estimate for age of host rock, no available evidence contradicts the 550Ma age for the ore. Consequently, this age must be considered a possible true age of ore formation at Nanisivik. If this is accepted, then $\triangle T$ for this deposit would be of the order of 670Ma (i.e. a range greater than the entire Phanerozoic) and basin compaction would therefore probably not be the genetic model for this MVT deposit.

Relation between SEDEX and MVT deposits

Earlier discussion had examined how basin compaction seemed to be a common genetic model for both SEDEX and MVT deposits. In Figure 4 this relation is expressed in terms of T_m, T_r, and $\triangle T$ for both deposit types. From this diagram it is apparent that, if a SEDEX deposit and an MVT deposit are both generated at the same time (i.e. the same T_m) and from the same source bed(s), then the closer the MVT fluid gets to the basin floor, the smaller is the value for $\triangle T$. Thus, although T_m is the same for both deposit types, each would have a different $\triangle T$ value. If T_m is the same for both, it is possible that both SEDEX and MVT deposits generated from the same sedimentary basin might be expected to have similar Pb-isotope values.

An example of a region where both SEDEX and MVT deposits occur close to one another and consequently could be considered to have been generated from the same source bed(s) is the McArthur River district, Northern Territory, Australia. Here, the Proterozoic McArthur Basin contains the stratiform HYC, Emu Plains, and W-Fold lead-zinc deposits (Lambert, 1976 and Walker et al., 1977) in half-graben, second-order basins within the larger basin. The Coxco MVT deposit occurs at the edge of the basin associated with narrow horsts on the flank of the Masterton Dome (Walker et al., 1983). The uplifted portions of the horsts were subjected to subaerial weathering with the resultant development of secondary porosity in carbonates which now host the Coxco deposit. The MVT Coxco deposit is contained within a carbonate formation (the Reward Dolomite) which stratigraphically immediately overlies the Barney Creek Formation, host to the HYC and other stratiform (SEDEX) lead-zinc deposits (Walker et al., 1983). Thus both MVT and SEDEX deposits are not only geographically close to each other (about 10km; Walker et al., 1983) but stratigraphically as well. Age of host rocks in the McArthur River area has been determined to be about 1680Ma by U-Pb dating of zircons in tuff marker beds (Page, 1981).

Figure 5 presents Pb-isotope data for both the HYC and Coxco deposits plotted on the Stacey-Kramer two-stage growth curve. On this diagram the similarity in Pb-isotopic compositions of the two deposits is apparent. Excluding the three aberrant values, the remaining data points yield

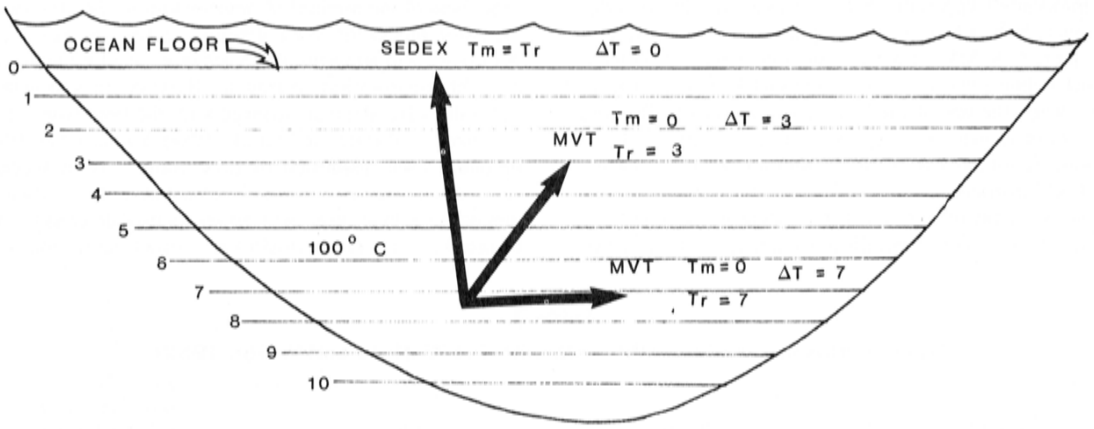


Figure 4. Schematic representation of a sedimentary basin relating T_m, T_r, and $\triangle T$ to SEDEX and MVT deposits. Horizontal lines represent isochrons within the sedimentary pile. Diagram illustrates differing values for $\triangle T$ for a SEDEX and two MVT deposits, all generated from the same source bed(s) at the same time.

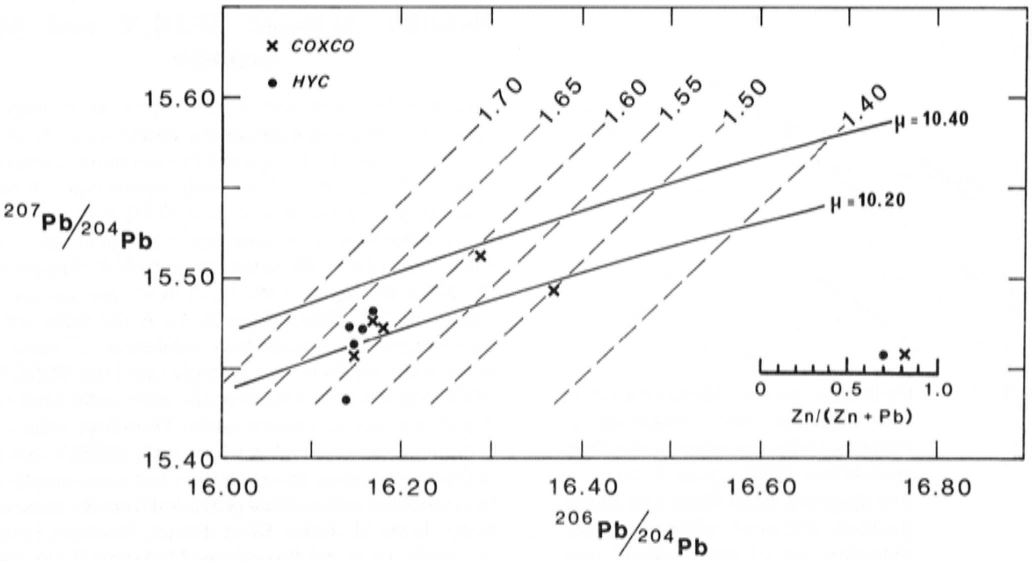


Figure 5. Pb-isotope plot of galenas from the Coxco and HYC deposits. Also shown (lower right) are Zn/(Zn+Pb) ratios for the two deposits. Data from Gulson (1975), Richards (1975), and Walker et al. (1983).

model lead ages very close to that of the host rock. The similarity in isotopic compositions would be expected for deposits formed from brines generated at about the same time from the same source bed(s).

The data for the Coxco deposit seem to support the basin expulsion model (within the limits of the available age data) as do the data from Silesia and Pine Point. However, the SE Missouri and Nanisivik data do not, at least not within the time constraints suggested by the Cathles and Smith analysis.

In Ireland, the geological constraints on age of mineralization, including, for example, the presence of a post-ore unconformity apparently truncating ore at Navan (Ashton et al., this vol.) and the abundance of syndiagenetic textures at Tynagh (Boast et al., 1981) stand in contradiction to the K-Ar data of Halliday and Mitchell (1983) indicating a much later age of ore emplacement.

Before drawing any final conclusions, it might be instructive to examine Pb-isotopic data from the MVT districts/deposits not discussed previously (Fig. 6). The great disparity in degree of homogeneity between districts is immediately apparent when all data are displayed in this manner. Shown here is the "J-lead" character of three of the large U.S. MVT districts. These districts contain leads which define a two-stage isochron which can determine T_m only when the age of the lead source is known. Because this is not known, two-stage plots are not useful for determining T_m for MVT deposits. In addition to the "classical" "J-lead" districts, however, the data in Figure 6 clearly show that many other MVT districts/deposits contain leads which are not only isotopically homogeneous but are sufficiently non-radiogenic that they give geologically acceptable model lead ages. This is in spite of recent statements to the contrary e.g. "Lead isotopes can also show a considerable range in any one district, and are commonly highly radiogenic, yielding future ages (negative model ages)." (Anderson and Macqueen, 1982, p. 110). The isotopic characteristics referred to by these authors apply to districts such as Upper Mississippi Valley, Tri-State, and SE Missouri, and obviously invalidate use of these data for determining T_m, the age of mineralization. In contrast, Pb-isotopes at Pine Point, Nanisivik, Silesia, and, to a lesser extent, Coxco, are all relatively homogeneous, are not of the "J-lead" type, and, consequently, should be considered in terms of providing acceptable ages of mineralization. In the case of Pine Point, Nanisivik, and especially Silesia, model lead isotope ages have been shown not to conflict with other geological evidence. In some circumstances, then, it appears that lead isotopes can yield values for T_m in MVT deposits which are at least as reliable as other, more conventional, methods.

If the values for T_m listed in Table 2 are accepted, regardless of the method of determination, then the basin expulsion model for MVT deposits, in spite of its current popularity and widespread acceptance, must be seriously brought into question, at least for those districts for which $\triangle T$ values are at great variance with the time constraints suggested by Cathles and Smith (1983). Because the 40Ma optimum value suggested by these authors is an average value calculated for "normal" intra-continental sedimentary basins with average over-all geothermal gradients, time of ore fluid generation could vary considerably from one

Table 3.
Fluid expulsion rates for sedimentary basins (Cathles and Smith, 1983)

Age(Ma)	D(km)	T(°C)	Expulsion rate (g/cm-sec.x10^3)
10	1.1	93°	3.1
40	3.5	147°	3.6
80	5.3	156°–179°	2.1

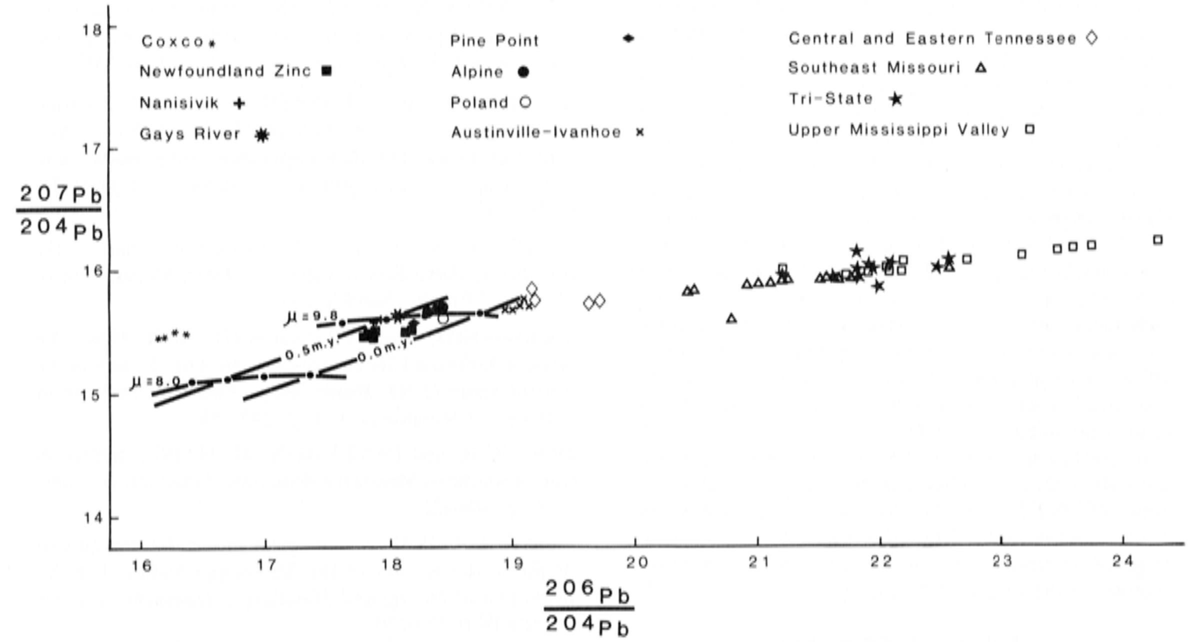


Figure 6. Pb-isotope plot of galenas from several MVT districts illustrating the wide range in degree of homogeneity between districts. Data source as follows: Coxco (Walker et al., 1983); Newfoundland Zinc (Fletcher, 1979); Nanisivik (D. F. Sangster, unpub. data); Gays River (Akande and Zentilli, 1984); Pine Point (D. F. Sangster, unpub. data); Alpine (Zartman et al., 1979); Brigo et al., 1977); Poland (Ridge and Smolarska, 1972; Zartman et al., 1979); Austinville-Ivanhoe (Foley et al., 1981); Central and E Tennessee (Crawford and Hoagland, 1968; Heyl et al., 1966; Gaylord and Briskey, 1983); SE Missouri (Doe and Delevaux, 1972; Sverjensky, 1981); Tri-State (Russell and Farquaher, 1960); Upper Mississippi Valley (Heyl et al., 1966).

basin to another, particularly between basins of widely differing tectonic settings. In basins of exceptionally high geothermal gradients, rift basins for example, the 100°C isotherm would be reached much sooner than in a "cool" basin such as a gentle downwarp in the continental interior. In the "hot" basins, metal leaching would take place much sooner (although at the same expandable-to-nonexpandable clay inversion temperature of approximately 100°C) than in the "cool" ones, with the result that ores could form earlier in the geological history of "hot" basins relative to the "cool" ones. That is to say, △T values in the former (e.g. Irish Carboniferous) might be expected to be smaller.

Summary

If, as postulated in the brine-expulsion theory, MVT deposits are indeed the result of diagenetic processes acting in a compacting sedimentary pile, the necessary processes can only operate effectively within a certain "time window" during the sedimentologic-diagenetic history of that basin. Thus, provided adequate age dating techniques are available, testing the basin expulsion, or other, model should be very feasible.

Frank Beales recognized the problem several years ago and chose to use palaeomagnetism as his age dating method (e.g. Beales et al., 1974 and Wu and Beales, 1981). This was a bold and imaginative research effort and, with proper sampling together with cryogenic magnetometers, deserves further consideration as a dating tool for deposits which do not normally contain minerals datable by standard geochronological methods.

Another possibility is the ^{39}Ar—^{40}Ar method which York et al. (1981) tested on pyrite from Viburnum Trend ores in SE Missouri. By this method they obtained a value of 549±20Ma. The younger limit of the error range of this date might be taken to indicate that $T_m = T_r$, suggesting at least a diagenetic age for this mineral.

A third method is Rb-Sr by which Lange et al. (1983) obtained an age of 392Ma on galena, also from Viburnum Trend ores. This is about 130Ma younger than host rocks and raises the question: is the pyrite one age (i.e. diagenetic) and the galena the result of another, much younger, mineralizing event?

Of course, sulphides are not the only minerals in MVT deposits, but notably lacking in these ores are the silicates (micas, amphiboles, feldspars, etc.) normally used in conventional age dating techniques. Common gangue minerals in MVT deposits are calcite and dolomite; quartz, barite, and fluorite are found in smaller quantities in some deposits. The feasibility of obtaining Rb-Sr isochrons in fluid inclusions in quartz was recently demonstrated by Shepherd and Darbyshire (1981) and offers an alternative, or supplement, to the direct dating of ore minerals described above.

Conclusion

The possibility of dating, separately, both ore and gangue minerals in MVT deposits opens up exciting new fields of research in ore genesis. Provided the techniques are developed to a sufficient degree of accuracy, dating of ore and gangue could assist in determining which minerals are of diagenetic origin, which are related to the ore-forming event, and which are the result of relatively modern karst or ground-water action. The time of initiation and termination of the mineralizing process might be determinable and, hence, related to the correct period in the sedimentological history of the source basin(s). This, in turn, might explain the diversity in lead isotopic characteristics between districts (Fig. 3), the wide range in metal ratios within a single district (e.g. Pine Point; Kyle, 1981) or between districts (Sangster, 1983), and why some deposits show a correlation between sulphur and lead isotope values (e.g. Viburnum Trend; Sverjensky et al., 1979) while most other districts do not. Finally, of course, reliable age dating techniques will permit economic geologists to test MVT models as widely disparate as those proposed by McGinnis (1968) and Cathles and Smith (1983) and, hopefully, to distinguish between one or more types of lead-zinc deposits in the Carboniferous of Ireland.

In conclusion, therefore, it seems abundantly clear that not only is there an overwhelming need for reliable age dating of MVT deposits, but that the necessary technology is also available, and a directed research effort is all that is required to achieve a major breakthrough in the understanding of this enigmatic deposit-type.

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Discussion

ERNEST OHLE (Salt Lake City, Utah) made the following comments:

I think I should correct a misimpression that was created by Don's reference to my published views on the origin of Mississippi Valley-type deposits. He implied that, over the years, I had changed my opinion. Such is not the case. In 1959 I stated that, in my view, MVT deposits had so many basic similarities that the fluids causing most, if not all, of them would prove to have had a similar origin. I meant this in the broadest sense. That is, I felt we would ultimately find that all of them were deposited from solutions that were primarily either (1) magmatic, (2) basinal brines, or (3) as was once supported by many Americans and is still advocated by some geologists on the European Continent, were groundwaters acting in a karstic environment. I still think this is a good possibility, and the differences we now observe in the area could well be the result of differences in the source, differences in the fluid-rock interaction during transport, or differences in the lithology or structure of the host at the point of deposition.

I have heard nothing at this conference which has led me to alter this view, and I would like to set the record straight.

REPLY:

Not realizing that my remarks may have misled certain of the audience, I am particularly pleased that Ernie has taken this opportunity to set the record straight. I don't believe that the issues which have apparently caused Ernie some distress are included in my paper, so I will attempt to answer him in the following remarks.

In my oral presentation I did, indeed, quote frequently from both Ernie's 1959 and 1980 papers.I did this because of the very high regard I have for his experience in MVT deposits and the manner in which he presents his ideas and concerns.

My own personal impression, after reading the two papers concerned, was that, in 1959, Ernie was emphasizing the common features of MVT deposits, whereas in 1980 he seemed to emphasize the differences. The essence of the two papers seemed to me to be expressed in the following two quotes: ". . . all of them had the same general mode of origin and that consideration of the group as a whole rather than individually offers a better chance of determining what was that mode of origin" (Ohle, 1959, p. 769). In 1980 (p. 163), with reference to the distinctive mineralogy of each MVT district, Ernie wrote "These individualities raise the question as to whether each ore had a different source, a different plumbing system, and a different timing from all the others". The context of the quote made it clear (to me at least) that "each ore" in the above quote referred, in fact, to each individual ore district; hence, I read into the 1980 paper (erroneously as it now appears) that the author then felt that each ore district should be considered separately (with regard to genesis), instead of being grouped, as was the advocation in 1959. Ernie's remarks in his statement here have made it clear that this was not the impression he intended to make, so I am very pleased that he took this opportunity to correct any misrepresentation I may have inadvertently made in reference to his publications.

There is much in Ernie Ohle's publications that I agree with and endorse. Evidence of this lies, in part, in the subject of my paper i.e. the necessity to be able to date the time of ore emplacement in MVT deposits. If I could be permitted to quote (correctly this time, it is hoped) from Ohle (1980, p. 165): ". . . if by some means the approximate age of ore deposition could be determined, it would have a needed, guiding effect on theories of Mississippi Valley-type ore formation". The problem is thus so succinctly and clearly stated that one can do no more than say "Amen to that".

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