Economic Geology
Vol. 77, 1982, pp. 392–412

The Emplacement of Zinc-Lead Sulfide Ores in the Upper Silesian District—A Contribution to the Understanding of Mississippi Valley-Type Deposits

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Abstract

This paper discusses the manner in which Upper Silesian zinc-lead ores of Mississippi Valley type were introduced into, and deposited within, the ore-bearing dolomite, the host rock of the ores. The ore-bearing dolomite is a neosome developed in Triassic carbonates through dolomitization of limestones and recrystallization of primary or early diagenetic dolomites. It contains three types of ore: (1) ore deposited in rock openings; (2) metasomatically emplaced ore; and (3) ore that crystallized in disaggregated, i.e., delithified, dolomite. The ores were emplaced by mineralizing solutions circulating through an aquifer(s) in lithified rocks. The action of these solutions, combined with that of mobilized ground waters, accounts for the formation of the ore-bearing dolomite. The sulfide ores definitely are epigenetic in relation to their host rocks, and there is no evidence that they were ever part of primary bottom sediments. Further, no evidence is known to us of lateral deposition within the Triassic strata. Mineralization worked outward from those rock volumes that contained the greatest abundance of solution voids. Ample geologic evidence, discussed in this paper, confirmed by measurements of temperature ranges for sulfide precipitation, clearly points to ascending hydrothermal solutions as the progenitors of the ore mineralization. These solutions are thought to be responsible for the formation of conspicuous mineralized karst structures (hydrothermal karsts) that are among the most important ore hosts in the Upper Silesian ore district.

The geologic evidence (as detailed in this paper) also indicates that the hydrothermal ore-bearing solutions rose on a broad front along the northeastern margin of the Silesian basin and, after gaining access to the Triassic aquifer, spread laterally to the south and southwest.

Introduction

THE zinc-lead ores of southwestern Poland (Fig. 1) occupy an important place among Mississippi Valley-type deposits. These once were designated as Upper Silesia-Mississippi Valley-type deposits (Dunham, 1950). In recent years, they have been designated as Cracow-Silesian or Cracovian-Silesian ores because their geographic extent is well beyond the administrative boundaries of Upper Silesia. In this paper, however, we will return to the traditional name and the ores under discussion will be referred to as Upper Silesian ores. The manner in which they were formed is still controversial. The dispute over this subject has followed the development of ideas on the genesis of similar ores all over the world and has centered on two principal questions: hydrothermal as opposed to nonhydrothermal emplacement and syngenetic as contrasted with epigenetic development of sulfides (for references see Michael, 1913; Ridge and Smolarska, 1972).

Not until the last decade, however, has the direct relationship of a considerable part of the Upper Silesian ores to underground karst structures been recognized. This direct relationship implies that the emplacement of ores and the formation of underground karst were parts of the same formative processes and were essentially simultaneous. Such an implication led to the interpretation of Upper Silesian ores in terms of hydrothermal karst processes (Bogacz et al., 1970; Sass-Gustkiewicz, 1970, 1974, 1975, 1975a; Dzulynski and Sass-Gustkiewicz, 1978).

The following report deals with the essentials of this interpretation. The discussion draws on the results of earlier investigations by the present authors, which

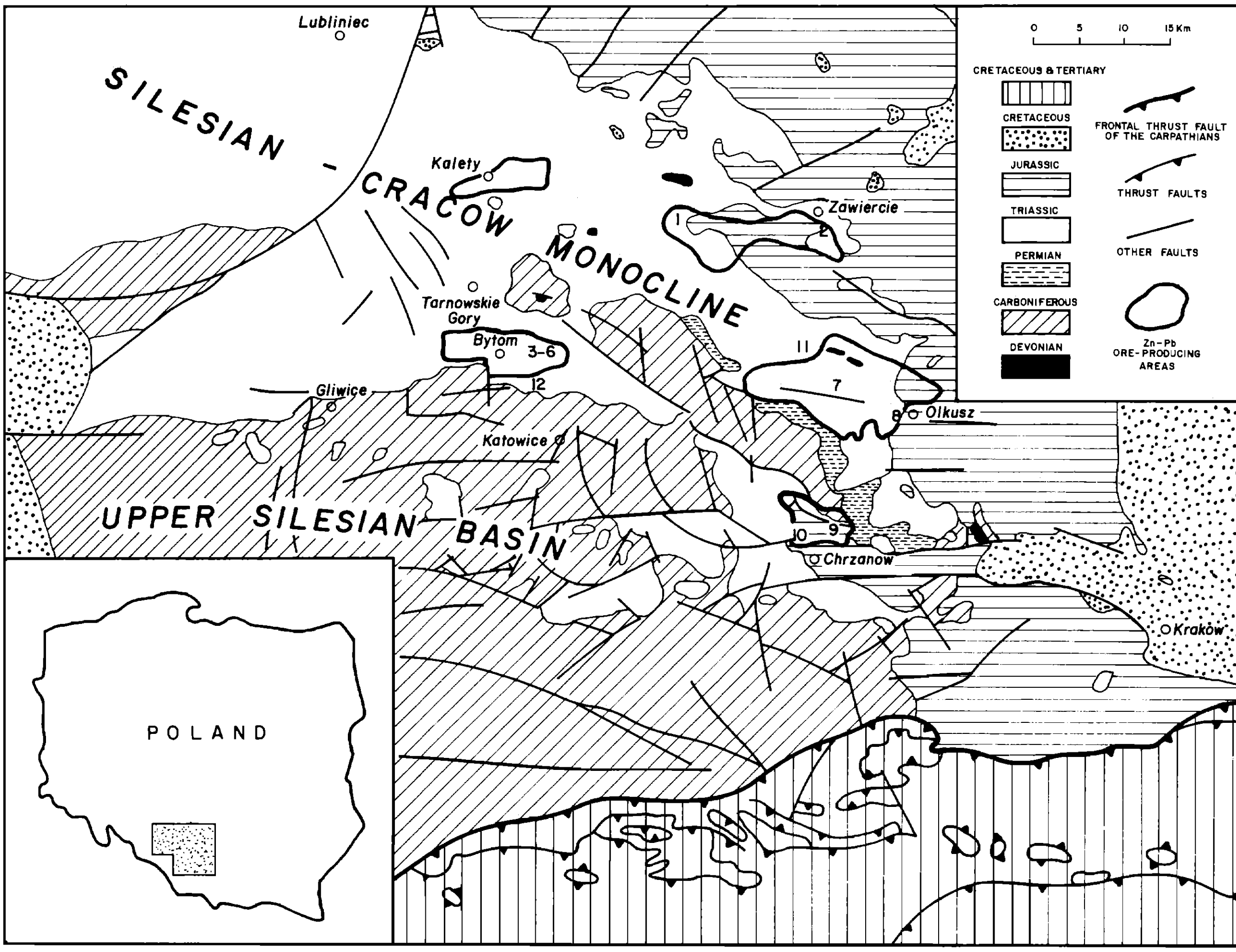

FIG. 1. Geologic sketch map of the Upper Silesian district, Poland. Modified after Zartman et al., 1980. The numbers of the map mark the locations of important mines in the district: 1, Wiktor Emanual; 2, Zawiercie; 3–6 Marchlewski, Orzel Bialy, Novy Dwor, Warynski; 7, Boleslaw; 8, Olkusz; 9, Trzebionka; 10, Matylda; 11, Chechlo; 12, Chorozow.

were scattered in different publications, and are now brought together and enlarged.

Consideration of the Upper Silesian deposits discussed here is limited to the mode of emplacement of Zn-Pb sulfides that are found in the Triassic strata. The ultimate manner of development of the mineralizing solutions and the mineralogy and geochemistry of the ores, as well as the source of the base metals, are beyond the scope of this paper.

Geologic Setting

An approximately 200-m-thick sequence of Triassic strata is the country rock of the sulfide ores. This sequence, comprised of five lithostratigraphic units bearing local names, is separated from the overlying Jurassic and the underlying Paleozoic or Precambrian rocks by major unconformities of regional extent (Fig. 2). In addition to minor hiatuses, indicative of submarine erosion and/or failure of deposition, the continuity of the Triassic sequence is interrupted by two slight unconformities of local extent, one between the Muschelkalk and Keuper and the other between the Keuper and Rhaetian.

The carbonate rocks of the Triassic sequence include: early diagenetic or primary dolostones, limestones, and marls. Extensive sedimentologic and lithologic descriptions of these rocks are omitted as irrelevant to this discussion. The sulfide ores do not reveal a direct relationship to any specific type of sedimentary structure or carbonate lithology although the Upper Silesian ores are associated with a specific type of carbonate facies (the meaning of such association will be dealt with later in this article).

Pertinent to our discussion are the following facts: the carbonate rocks of the Triassic sequence represent shallow and very shallow marine sediments, deposited

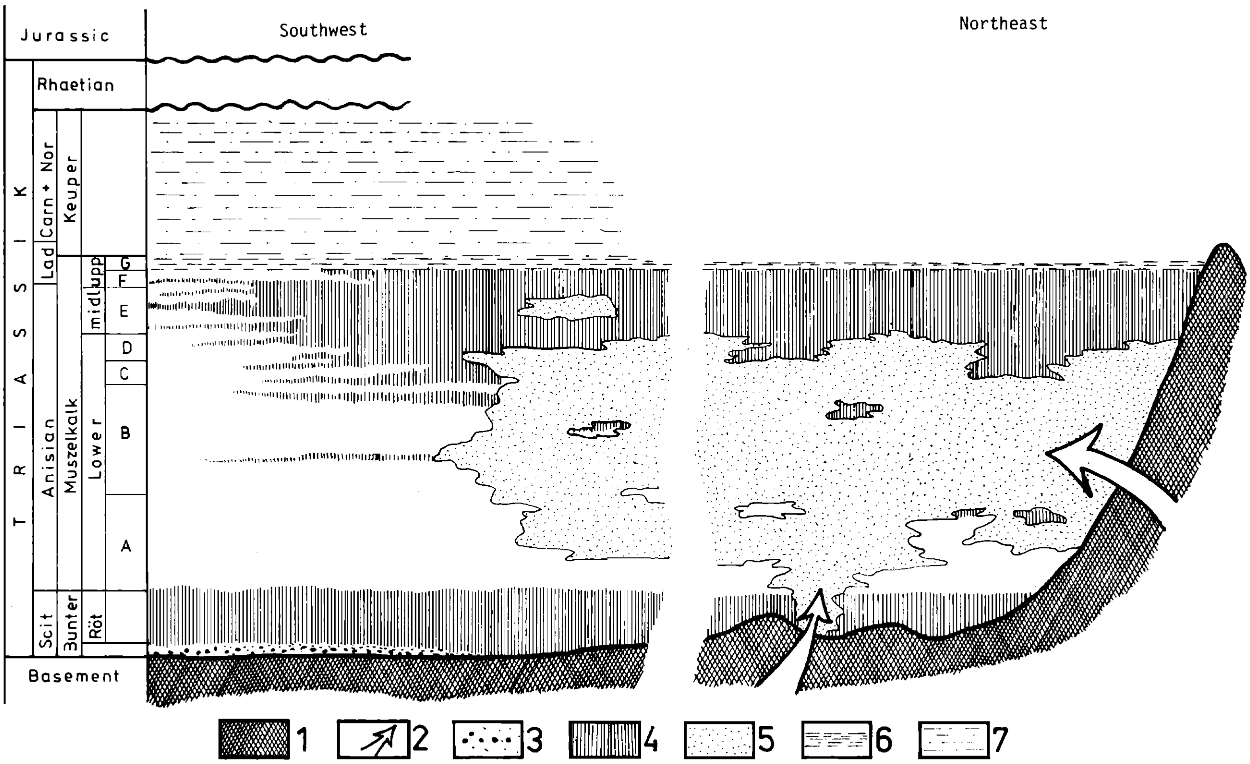

FIG. 2. Diagramatic section through Muschelkalk in Silesian basin from northeast to southwest. 1, pre-Triassic rocks; 2, routes of ascending hydrothermal solutions; 3, Bunter Sandstone; 4, early diagenetic dolostones; 5, ore-bearing dolomite; 6, marine argillaceous sediments; 7, nonmarine, chiefly argillaceous sediments; A, Gogolin Beds; B, Gorazdze Beds; C, Trebratula Beds; D, Karchowice Beds; E, Diplopora Dolomite; F, Tarnowice and Wilkowice Beds; G, Boruszowice Beds. Modified after Bogacz et al., 1975, and Niec, 1980.

under oxidizing and, locally, high energy conditions. The lower and uppermost members of the carbonate sequence, as well as the succeeding nonmarine Keuper, contain abundant marly and argillaceous sediments. Accordingly, the mineralized carbonate rocks are confined between two clay-rich units of relatively low permeability.

In much of the Upper Silesian region, the Triassic strata overlie the slightly disturbed upper Carboniferous Coal Measures. Along the northern and northeastern margin of the Silesian basin, these strata rest with a transgressive overlap on middle or lower Paleozoic and Precambrian rocks. These rocks are strongly disturbed and make up a positive structural element known as the Myszkow-Cracow elevation (Siedlecki, 1962). This structural elevation is part of an extensive orogenic belt that includes the remnants of Caledonian structures but, in its present shape, was formed during Variscan movements (see Przenioslo, 1976). The elevation is also characterized by the presence of abundant intrusive and volcanic rocks produced during middle and late Paleozoic igneous activity (see Haranczyk, 1979, 1980). The southern flank of the elevation coincides with a deep lineament indicated by gravity anomalies.

The previously mentioned transgressive overlap reflects the relief of the pre-Triassic land surface on which the resistant Devonian carbonate rocks occurred relatively high in topography and formed islands in the Muschelkalk sea. These islands are recorded in the present buried hill topography that is among the notable features of the Upper Silesian ore district. It should be added that the amount of early diagenetic dolostones in the Triassic sequence markedly increases toward these paleo-relief elevations.

The tectonics of the Triassic strata are relatively simple. Over large areas, these strata are almost flat lying, and their dips seldom exceed 5°. These strata were first affected by early Cimmerian movements at the close of Triassic time and prior to the Jurassic cycle of sedimentation; these movements produced broad undulations. Faults that are indisputably related to the early Cimmerian movements hitherto were known only from the area to the east of the Upper Silesian ore district. These movements (post-Jurassic, pre-Middle Cretaceous) resulted in slight

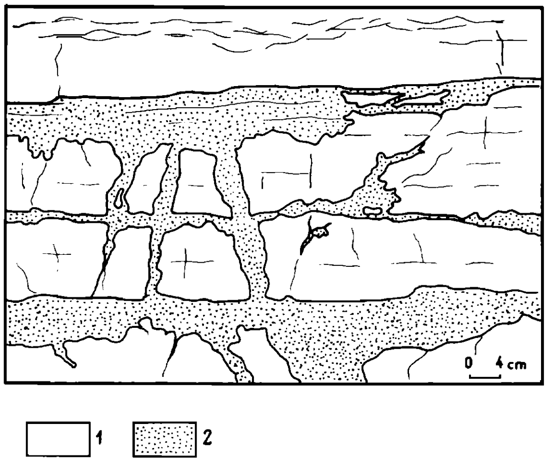

FIG. 3. Metasomatic veins of sulfide-rich ore-bearing dolomite (2) in limestone (1). Trzebionka mine.

uplifts accompanied by weak unconformities. Major tectonic faulting occurred in early Tertiary time and during the Miocene. The latter movements developed horst and graben structures (Dzulynski, 1953). These grabens were filled by Miocene marine clays both while the structures were being formed and after faulting had ceased.

The Triassic carbonate rocks were first exposed to intensive karstification in early Jurassic time. A second and extensive karstification and weathering occurred in early Tertiary time, prior to the middle Miocene marine transgression.

The Ore-Bearing Dolomite

A distinct unit of Triassic strata in the Upper Silesian district is the ore-bearing dolomite, the host rock of the sulfide ores. The origin of this dolomite has long been disputed. With few exceptions (e.g., Althans, 1891; Gruszczyk, 1967; Smolarska, 1968), the general concensus today is that it is epigenetic. This opinion has been strengthened by recent investigations of contact relationships between the dolomite and the remaining Triassic carbonates (Bogacz and Subczynski, 1972).

The ore-bearing dolomite occurs in the form of extensive, roughly tabular bodies, whose horizontal dimensions greatly exceed the vertical ones. These bodies show metasomatic and crosscutting contacts with surrounding limestones (Figs. 3 and 4) and, especially, with early diagenetic dolostones (Bogacz and Subczynski, 1972; Bogacz et al., 1975). Consequently, the dolomite is a neosome with respect to the remaining Triassic carbonates, which will be referred to as the paleosome. This neosome, which is made up of a mosaic of hypidiomorphic crystals, tends to occur on the west side of the previously mentioned Myszkow-Cracow elevation, where the original facies of the Muschelkalk was predominantly primary dolostone; it is conspicuously absent in other regions. Although the dolomite covers a considerable area, its distribution, as compared with that of the remaining Triassic carbonate rocks, is very limited.

Geologists who have studied the Upper Silesian ores have not reached agreement on the mode of formation of the dolomite and, what is particularly pertinent to our discussion, its relationship to the ores. Whereas for most investigators, the dolomite and the ores are products of the same formative processes, some authors (Assmann, 1926; Galkiewicz, 1967; Sliwinski, 1969) consider the formation of the dolomite and the emplacement of ores as partly or entirely separate events. Microscopic examination (Mochnacka and Sass-Gustkiewicz, 1978) confirms that the ore-bearing dolomite and the sulfide ores in it are inseparable in origin and are parts of the same formative processes. However, only the disseminated Zn

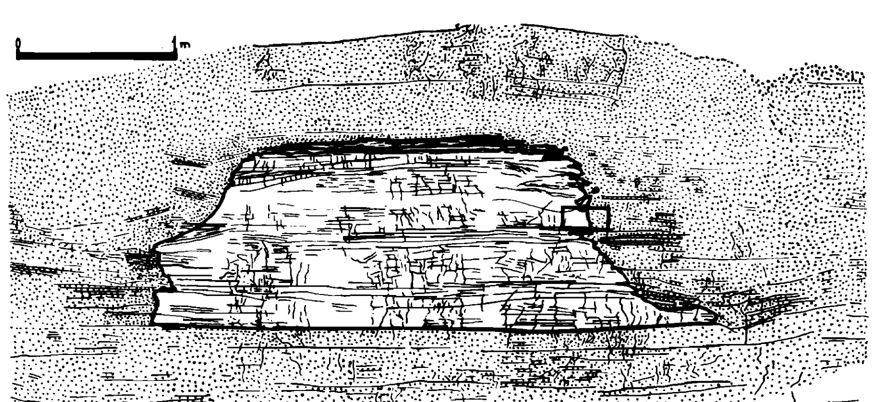

FIG. 4. Relict of limestone in sulfide-rich ore-bearing dolomite (dotted area). Rectangular inset shown in Figure 3. After Bogacz and Sobczynski, 1972.

and Fe sulfides are contemporaneous with and directly related to the processes involved in the dolomite formation (Haranczyk, 1970; Mochnacka and Sass-Gustkiewicz, 1978). The galena and all other more massive sulfide ores appear later in the paragenetic sequence.

The ore-bearing dolomite resulted from dolomitization of limestones and recrystallization of early diagenetic dolostones that existed in the space now occupied by the neosome. It has been suggested that the Mg ions required for dolomitization of limestones were derived, to a considerable degree, from the early diagenetic dolomites. These ions, freed during the transformation of such dolomites and the emplacement of sulfides, were actively involved in the dolomitization of limestones (Bogacz and Sobczynski, 1975).

The ore-bearing dolomite originated from a succession of metasomatic processes and its genesis is related to the transfer (movement) of aqueous solutions through the Triassic aquifer. There is ample evidence that these were ascending hydrothermal solutions (see below). Their action, presumably combined with that of mobilized ground waters, may account for the formation of the ore-bearing dolomite (Bogacz and Sobczynski, 1975).

The age of the ore-bearing dolomite is still in dispute, depending on the mode of origin adopted. The geologic evidence, however, indicates that the bulk of this dolomite was formed after the deposition of the Muschelkalk but prior to the Jurassic cycle of sedimentation (Petrascheck, 1918). During early Jurassic time, it was exposed to weathering and karstification.

The dolomite exhibits a multitude of cracks of diverse origin. Some of these cracks are related to stress redistribution resulting from the formation of this neosome. Accordingly, it is very susceptible to brittle failure. This had an important bearing upon the development of orebodies.

Mineralogy and Age of Mineralization

The composition of the sulfide ores in the ore-bearing dolomite is simple. The ore minerals are sphalerite, galena, marcasite, and pyrite. The associated minerals are very rare and include chiefly arsenosulfides (e.g., Haranczyk, 1979). The temperature range for sulfide precipitation, established on the basis of gas-fluid inclusions, is 95° to 140°C (Kozlowski et al., 1980).

Some work recently has been done on the isotopic composition of the ores under consideration (Ridge and Smolarska, 1972; Haranczyk, 1974, 1979; Zartman et al., 1980). However, the isotopic data are still open to discussion and differences in interpretation. For example, the uniform composition of lead isotopes (Zartman et al., 1980) has led to a proposal for "a syngenetic or early diagenetic origin by which both zinc and lead were scavenged from chemical sediments, probably the Middle Triassic carbonate rocks themselves, and moved without fractionation by epigenetic processes to sites of deposition as stratabound ores."

Such an interpretation is in disagreement with the results of studies on the isotopic composition of sulfur (Haranczyk, 1979) and, as we shall see later, is entirely inconsistent with essentially all, if not all, available evidence. We note here that many questions concerning the mineralogy and geochemistry of the Upper Silesian ores might have been clarified if the samples taken had been located in relation to specific ore structures. This, however, has seldom, if ever, been done.

We have, as yet, no conclusive information on the absolute age of ores in the host dolomite (Borucki, 1978). Geologic evidence permits only a rough estimation of the age of mineralization. Consequently, considerable diversity of opinion exists on this subject. The ores most certainly are older than the Neogene. The pre-Miocene sink holes contain weathered clastic fragments of galena (Michael, 1913; Bogacz et al., 1970; Panek and Szuwarzynski, 1975) and the Neogene faults are postore dislocations. Sporadic and very insignificant occurrences of sulfides in the Jurassic led to the conclusion that the ores in the dolomite are partly or entirely of post-Jurassic age. While this may be true for a very minor part of the ores, the bulk of these deposits appears to have been emplaced prior to the Middle Jurassic transgression, concurrent with and shortly after the formation of the host dolomite (e.g., Petrascheck, 1918; Duwensee, 1929; Bogacz et al., 1970).

Pertinent to our considerations is the fact that the Paleozoic and Precambrian rocks underlying the Triassic strata contain abundant, although not mineable, occurrences of polymetallic sulfide ores. The principal minerals of these ores include, among others, chalcopyrite, pyrite, marcasite, sphalerite, and arsenopyrite (Gorecka, 1973; Haranczyk, 1979). The ores occur in steep veins of considerable vertical extent, sulfide ores having been reported from drill records to a depth of more than 1,000 m (Banas and Piekarski, 1978). The hydrothermal and epigenetic character of these ores has never been seriously questioned. Significantly, these ores are surrounded by secondary dolomites that, in many respects, are similar to those in the Triassic (Kuzniar, 1929; Haranczyk, 1970; Narkiewicz, 1979).

Many of the ore veins in Paleozoic and Precambrian rocks are related to late Paleozoic igneous activity and predate the Triassic. Some of them, however, are known to pass uninterruptedly from

Paleozoic to Triassic rocks. Such veins show the same mineralogical composition as the principal strata-bound sulfide deposits in the dolomite.

Summing up: sulfide ores in different formations of the Upper Silesian district indicate that there have been at least three different periods of sulfide mineralization separated from one another by large time intervals. The first occurred at the close of the Paleozoic; the second and the chief one between the end of the Muschelkalk and the Middle Jurassic transgression; and the third, and very insignificant, mineralization occurred during Cretaceous and/or early Tertiary time. Such a multiple sulfide mineralization, confined to one specific sector of the earth's crust, cannot be overlooked in considerations concerning the genesis of the sulfide ores in the Triassic strata.

Orebodies

The bulk of the zinc and lead ores is contained in the ore-bearing dolomite. Irregular and very minor occurrences of sulfide ores in limestones and early diagenetic dolomites are limited to solution cavities situated close to the mineralized boundaries of the dolomite. Outside the dolomite and its margins, the Triassic paleosome is barren.

In small amounts, sulfide minerals are disseminated throughout much of the host dolomite. These are regarded as representing early stages in the paragenetic sequence (Haranczyk, 1979; Mochnacka and Sass-Gustkiewicz, 1980). In the following discussion, however, attention is focused on the orebodies proper.

The irregularly shaped, roughly tabular, and/or nestlike orebodies may assume various positions within the dolomite. There seems to be, however, a tendency for some of these orebodies to occur along three levels or ore horizons (Duwensee, 1929; Zwierzycki, 1950; Sobczynski and Szuwarzynski, 1974). Such horizons are not congruent with stratigraphic horizons and are separated from one another by barren rock intervals measuring several meters in thickness. The lowermost of the ore horizons is located near the lower metasomatic boundary of the dolomite. In general, the sulfide ores in the Triassic rocks are strata bound but not stratiform.

The orebodies under consideration consist of cavity-filling ores, metasomatic ores, and ores in granularly disaggregated dolomite. The types of ores are coexistent in space and are mutually interrelated. However, in different orebodies, one or another type may predominate. Similar situations may exist in different parts of a single orebody.

In general, the orebodies reveal the following sequence of events: (1) formation of the host dolomite and emplacement of disseminated sulfides, (2) replacement of the dolomite by sulfides, and (3) dissolution of the dolomite and emplacement of cavity-filling ores. To a considerable extent, these processes were contemporaneous, recurrent, and overlapping, but as a whole, they occurred in this order (similar situations have been reported from other carbonate-hosted ores, e.g., Bain et al., 1901). The disaggregation and the emplacement of ores in disaggregated rocks preceded, accompanied, or followed the formation of metasomatic and cavity-filling ores; all three are integral parts of one formative process.

Ores in Disaggregated Dolomites

Although their volume is insignificant, the sulfide ores associated with granular disaggregation (delithification) of carbonate rocks are important for the insight they provide on the origin of some ore structures in carbonate-hosted deposits. Dolomites and, to a lesser extent, limestones are known to disaggregate into a friable and porous mass of grains through recrystallization and subsequent dissolution along crystal edges. Such disaggregation is promoted by the disrupting action of crystallizing salts and is chiefly effected by slow nonintegrated movement of aqueous solutions of any origin and temperature. The products of disaggregation are commonly referred to as sanded (e.g., Lovering et al., 1949; Heyl et al. 1955). However, pulverulent (Jacucs, 1977) is a more acceptable term because these Upper Silesian carbonate crystals are reduced to fine, silt-sized particles. The final product of disaggregation is a semicoherent or incoherent mass of fine particles. Such a mass ruptures under weak stress and, if water saturated, may yield to plastic flow and behave in a manner similar to that of unconsolidated carbonate sediments. This has an important bearing on the development of specific ore structures (see below). Finally, the disaggregated mass may be recemented and thus again transformed into a hard crystalline carbonate rock that is totally devoid of any primary or early diagenetic structures.

The disaggregated grains commonly are subject to corrasion by mechanical means or by dissolution. They are readily moved and redeposited by underground fluids and laid down in cavities in which they constitute an essential part of the internal sediments. The disaggregated grains, enriched in sulfides, also form clastic dolomite veins that occur sporadically in host dolomite.

The disaggregation is also associated with solution thinning of the rocks involved (due to the settling of particles reduced in size by dissolution or entirely dissolved by that process). This results in the development of voids along the upper boundaries of sanded layers (Figs. 5 and 6) and is followed by stress redistribution that may lead to the formation of cracks and displacements in hard parts of the rocks (Ridge, 1968; Dzulynski and Kubicz, 1971).

The disaggregated parts of the host dolomite occur

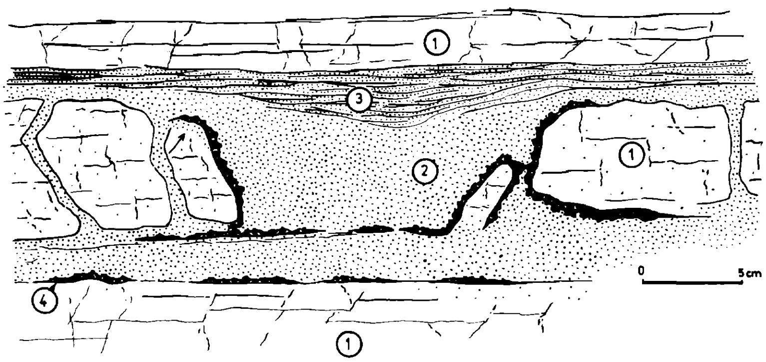

FIG. 5. Galena incrustations (4) lining boundaries of nondisaggregated dolomite (1). Note free crystal faces protruding against disaggregated dolomite (2) and incipient postore disaggregation (arrow); (3) cavity at top of disaggregated layer filled with clastic dolomite and clay. Katy mine, after Bogacz et al., 1973b.

as irregular wall-rock alterations or in the form of roughly tabular bodies. These bodies serve not only as conduits for mineralizing solutions but also as hosts for sulfide ores whose structures are otherwise not encountered among epigenetic ores deposited in preexisting rocks. Such ore structures are found in examples from galena and sphalerite mineralization.

In the disaggregated parts of the host dolomite, galena occurs in the form of euhedral crystals or clusters of crystals. It also lines the boundaries of sanded bodies and the relics of rocks that have not been disaggregated (Fig. 5). Consequently, depending on the outline of such boundaries, the galena linings may be straight or irregular (Bogacz et al., 1975). Such linings or strips show a distinct asymmetry, with free crystal faces on only one side, protruding against the disaggregated mass. The flat bottoms of such crystals conform to the curved contours of the still-lithified parts of the dolomite. In this respect, the strips of galena bear a close similarity to drusy encrustations in empty voids.

In the dolomite, granular disaggregation and emplacement of galena were overlapping and essentially synchronous processes. Disaggregation continued after encrustation of still-lithified relics. Where such progressive disaggregation has led to the disappearance of the relics, the ore encrustations become suspended in a mass of disaggregated particles (Fig. 6). This type of galena ore has been described as vermicular galena (Bogacz et al., 1973b). The strings of vermicular galena marking the original boundaries of relics are sometimes fractured, fragmented, and dislocated by microfaults. These deformations result from unequal settling of disaggregated particles.

These examples of disaggregation and galena ores appear to be superimposed on earlier sphalerite ores and may correspond to the younger, post-Jurassic phase of mineralization. Similar alterations, although obscured by subsequent recementation, are also known to be associated with the main, pre-Middle Jurassic mineralization.

An instructive case of sphalerite mineralization in disaggregated and brecciated dolomite is shown in Figure 7. Prior to disaggregation, the dolomite has already been cut by bedding-controlled sphalerite veins which, in the course of disaggregation, became fragmented and the disjointed fragments displaced. In places, these fragments still are aligned in strings that mark the position of the original veins (Fig. 7). The disaggregation was followed by a new sphalerite mineralization, which resulted in partial replacement of grains and deposition of sphalerite in the grain interstices.

Summarizing these points, we come to the following conclusions:

1. The disaggregated dolomites make possible the unhindered growth of sulfide minerals. Such minerals take the form of euhedral crystals or drusy incrustations that are otherwise observed to develop in unconsolidated, newly laid sediments or on the walls of open cavities.

2. The unequal settling of disaggregated grains may lead to fragmentation of ores penecontempo-

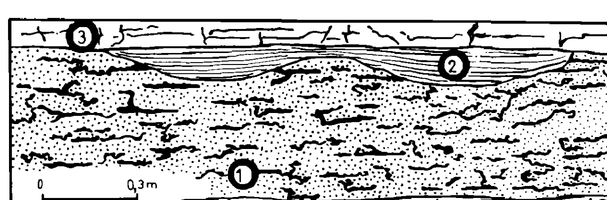

FIG. 6. Galena incrustations suspended in disaggregated dolomite layer (1). Note karst cavity filled with clastic dolomite (2) and developed between disaggregated (1) and undisaggregated (3) dolomite layers. Katy mine, after Bogacz et al., 1973b.

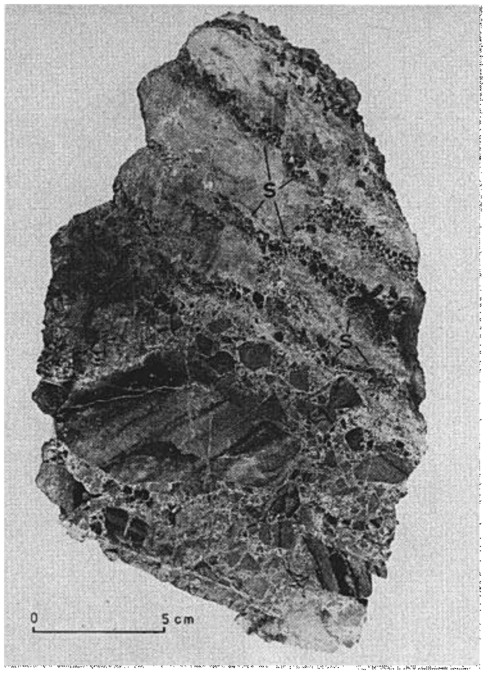

FIG. 7. Disaggregated and brecciated dolomite, partly impregnated with sphalerite. Note fragmented and dislocated sphalerite veins predating disaggregation. Trzebionka mine, after Dzulynski and Sass-Gustkiewicz, 1978.

raneous with, or predating, the disaggregation. Such clastic fragments are similar to those resulting from fragmentation and redeposition under subaqueous conditions.

3. The disaggregated carbonate rocks are sources of fine particles that constitute much of the internal sediments in cavities.

4. The settling of grains brings about the development of voids along the top of layers that are affected by disaggregation.

Metasomatic Ores

Metasomatic sphalerite and galena ores constitute an important part of the Upper Silesian deposits.

Metasomatic sphalerite ores

These ores occur either as irregular patchy and nestlike accumulations or take the form of roughly tabular bodies trending parallel to the bedding (Fig. 8). The ores in question show crosscutting contacts with the enclosing dolomite, and the boundaries of the metasomatic orebodies are very similar to those that delineate the ore-bearing dolomite. Such boundaries are gradational over a distance of millimeters or centimeters.

The transitional zone between the metasomatic ore and the barren host dolomite is characterized by the presence of isolated sphalerite grains. These grains are distributed in such a way that their abundance and size increases toward the sphalerite ore. Where the host dolomite contains vestiges of stratification, the metasomatic ores may show a jagged appearance with narrow sphalerite veins projecting into the host dolomite and tapering toward their distal ends (Figs. 8 and 9). Such veins are chiefly developed along stratification surfaces (Bogacz et al., 1973a).

The tabular sphalerite ores are characterized by ribbon structure (Fig. 10), and the ores showing such a structure are regarded as intermediate in type between the metasomatic ores proper and cavity-filling ores (Walker, 1928). A notable feature of ribbon-type ores is sheet cavities lined with drusy sulfide crystals and bordered, on both sides, by replacement rims. Such rims are comprised of massive aggregates of sphalerite crystals. These aggregates give way to dispersion aureoles of isolated sphalerite crystals, the abundance and size of which decrease with increasing distance from the cavities. The isolated sphalerite crystals, too, are of replacement origin.

The sheet cavities and the associated replacement rims occur in parallel sets, producing repetitive ore sequences or ore rhythms (Bogacz et al., 1973a), which can be seen in vertical cross sections through the ore. The replacement rims growing from adjacent sheet cavities may or may not coalesce. If they do not, then the ore rhythms will also include relics of

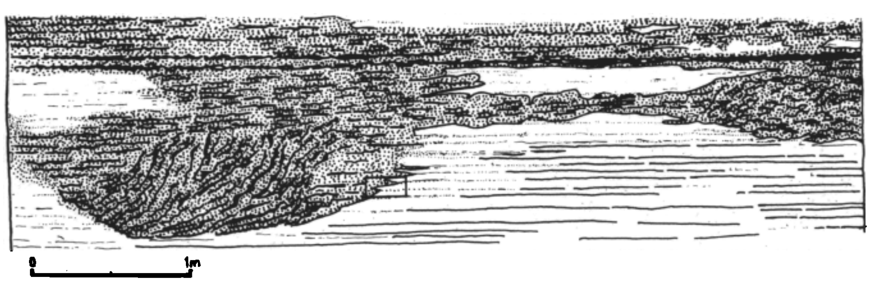

FIG. 8. Metasomatic sphalerite ores (dotted) showing ribbon structures. Narrow voids (black) show parallel bedding and oblique patterns. Rectangular insert shown in Figure 9. Trzebionka mine.

the host dolomite. No difference in age is discernible among the various ore rhythms.

The ribbon-shaped sphalerite ores tend to develop in laminated dolomites. In such a situation, the narrow sheet cavities are solutionally widened sedimentary interfaces or dissolved laminae. These ores show many deviations from their bedding-controlled arrangement. They may bend up or down against the unmineralized parts of the dolomite. The ribbons also may trend obliquely to the bedding planes (Fig. 8), giving rise to specific cross patterns. In some instances, the cross patterns of the ores are inherited from the former cross stratification. In other instances, they only simulate the sedimentary patterns (this appears to be the case with the alleged replaced cross strata depicted in pl. XXXIX, fig. 1, and pl. XXX, figs. 1 and 2, in Bogacz et al., 1973a).

The origin of oblique patterns that visibly deviate from the sedimentary interface patterns is not yet clear and is, presumably, diverse. One explanation is that such patterns have developed from rhythmic diffusion banding reflecting the spread of replacement solutions (Mochnacka and Sass-Gustkiewicz, 1980). Patterns of this type have been produced in experiments on metasomatic alterations in structurally nearly homogeneous bodies (Pospelov, 1973). Another explanation is that the oblique ribbon patterns may reflect the fracture pattern developed in the neosome during its formation and/or subsequent alterations. Whatever their origin, however, the ribbon patterns follow the easiest path of solution movement through the rocks. Such directions may be controlled by vestiges of original sedimentary interfaces, fracturing, diffusion fronts, or some other controlling factors not yet recognized. The coexistence, in one single metasomatic orebody, of inherited and newly produced ore patterns is common. Such a coexistence is regarded as one of the paradoxes displayed by metasomatic processes (Pospelov, 1973). It should be added that where sulfide mineralization is very strong, the ribbon pattern becomes increasingly more complicated, and the associated solution voids become larger and highly irregular.

FIG. 10. Detail of metasomatic sphalerite ore showing ribbon structure. Ore-lined voids chiefly parallel to bedding surfaces. Trzebionka mine.

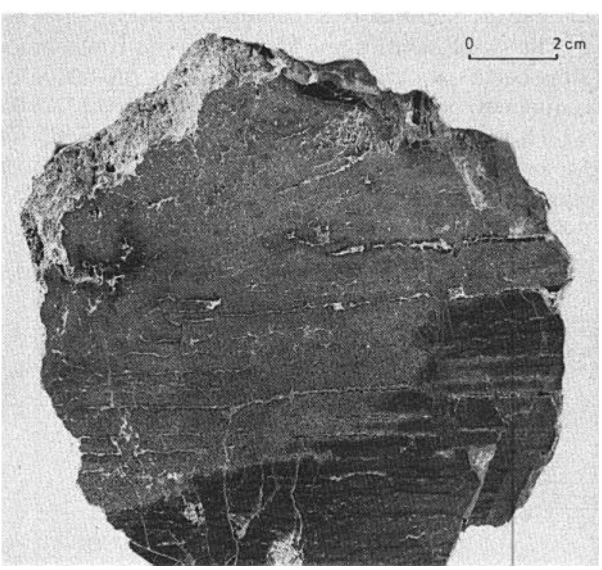

FIG. 9. Contact between metasomatic ore (light) and barren dolomite. Compare with Figure 8. Trzebionka mine.

Metasomatic galena ores

In most instances, these ores are massive and show sharp crosscutting contacts with the enclosing dolomite (Fig. 11). Galena preferentially replaces sphalerite. The host dolomite is rarely subject to galena

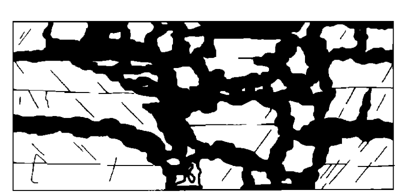

FIG. 11. Replacement structures of galena. 1, ore-bearing dolomite; 2, galena. Olkusz mine, after Sass-Gustkiewicz, 1975a.

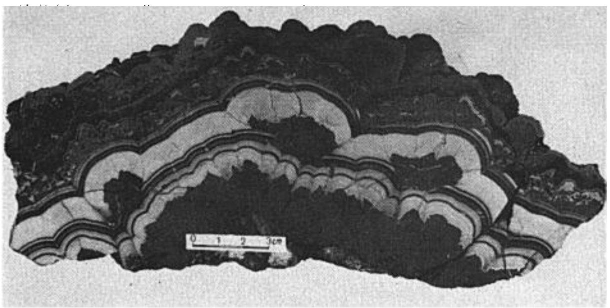

FIG. 12. Detail of ore incrustation lining interfragmental voids of mineralized karst breccia. Light = zinc-blende, black = galena. Olkusz mine, after Sass-Gustkiewicz, 1975a.

replacement; this is observed only where all the available sphalerite had already been replaced. Accordingly, the metasomatic galena bodies postdate the formation of the sphalerite ores (Sass-Gustkiewicz, 1975).

Summarizing, the metasomatic sphalerite and galena ores are distinctly epigenetic with respect to the paleosome. Emphasis is placed on the fact that there is no evidence of lateral secretion from areas of disseminated mineralization to more massive sulfide volumes, nor is there any trace of leaching that such secretion would entail. The only conclusion that can be drawn from the exposures examined is that sulfide replacement proceeded outward from areas of maximum mineralization which, in most instances, are also characterized by an abundance of solution voids.

Cavity-Filling Ores

Much of the sulfide ore in the ore-bearing dolomite is contained in rock openings. Such ores include sulfide precipitates and internal, ore-bearing sediments.

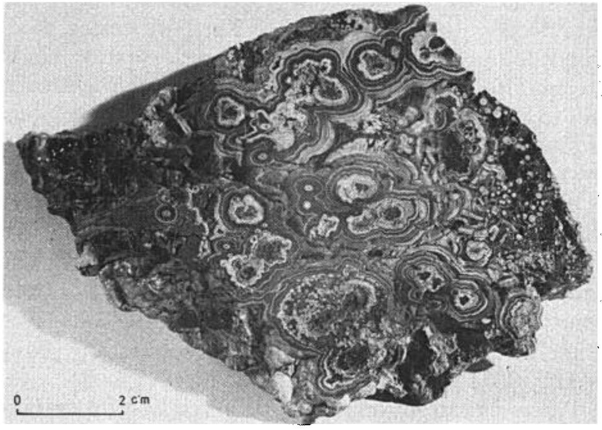

FIG. 13. Collomorphic grapelike and tubular sphalerite precipitates. Boleslaw mine.

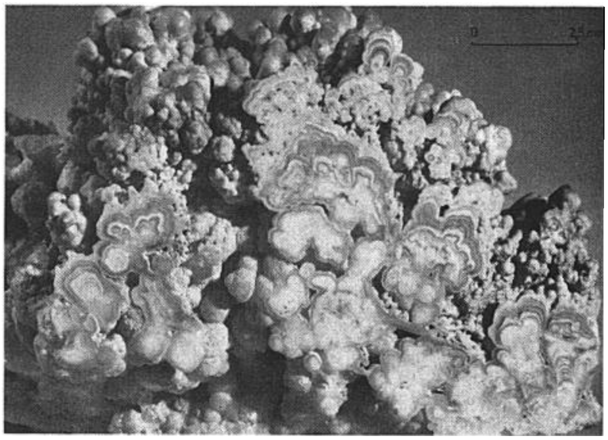

FIG. 14. Grapelike aragonite precipitates from recent hydrothermal caves, Budapest.

Sulfide precipitates

These show morphologies similar to those described from other Mississippi Valley-type deposits. Among the most common are drusy, colloform, mammilary, and grapelike morphologies (Figs. 12 and 13), which are indicative of precipitation under phreatic conditions. The majority of such precipitates crystallized directly on the walls of openings. Some appear to have nucleated in solution and then settled under gravity control on horizontal and subhorizontal surfaces. The sulfide precipitates indicative of vadose conditions such as stalactites, stalagmites, and dripperies of dripstones are rare (Bogacz et al., 1970; Sobczynski and Szuwarzynski, 1975). The position of these vadose forms in the general paragenetic sequence of Upper Silesian ores is not yet clear, and there is a possibility that such forms may represent younger, remobilized sulfides (Bogacz et al., 1975). All the morphologies revealed by the sulfide ores are identical with those of carbonate precipitates that are known from recent hydrothermal and cold meteoric karst caverns (compare Figs. 13 and 14).

Internal clastic sediments

The sediments, filling the rock openings in the ore-bearing dolomite consist of solutional residues, disaggregated dolomite grains, clastic ore fragments, and authigenic sulfide crystals. Such sediments may show sedimentary structures and soft rock deformation (Fig. 15) that are known to occur in external sediments laid down on the sea floor. In some instances, the amount of clastic ore fragments and authigenic sulfide minerals is so high that the internal sediments may be spoken of as sedimentary ores (Fig. 16) (Sass-Gustkiewicz, 1975b). The ore-bearing internal sediments constitute an infinitely small fraction of Upper Silesian deposits and are not more common in other carbonate-hosted ores. The significance of such deposits lies only in the fact that they were often mistaken for external sediments and were used as the chief argument in favor of a syngenetic interpretation for many strata-bound, carbonate-hosted sulfide ores (e.g., Schneider, 1964; Schulz, 1964).

To the category of internal sediments also belong the so-called vitriolic clays, named thus after efflorescing iron sulfates (Kuzniar, 1929; Zwierzycki, 1950). These black residual clays, regarded by some authors as normal sedimentary intercalations in the Triassic sequence (Gürich, 1903; Zawislak, 1965), are infillings of karst openings which developed along the lower boundary of the ore-bearing dolomite (Horzemski, 1962; Bogacz et al., 1970).

The recognition of the true nature of rock openings as ore hosts is of primary importance for a proper interpretation of sulfide deposits. Such recognition, wherever it can be ascertained, should serve as a basis for the following interpretation, which is chiefly centered around sulfide ores in karst cavities because such cavities are the most common ore host in the ore-bearing dolomite.

Karst Cavities as Ore Receptacles

The existence of sulfide ores in solution cavities has long been recognized in Mississippi Valley-type deposits. It is, however, only recently and with the recognition of the karstic nature of such cavities that this problem has received the attention it merits. The interest in mineralized karst structures (Bogacz et al., 1970, 1973b; Sass-Gustkiewicz, 1970, 1974, 1975a, 1975b; Dzulynski, 1976) occurred at the same time for Upper Silesian deposits as for other ore districts (Bernard, 1973; Hoagland et al., 1965; Lagny, 1975; Orgeval, 1976) but has produced a different interpretation. Before discussing ore-bearing karst structures in the dolomite, the following comments are necessary.

FIG. 16. Detail of internal sedimentary ores with clastic ore fragments. Olkusz mine, after Sass-Gustkiewicz, 1975b.

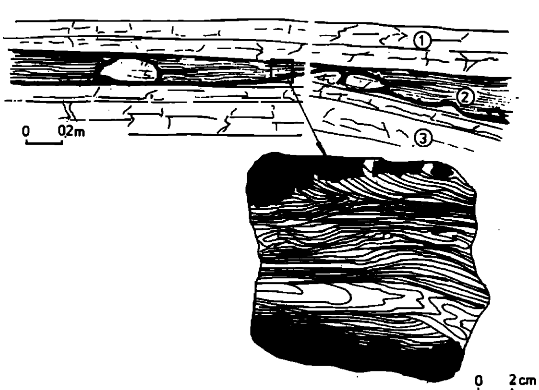

FIG. 15. Bedding-controlled sag fissure showing galena incrustations and filled with internal sediments (clastic dolomite). Katy mine, after Bogacz et al., 1973b.

The term underground karst applies to structures and deposits (speleothems) that are produced by the action of aggressive aqueous solutions of any origin and temperature. Those produced by hot solutions are called hydrothermal or thermomineral karst features (Kunsky, 1957; Maksimovich, 1969). Underground karst structures include dissolution openings, that is, those produced and/or resculptured by dissolution, and rock deformations resulting from stress redistribution, which in turn results from solutional removal of soluble rocks. Among karst deformations there are collapse breccias, minor gravity faults, and fractures ("karst tectonics," Balwierz and Dzulynski, 1976). All these deformations are associated with the appearance of deformation voids. Such voids also intrude the karst openings although their walls may not be enlarged or resculptured by dissolution.

The karst-induced deformation voids show properties that are common to other deformation voids produced outside the realm of karst processes. Pertinent to our considerations is that deformation voids are manifestations of dilatant behavior of rocks subject to brittle deformation. Dilatant zones are regions of low fluid pressure and any available fluid will move toward the zones of maximum dilatancy to fill the voids (Mead, 1925). This has an obvious bearing on the migration of ore fluids and the precipitation of ore minerals which is dependent upon a decrease in pressure. The dilatant zones also provide favorable conditions for the mingling of different fluids—another factor that controls sulfide precipitation (Bain et al., 1901).

Particular attention should be given to solution collapse breccias which are among the most visible manifestations of karst tectonics and are important ore

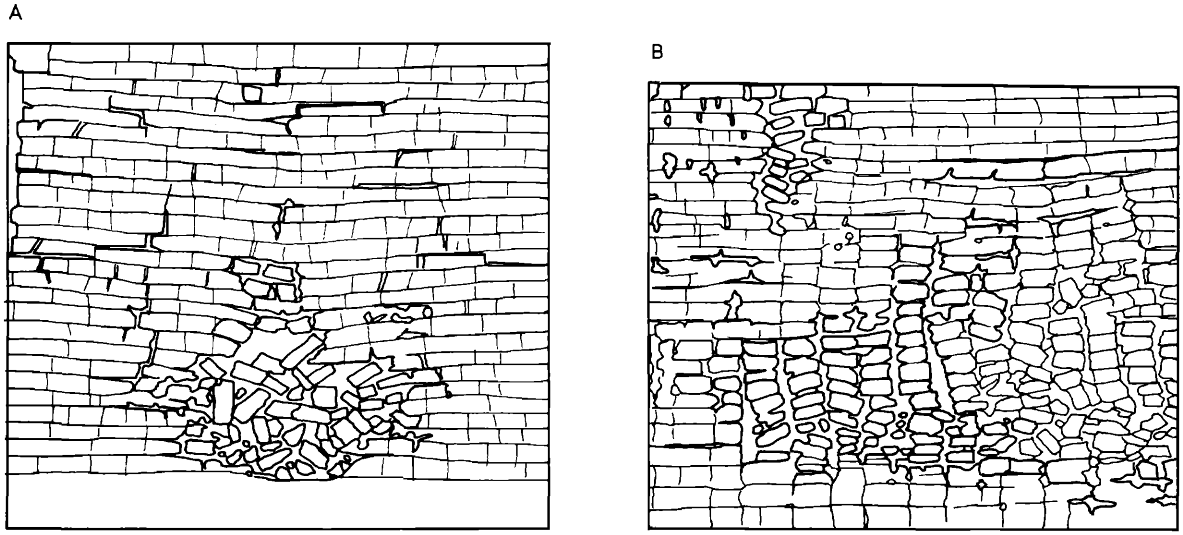

FIG. 17. Experimental solution collapse breccias produced under phreatic condition by flow of water through bedded and fractured model aquifer. A, cave collapse breccia originated from massive and piecemeal roof failure; B, breccia resulted from piecemeal derangement of model aquifer subject to dissolution along great number of transmissive fractures. After Balwierz and Dzulynski, 1976.

collectors in Upper Silesian deposits. The formation mechanism of such breccias is known from observations of recent karst collapse structures (Davies, 1951; White and White, 1969) and from experiments (Fig. 17) (Balwierz and Dzulynski, 1976). Although massive roof failure of large caverns is among the factors promoting brecciation, in layered and fractured rocks extensive breccia bodies may develop in the absence of major caves. Such bodies develop under phreatic and/or vadose conditions through progressive, piecemeal breaking of the rock involved and differential settling of detached blocks. This occurs concurrently with the removal in solution of rock material in the lower portion of the breccia bodies. A prolonged and integrated aggressive flow of solutions through the rock volume in question is the primary requirement for the development of large breccia bodies. With the cessation of solution movement flow transfer and the jamming together of broken rock fragments, the development of breccias is temporarily arrested. It is, however, reactivated with the resumption of the solution flow.

The question that arises is what is the relationship between the hydrothermal ores and the karst structures? Such a relationship may be direct or indirect. Either the hydrothermal ores and the karst structures are products of essentially the same formative processes or the coexistence of hydrothermal ores and karst structures results from a coincidental superposition of unrelated events. It will be shown later that in the ore-bearing dolomite there is a direct genetic relationship between the hydrothermal sulfide ores and the karst.

Mineralized karst breccias

The previously mentioned, direct genetic relationship between hydrothermal sulfide ores and underground karst structures can best be observed in solution collapse breccias. The development of such breccias is promoted by the fractured character of the ore-bearing dolomite and vestiges of stratification that are inherited from the paleosome. The breccias in question occur at different places within the dolomite, but preferentially they tend to develop along the lower metasomatic boundary of this neosome (Fig. 18).

The solution collapse origin of the breccias under consideration was recognized by Hewett (1928) and Kuzniar (1929). However, the karstic nature of these structures was largely ignored and, until the work by Ridge (1968), Sass-Gustkiewicz (1970, 1974), and Bogacz et al. (1970), the breccias were regarded by most investigators as either tectonic or sedimentary features.

The ore-bearing breccias in the dolomite are similar to those described from other Mississippi Valley-type deposits. They consist of angular dolomite fragments with interstices filled with sulfide ores and/or finer rock matrix of the same composition as that of the large blocks (Fig. 19). The breccias fall into two categories: the self-supported breccias in which the larger fragments are in contact with one another and

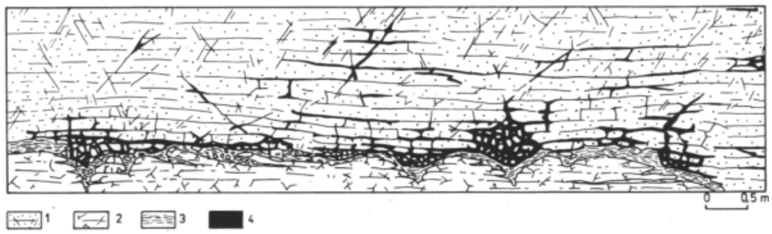

FIG. 18. Incipient brecciation and fracturing above sediment-filled cavity developed along lower metasomatic boundary of ore-bearing dolomite. 1, ore-bearing dolomite; 2, limestone; 3, internal sediments; 4, ore minerals. Pomorzany mine.

the matrix-supported or "pudding breccias" (Norton, 1916) in which the larger fragments are suspended in a mass of finer particles. The first type constitutes the great bulk of the breccias and occurs in central and upper portions of the breccia bodies. The second, much less abundant, tends to concentrate near the base of the breccia bodies. There are all gradations between these two types (Fig. 20).

The karstic origin of the breccias discussed is shown by the following features (Sass-Gustkiewicz, 1974; Dzulynski and Sass-Gustkiewicz, 1978): (1) the breccias occur in the form of highly irregular, tabular, or nestlike bodies that commonly are bedding controlled, and branching, (2) the lowermost boundaries of the breccias are solution surfaces representing the former floors of karst caverns, (3) the solution surfaces are covered with internal, sometimes stratified, cave sediments grading upward into a chaotic mass of angular blocks, (4) the lateral and upper boundaries of the breccias are commonly gradational and the chaotic rubble of blocks is seen to pass, through crackle breccias, into a network of cracks and fractures which, in some transverse sections through the breccia bodies, approximates the pattern of tension domes (Fig. 20) (Sass-Gustkiewicz, 1974).

The breccias under consideration resulted from a succession of brecciation and mineralization stages. For example, in the Olkusz mine, Sass-Gustkiewicz (1975) has recognized five stages of brecciation. Each stage of mineralization is characterized by its own specific assemblage of ore minerals. The sulfides belonging to different stages have the same composition but may differ in texture, mode of occurrence, and quantitative associations. The successively younger sulfide minerals enclose and/or envelop the clastic products of earlier mineralization and brecciation. Furthermore, the breccia bodies, as seen in plan view, show concentric and zonal arrangements of sulfides, with the younger stages covering progressively more extensive areas (Fig. 21). Such an arrangement reflects the lateral growth of the mineralized breccia bodies.

The previously described relationships are best explained in terms of a prolonged and intensive flow of mineralizing and dissolving solutions through the same breccia body. These relationships also reflect the paragenetic order and provide a record of changes in the character of the solutions involved. The alternating and successive stages of brecciation and mineralization followed shortly one upon another, and there is no evidence of an interference of any oxidizing aqueous solutions between the stages of sulfide mineralization. Thus, an important conclusion is that the breccia formation and the emplacement of sulfide ores were parts of the same formative process rather than a repeated coincidental superposition of two different and genetically unrelated events.

There have been overlapping and successive brecciation and mineralization episodes. In general, brecciation occurred before the emplacement of cavity-filling ores. However, for large breccia bodies, these processes were essentially penecontemporaneous. This supports the conclusions reached by several authors with respect to similar ore-bearing breccias in other districts (e.g., Ohle, 1959; Hoagland et al., 1965; Ridge, 1968). This brecciation mechanism may explain the existence of barren parts within a single,

FIG. 19. Detail of mineralized solution collapse breccia. Blocks of dolomite (gray) covered with ore incrustation presented in Figure 12. Olkusz mine.

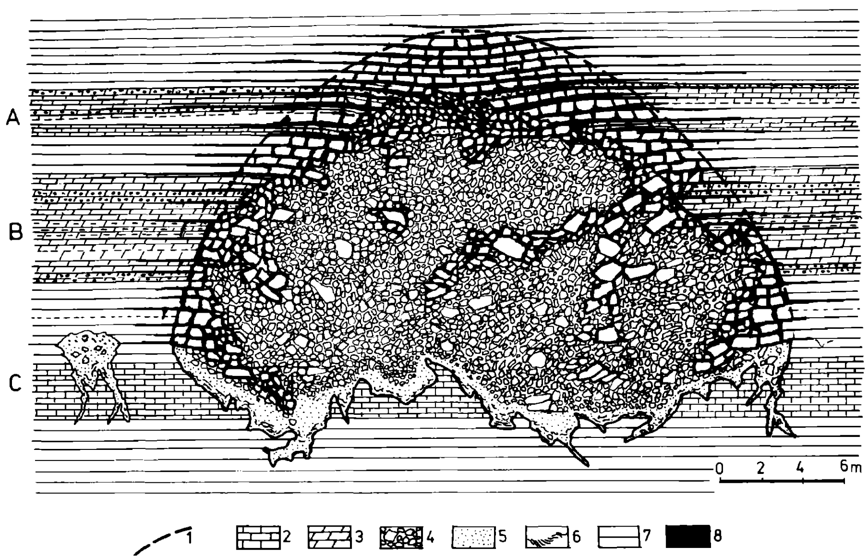

FIG. 20. Mineralized karst breccia reconstructed from partial sections exposed in mine workings (A, B, C); Black area = sulfide mineralization; 1 = limit of pressure dome, 2 = limestones, 3 = dolomites, 4 = breccia, 5 = fine-grained clastic dolomite, 6 = laminated sediments, 7 = reconstructed unexposed parts of the breccia body; modified after Sass-Gustkiewicz, 1974.

mineralized breccia body. However, yet unrecognized factors also may account for the fact that some parts of the breccia bodies were more receptive to ores than the others (Ridge, 1968).

In some instances, dissolving and mineralizing solutions have spread through already-formed breccia structure in such a way that the finer rock matrix was dissolved in preference to larger rock fragments. This

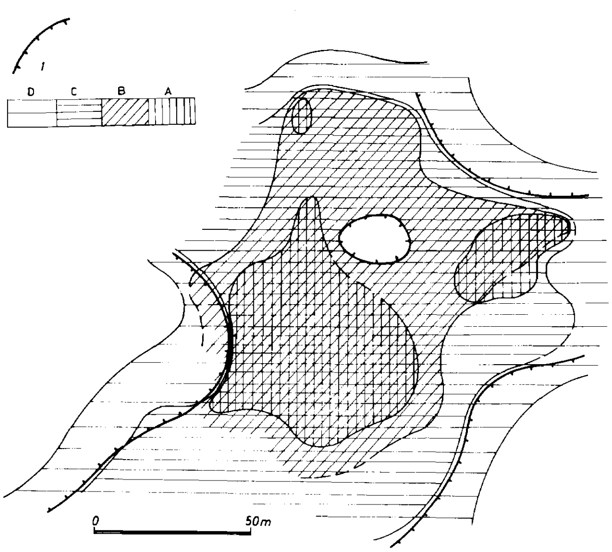

FIG. 21. Horizontal section through breccia body showing successive stages of sulfide mineralization (A, B, C, D) arranged in concentric pattern with younger stages covering progressively more extensive areas. 1, boundary of breccia. Modified after Sass-Gustkiewicz, 1975a.

was due to the relatively high permeability of the matrix and the large total surface area of grains exposed to dissolution. In matrix-supported breccias such selective dissolution resulted in the appearance of condensed breccias (Dzulynski and Sass-Gustkiewicz, 1978), namely, with progressing dissolution, the larger fragments became unsupported and accumulated in a more condensed manner in the newly formed solution voids. Here again, mineralization and dissolution were penecontemporaneous processes. The larger rock fragments became partly, in places entirely, enveloped by sulfide encrustations. In addition, the rock fragments themselves may have been subject to replacement proceeding from the margins inward. This is yet another way in which so-called cockade structure may originate.

The fact that gravity-induced collapse accounts for the majority of large ore-bearing breccias in Upper Silesian deposits does not exclude the action of other agents. For instance, the force of crystallization promotes the extension of fractures (cf. Gignoux and Avnimelech, 1937; Sawkins, 1969) and brings about the appearance of agmatic breccias (Fig. 22) (Dietrich and Mehner, 1961). Also, the disruption of dolomite fragments that are partly or entirely enclosed in a mass of disaggregated dolomitic particles should be noted (Fig. 7). Such fragments are broken into smaller pieces by open fractures, tightly filled with disaggregated grains. The disruption might have been initiated originally by the growth of sulfide crystals, but the further extension and wedging of the fractures presumably was accomplished by the injection of a water-saturated mass of disaggregated grains or by chemical brecciation as proposed by Sawkins (1969). The disjointed fragments then may have been dispersed and broken into still smaller pieces in much the same way. These types of brecciation, although quantitatively unimportant, are commonly associated with the previously discussed mineralized karst breccias. Reference to some other possible factors involved in the brecciation of the host rocks of ores will be given later in this article.

Mineralized fractures consequent upon dissolution

The previously discussed breccias pass laterally and upward into a network of mineralized fractures. The great majority of such fractures and minor gravity faults that disturb the ore-bearing dolomite belong to the category of karst deformations and stand in a direct genetic relationship to the infilling sulfide ores. In general, the fractures and faults under consideration do not extend beyond the limits of the dolomite and terminate abruptly at the lower boundary of this neosome. As noted, most of these discontinuities are related to solutional collapse structures and solutional thinning associated with granular disaggregation. Some appear to be related to metasomatic processes that brought about the deposition of replacement ores. Although such processes follow approximately Lindgren's law of constant volume, the net result is some solutional thinning of the layers involved. As indicated by Ridge (1968, p. B11) "the stresses thus generated in both thinned and unthinned beds by the removal of support, sooner or later cause the rock to fail."

Attention is called to sag fractures that develop along bedding interfaces in strata overlying the solution collapse structures or rocks subject to solution thinning and metasomatic mineralization. The sag fissues filled with sulfide ores give rise to conspicuous stratiform bodies congruent with the bedding of the host dolomite. Such bodies formerly were regarded

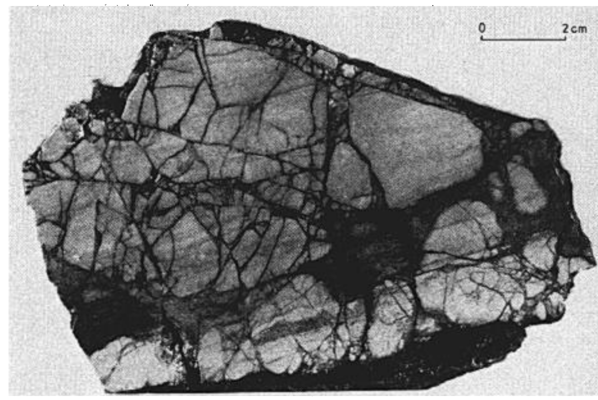

FIG. 23. Typical example of triangular karst cavern filled with internal sediments.

as synsedimentary sulfide layers. More confusing are sag fractures filled with ore-bearing internal sediments. If both the fractures and internal sediments were produced when the strata were horizontal, the resulting tightly filled fractures will bear a striking similarity to ordinary sedimentary intercalations with which they have often been confused (Fig. 15).

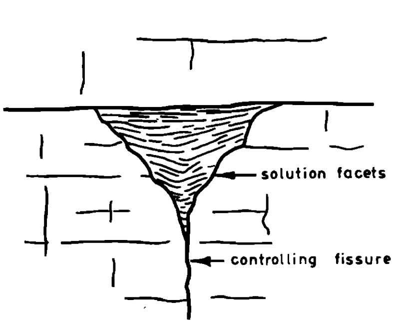

FIG. 22. Agmatic brecciation and fracturing of limestone as presumed effect of changes in fluid pressure. Detail of upper wall of bedding controlled cavity (x). Cavity and fractures filled with galena. Note incomplete replacement of limestone by galena (grayish area). Trzebionka mine.

Mineralized solution cavities

The ore-bearing dolomite is riddled with countless solution conduits that are lined or filled with sulfide ores. Many such conduits also are surrounded by an aureole of sulfides which replace the host dolomite. The mineralized solution caverns generally are small. The character of the dolomite prevents the development of larger caves. With solutional enlargement the caverns are invariably subject to cavern breakdown. Indeed, there are complete gradations from small mineralized solution conduits with intact roofs, through larger caverns with partly collapsed ceilings, to the previously described ore-bearing breccias. This gradation justifies the conclusion that there is a direct genetic relationship between the ores and cavities and that both are products of the same formative processes.

The geometry of the mineralized solution cavities is largely dependent on the nature of the controlling factors. For instance, the preponderant role of bedding surfaces in the transfer of mineralizing solutions accounts for the abundance of low-ceilinged, tabular cavities. Attention, however, should be called to cavities that tend to develop at the top of sanded layers and at the junction of vertical fractures and bedding surfaces (Figs. 6 and 23). Such caverns commonly have plano-convex or triangular cross sections ("triangular caves," Lange, 1963; Goodman, 1964).

Plano-convex and triangular caverns are very rare in Upper Silesian deposits (Michael, 1913; Bogacz et al., 1975) and are not common in other Mississippi

Valley-type deposits. However, they deserve attention because of the impact they have had on the dispute concerning the origin of many carbonate-hosted deposits, i.e., if filled with internal sediments, they bear a superficial and confusing similarity to submarine scour-and-fill structures. In our opinion, all the alleged erosion furrows containing clastic fragments of ores and cited as evidence of a syngenetic origin of alpine and other deposits (Schneider, 1964; Schulz, 1964; Park and Amstutz, 1968) are infillings of plano-convex or triangular caves (Dzulynski and Sass-Gustkiewicz, 1977).

Summarizing the foregoing points, we conclude that the cavity-filling ores stand in direct genetic relationship to their karst receptacles. Both the karst cavities and ores are products of the same formative processes and are essentially contemporaneous and, hence, confirm the idea, fundamental to all classic hydrothermal interpretations of carbonate-hosted sulfide ores, that "solution and deposition go hand in hand and are not only coordinate but usually are contemporaneous processes" (Bain et al., 1901, p. 105).

Ores in Tectonic Voids

Not much space is devoted here to tectonic voids serving as ore receptacles. Most of what has been previously regarded as tectonic breccias and faults (Seidl, 1960; Duwensee, 1929; Galkiewicz, 1967) has turned out to be caused by karst processes ("karst tectonics" in the sense of Balwierz and Dzulynski, 1976). One of the confusing problems afforded by the ores in the ore-bearing dolomite is a lack of visible genetic connection between sulfide mineralization and the majority of faults. Most of the faults that cut the dolomite are postore displacements.

Attention is called, however, to ore veins in vertical fractures that follow the tectonic pattern of the region but are devoid of visible displacement. In the Triassic strata, such ore veins are rare, presumably because of the relatively insignificant thickness of these strata and the low position of ores in the stratigraphic column. The veins under consideration may represent prolongations of some ore veins from the Paleozoic period, which, because of their mineralogical composition, may be regarded as integral parts of stratabound deposits in the Triassic. The ore veins in Paleozoic rocks are controlled by tectonic features and their pattern is among the factors influencing the distribution of ores in the Triassic (see also Przenioslo, 1976).

This question has not been sufficiently studied, but its implications are obvious since it stimulates speculation concerning the possible feeding channels. It should be noted that prominent vertical or subvertical tectonic fractures devoid of visible displacement but commonly showing evidence of multiple reopening and ore infilling are known to occur in other carbonate-hosted deposits (e.g., Raibl in the eastern Alps). Bain et al. (1901, p. 132) have designated these types of fractures as crevices and the ores in them as crevice deposits in contrast to fissures and fissure deposits. The fissures refer to fractures that are accompanied by faulting. Such a differentiation of crevices and crevice deposits is of great theoretical and practical importance. There also is a growing awareness of the implications that such structures may have for the genesis and tectonic setting of Mississippi Valley-type deposits (Dzulynski and Sass-Gustkiewicz, 1980; Sawkins, 1980).

Mineralized crevices reveal magmatic brecciation that may well be interpreted in terms of hydraulic fracturing produced by the forcible injection of ore-bearing solutions into the walls of crevices. Similar effects may also be associated with a sudden drop in pressure and a consequent bursting apart of the rocks into which the solutions have permeated under high pressure (see e.g., Bridgeman, 1952; Kents, 1964; Phillips, 1972; Masson, 1972).

General Direction of Ore-Fluid Transfer

The ore structures previously discussed point to the transfer of mineralizing solutions as the principal factor in shaping the present orebodies. Pertinent to our considerations is the general direction of ore fluid motion.

The general direction of the ore fluid movement does not necessarily point to the source of the base metals but implies the direction from which such metals were delivered to the present orebodies. The general direction can be inferred from the regional geologic structure and by elimination of less probable directions of ore fluid movement such as descending movement and lateral supply from the Triassic aquifer.

Those who believe in an in situ source of metals (e.g., Gruszczyk, 1967; Smolarska, 1968; Zartman et al., 1980; Pawlowska and Wedow, 1980) think that the present epigenetic ores resulted from concentrations of primary sulfides previously disseminated in the paleosome. If this were the case, we would expect to find evidence of solution movement from the paleosome toward the neosome and relics of unquestionable sedimentary ores in the former. This, however, is not the case. As already noted, the contact relationships between the neosome and paleosome bear a record of solution transfer in the opposite direction. Whatever primary sulfide concentrations in the Triassic strata there may be, they do not appear to have made any contribution to the formation of the present orebodies.

Descent of mineralizing solutions from the rocks overlying the Triassic strata (Althans, 1891; Assman,

1948) is untenable in view of the now-available geologic evidence. Most of the ores in the Triassic rocks were deposited before the Middle Jurassic, so that the ore elements could not have come from above. Even supposing a pre-Middle Jurassic age of the ores, so little ore mineralization is present in Jurassic and younger rocks that the younger beds could not have been the source of the ore elements.

Therefore, metalliferous solutions ascending from the rocks underlying the Triassic is the only viable hypothesis, i.e., the ascending solutions on reaching the near-surface regions are hydrothermal solutions inasmuch as their temperature is higher than that of the rocks permeated. Such ascending solutions have been repeatedly postulated by hydrothermalists, and the idea fits well with the geologic evidence. It has also received strong support from the previously mentioned analyses of gas-fluid inclusions (Kozlowski et al., 1980). Thus, in spite of recent criticism and rejection on the part of some geologists, the hydrothermal hypothesis (in the broad sense of hot solutions rising from major depths) is still capable of explaining adequately and simply the facts known about the Upper Silesian ores and many other Mississippi Valley-type deposits. This last parenthetical qualification does not, however, bar a contribution (major or minor) from magmatic sources.

Hydrothermal Karst and Its Role in the Shaping of Upper Silesian Ores

From the foregoing considerations it appears that most of the rock openings serving as ore receptacles in the ore-bearing dolomite are karst openings. In general, the presence of sulfide ores in karst cavities is explained in terms of three, not mutually exclusive possibilities (Walker, 1928): (1) the karst cavities and their ores result from supergene processes involving cold meteoric and/or marine waters, (2) the karst cavities are produced by cold meteoric waters and act as traps for ores introduced by rising hydrothermal solutions, and (3) both the karst cavities and the ores result penecontemporaneously from the action of hot ore-bearing solutions.

The first possibility, which has met with wide acceptance by geologists who oppose the hydrothermal genesis of sulfide ores (Rouvier, 1971; Bernard, 1973; Lagny, 1975), is unlikely with respect to Upper Silesian deposits in view of what has been said in the preceeding sections. The second possibility (e.g., Hill et al., 1971; McCormick et al., 1971) cannot be so summarily discarded. The interaction of cold meteoric waters and hydrothermal solutions is a common occurrence in areas affected by recent hydrothermal karst processes. Accordingly, a situation can be visualized in which hot metalliferous solutions gain access into preexisting cold water karst cavities and deposit sulfide ores in such cavities. However, only a very minor part of Upper Silesian deposits can be accounted for in this way, because outside the dolomite and its contained orebodies there are very few karst cavities that can be regarded as contemporaneous with the emplacement of sulfides. It is thus the third possibility that is most likely and fits best the geologic evidence of Upper Silesian deposits. Consequently, the next logical inference is that the ore-bearing karst structures in the dolomite represent hydrothermal or thermomineral karst features (using the nomenclature already well established in karst sciences).

Inasmuch as the existence of hydrothermal karst phenomena are sometimes ignored or even denied by some ore geologists (Bernard, 1973), it seems advisable to recall here that hydrothermal karst structures are observed to have developed recently (for references see Dzulynski, 1976; Jakucs, 1977). There also is ample evidence that hydrothermal solutions produce extensive breccias and systems of caverns that have been traced to a depth of more than 3,000 m. Admittedly, however, the known examples of hydrothermal karst structures are essentially barren, although insignificant amounts of sulfides, fluorite, and barite have been reported (Ozoray, 1961).

The processes leading to the formation of hydrothermal karst structures are essentially the same as those involved in the formation of cold meteoric karst forms, but hot solutions and high pressures may provide additional factors, including hydraulic fracturing (Phillips, 1972), hydraulic explosions (Muffler et al., 1972), and convective currents (Rudnicki, 1979). It is, however, premature to assess the role such factors may have had in shaping Upper Silesian deposits.

In ore geology, the concept of hydrothermal karst development is not new and has been stated implicitly in many publications where ore-filled cavities are assigned to the same formative processes by which the ores were deposited (e.g., Walker, 1928; Park and Cannon, 1943; Ohle, 1959, 1980; Callahan, 1974; Ridge, 1968). Thus viewed, the terms hydrothermal or thermomineral karst are modern expressions only of old ideas inherent to the hydrothermal interpretation of Mississippi Valley-type deposits. The concept of hydrothermal karst, as applied to this type of deposit (Bogacz et al., 1970), provides a plausible explanation for mineralized karst structures that previously have been variously interpreted by students of sulfide ores in carbonate rocks.

It is realized, however, that sulfide ores, being unstable in near-surface regions, are subject to various alterations. Such alterations include supergene reprecipitation (remobilization) of sulfides and reactivation of karst processes by means of cold meteoric waters. The Upper Silesian ores show no more than minor evidence of such remobilization—for instance, the presence of euhedral galena crystals in the shells of molluscs in Miocene sediments directly overlying the ore-bearing dolomite (Bogacz et al., 1970) and the presence of galena precipitates in pre-Miocene sink holes (Bogacz and Sobezynski, 1972; Panek and Szuwarzynski, 1975). Such secondary sulfides are very insignificant in amount in comparison with the total quantity of nonsecondary sulfide ores in karst cavities.

The question that now arises is the position of hydrothermal karst ores with respect to metasomatic deposits and to those emplaced in disaggregated dolomites. As is well known, the granular disaggregation of carbonate rocks can be developed by other than karst processes. Disaggregation or sanding is, however, among the characteristic wall-rock alterations of recent hydrothermal caves that were produced by hot solutions (Jakucs, 1977). Consequently, the sulfide ores in the disaggregated carbonate rocks may be considered to be hydrothermal karst ores, provided the sulfides are hydrothermal and the disaggregation is visibly related to indisputable hydrothermal karst ores.

Although metasomatic wall-rock alteration is known to be associated with karst structures of hydrothermal and cold meteoric origin, it would be wrong to include the overwhelmingly metasomatic ores of Upper Silesia in the category of hydrothermal karst phenomena. Both metasomatic and hydrothermal karst ores are integral parts of Upper Silesian and other Mississippi Valley-type deposits, although it is hard to draw a sharp boundary between these two types of ores.

Formation Model of Triassic Ores in the Upper Silesian District

The geologic evidence of the Upper Silesian district and the information provided by the ores themselves strongly support a classic, epigenetic hypogene formation model for Upper Silesian deposits. The basic premises are the introduction of base metals from sources located well below the Triassic host rocks and the emplacement of ores in already lithified strata.

Geologic evidence also indicates that hydrothermal metalliferous solutions rose on a broad front along the northeastern margin of the Silesian basin (Bogacz et al., 1970, 1975). As already noted, among the profusion of subvertical ore veins that cut pre-upper Paleozoic rocks of the marginal zone of the Silesian basin are some veins that show the same composition as ores in the Triassic rocks. Such ore veins may represent the ancient feeding channels through which the hydrothermal ore-bearing solutions rose to the pre-Triassic unconformity surface. Such solutions might have gained access into Triassic carbonate rocks through the transgressive overlap on pre-upper Paleozoic and, notably, Devonian carbonate rocks. It is in this sort of situation that direct passage from Paleozoic to Triassic strata is observed. The solutions that thus gained access into the Triassic aquifer spread laterally to the south and southwest (Bogacz et al., 1970, 1975).

To understand the essentially parallel bedding character of Upper Silesian deposits as well as of other Mississippi Valley-type ores, it is important to emphasize that the emplacement of these ores occurred in nearly horizontal strata. In addition, the relief of the region at the time of ore emplacement was very low, as was its elevation above sea level. Hence, the bedding surfaces are the most important factors controlling the transfer of underground solutions and the formation of karst cavities. In seeking an explanation for the localization of ores along specific levels within the carbonate aquifer additional factors should be taken into account. One is the original resistivity to fluid motion and the porosity of the layers involved (Haranczyk, 1963). Clearly, this factor may not be discernible from the present character of the rocks. Among the other factors there are: specific groundwater horizons and consequent mingling of different solutions, the position of the water table (Dzulynski and Sass-Gustkiewicz, 1977, 1980), suitable screens barring upward and downward spread of solutions (e.g., Pellisonier, 1967; Niec, 1980), and saline-fresh water interfaces (possible implications of such a surface have been rised by Rudnicki, 1980).

The dolomitization of limestones, preceding the emplacement of ores, must have been associated with the removal of considerable amounts of calcium carbonate. There is a good possibility that a part of this calcium carbonate was deposited on the surface. Of particular interest, in this respect, are lenses of pure crystalline limestones (the so-called Wozniki limestones) in the nonmarine Liassic sediments of the Upper Silesian district. These fresh water limestones, which contain insignificant amounts of Zn-Pb sulfides, are best explained as carbonates from thermal springs. Such springs might represent the surficial effects of a subterranean circulation that, at an appreciable depth, resulted in the formation of the dolomite and the emplacement of ores (Bogacz et al., 1970). This formation model, apart from some details, represents the classic hydrothermal interpretation of the Upper Silesian ores and many similar deposits elsewhere. It is still far from being complete and there are many unanswered questions.

As already noted, the morphologies of the sulfide precipitates belonging to the main stage of mineralization are mostly indicative of phreatic conditions. The question that arises is whether the local and rare vadose forms belong to the same stage of mineralization or are products of later alterations superimposed upon the deposited ore (e.g., remobilization).

Another fact that may bear on the ore genesis is that in this one ore-bearing area the pre-Triassic basement contains an abundance of igneous rocks. The basement rocks of the remainder of the Silesian basin to the southwest and of the Miechow-Sandomierz basin to the east are composed essentially of nonigneous rocks, and the Triassic rocks in the nonigneous areas contain no orebodies. Of course, all these igneous rocks are older than the Triassic. However, the possibility of later but deeply seated and unknown igneous activity, of which the ores may be the only evidence, must be considered. Also the possibility that Triassic ore-forming fluids were the last phase of Paleozoic igneous activity should be given attention (Prseniolo, 1976). The presence of Triassic-type minerals in veins in the Devonian carbonates lends some support to one or the other of these two concepts.

As was mentioned at the beginning of this paper, such problems as: the source of the ore-forming fluids, the manner in which they carried their metals and sulfur, the reasons for the paragenetic sequences in which the minerals were deposited, the causes of the varied contents of trace elements in the variety of sulfide minerals in general and in the specific stages of mineral paragenesis, the meaning of the uniformity of lead isotope ratios, and the study of oxygen isotopes, particularly in dolomite, are largely beyond the scope of this paper. Nevertheless, the study, and eventually the solution, of these problems remains vital to a complete understanding of the ore-forming mechanisms that resulted in the emplacement of the Upper Silesian ores.

Conclusions

Evidence has been advanced to show that the following processes acted to emplace the Upper Silesian ores: (1) penetration of hot ore-bearing solutions into and through the Triassic aquifer, (2) conversion of a small fraction of the Triassic carbonates to dolomite which became the host rock for disseminated sulfides, (3) large-scale massive replacement of dolomite by sulfides, (4) development of numerous karst openings, during which considerable volumes of collapse breccias were produced and the open space thus created largely filled by ore solution-deposited sulfides, and (5) disaggregation of appreciable volumes of already lithified dolomite into some of the voids in which ore sulfides were deposited. These processes were essentially contemporaneous, recurrent, and overlapping but, in the larger sense, occurred in the order given. All five processes were parts of one major formative event.

Presumptive evidence exists that the ore fluids entered the Triassic aquifer along the northeast margin of the Silesian basin and then spread south and southwest through the more permeable formations. It also appears certain that these solutions were hot and ascending. Further than this we cannot and should not speculate here; specifically, we are not yet prepared to present a firm position as to how and where the ore-forming fluids obtained their heat, metals, and sulfur, but the problem remains one that demands additional study.

June 29, October 30, 1981

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