Zinc-Lead-Copper Resources and General Geology of The Upper Mississippi Valley District

GEOLOGICAL SURVEY BULLETIN 1015-G

Prepared in cooperation with the Wisconsin Geological and Natural History Survey, the Illinois State Geological Survey, and the Iowa Geological Survey

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By ALLEN V. HEYL, ERWIN J. LYONS, ALLEN F. AGNEW, *and* CHARLES H. BEHRE, Jr

Information on Illinois furnished by H. B. WILLMAN *and* R. R. REYNOLDS

A CONTRIBUTION TO ECONOMIC GEOLOGY

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ZINC-LEAD-COPPER RESOURCES AND GENERAL GEOLOGY OF THE UPPER MISSISSIPPI VALLEY DISTRICT

By Allen V. Heyl, Erwin J. Lyons, Allen F. Agnew, and Charles H. Behre, Jr.

ABSTRACT

The Upper Mississippi Valley zinc-lead district in southwestern Wisconsin, northwestern Illinois, and northeastern Iowa contains thousands of small lead mines, about 400 zinc mines, and a few small copper mines. The ores are chiefly in the Galena dolomite and in the limestones and dolomites of the Decorah formation and upper part of the Platteville formation, all of Middle Ordovician age. Locally, minable deposits have been found in the Prairie du Chien group of Early Ordovician age, and small deposits of lead and iron sulfides have been found in the formations of Cambrian and Silurian age. The area has been gently flexed, and folds of three orders of magnitude are recognized.

Zinc ore deposits are commonly linear or elliptical in plan. The ore is in the form of veins, replacements, and impregnations, and it occurs along shears, small reverse faults, and bedding-plane faults related to the intermediate and small folds. Gash-vein deposits, most of which are restricted to the Galena dolomite, occur as replacement veins along vertical joints. The main primary minerals are quartz, dolomite, pyrite, marcasite, sphalerite, galena, chalcopyrite, barite, and calcite.

The east, south, and west boundaries of mineralization are hidden either by overlying Silurian rocks or Pleistocene glacial deposits. The north boundary of the area of known deposits lies at the eroded edge of the southward-dipping Ordovician strata that were most favorable for ore deposition, but its original position may have been farther north. In a few places, where the ore deposits are small, lean, and widely spaced, the actual limit of the district can probably be defined. Calcite and small quantities of galena, marcasite, and pyrite are the main minerals of these marginal deposits. In many parts of the district, mines are closely spaced, but between these parts only a few deposits are known. Lack of ore deposition, local erosion of the favorable beds, patches of overlying rocks that hide the favorable beds, and lack of prospecting determine the size and location of the mining centers.

INTRODUCTION

This report discusses the general geology of the Upper Mississippi Valley zinc-lead district, the distribution of ore deposits, and some relations of the ore deposits to the major geologic features. The district includes an area of about 3,000 square miles in southwestern Wisconsin, northwestern Illinois, and a narrow fringe of northeastern Iowa (pl. 25) drained by the Mississippi River and its tributaries. The central part is a rolling plain dissected by the major streams to a depth of about 300 feet; the marginal areas are relatively hilly.

Within the district are thousands of small lead mines, about 400 zinc mines, and a few small copper mines. For convenience in numbering, these mines were arbitrarily grouped. The distribution of these groups and of the mining areas is shown in plate 25. In another report [1] the mines are listed and individually located. The deposits in the Prairie du Chien group are differentiated from those in the Platteville, Decorah and Galena formations and those in the Lower Silurian dolomite in plate 25. The boundary of the Silurian escarpment is shown, but because of the numerous mine workings the boundary between the Middle and Lower Ordovician beds could not be represented. Grant and Burchard (1907) have delineated this contact in the central part of the district at the same scale as plate 25. Many of the reports in the selected bibliography give further details on the geology of the district and on individual mines.

In 1942 the U. S. Geological Survey began a detailed restudy of the geology and ore deposits of this district. Since 1945 the work in Wisconsin has been done in cooperation with the Wisconsin Geological and Natural History Survey. Although the geologic studies are being continued (1955), this report and related reports [2] that are now in preparation are based on work that was completed in July 1950. In 1943 the Illinois State Geological Survey started a geologic study of the Illinois part of the district, and this investigation is also being continued (1954).

The data used in this report, including the distribution of ore deposits shown in plate 25, were obtained largely by field mapping, by compilations from aerial photographs, and, where other information was lacking, from maps and geologic reports. The mapping in Wisconsin and Iowa was done by the writers, assisted by M. L. Heyl, A. E. Flint, J. J. Theiler, C. W. Tandy, J. P. Moor, H. G. Hershey, and Carl Spradling. The lead mine areas and fold axes in Illinois were mapped by H. B. Willman and R. R. Reynolds of the Illinois State Geological Survey. Information concerning the location and geologic occurrence of zinc and lead deposits was compiled at a scale of 1 mile per inch by the writers, and prints were made available in open

[1] Heyl, A. V., Agnew, A. F., Lyons, E. J., and Behre, C. H., Jr., Geology of the zinc and lead deposits of the Upper Mississippi Valley district. In preparation as a Geological Survey report.

[2] Heyl, A. V., and others op. cit.

Agnew, A. F., Heyl, A. V., Behre, C. H., Jr., and Lyons, E. J., Stratigraphy of the Upper Mississippi Valley district. In preparation as a Geological Survey report.

file in 1951. In order to present and emphasize the major features of the district, plate 25 was compiled; this was done mainly by Reta E. Linebaugh.

Many individuals, mining companies, and the State geological surveys of Wisconsin, Illinois, and Iowa gave valuable information. Because contributors are so numerous, it is impossible to acknowledge each one; however, we wish to thank them as a group for their help.

GEOLOGY

The Upper Mississippi Valley mining district is about 100 miles south of the main area of outcrop of rocks of the pre-Cambrian shield in Wisconsin (Bean, 1944). The lead, zinc, and copper ore deposits are in the northern fringe of gently flexed Paleozoic sedimentary rocks that overlap the shield area. Most of the known lead, zinc, and copper deposits are restricted to the dolomites, limestones, and shales of Middle Ordovician age (fig. 33), but deposits are found in all other Paleozoic rocks exposed in the district.

Most of the district lies within the Driftless Area (Grant and Burchard, 1907, p. 2–3; Shaw and Trowbridge, 1916, p. 1–2, 7), but glaciers of pre-Wisconsin age have crossed the eastern and western boundaries and part of the southern boundary (pl. 25). The nearest glacial deposits of Wisconsin age are found in the immediate vicinity of Madison, Wis. The glacial deposits of pre-Wisconsin age thin gradually toward the boundary of the Driftless Area and are represented by only small remnants of drift. Pleistocene bench and terrace gravels, sands, and clays are common in the valleys of the principal rivers that flow across the Driftless Area from the surrounding country. Deposits of interglacial loess of pre-Wisconsin age that are as much as 50 feet thick cap the bluffs along both sides of the Mississippi River and extend several miles away from the river.

STRATIGRAPHY

The rocks exposed in the district are Cambrian, Ordovician, and Silurian in age (fig. 33). Rocks of the pre-Cambrian basement have been found only in wells at depths of 1,500 to 2,000 feet. The oldest rocks exposed—the Franconia and Trempealeau formations of Late Cambrian age—crop out only along the Wisconsin River and near Madison, Wis. The Prairie du Chien group of Early Ordovician age is exposed in some of the deep valleys and along the north and east margins of the district (Grant and Burchard, 1907). Most of the outcrops in the district are Galena dolomite, but exposures of the Platteville formation and St. Peter sandstone are common, particularly in the valleys. Maquoketa shale of Late Ordovician age (Grant and Burchard, 1907; Shaw and Trowbridge, 1916) covers

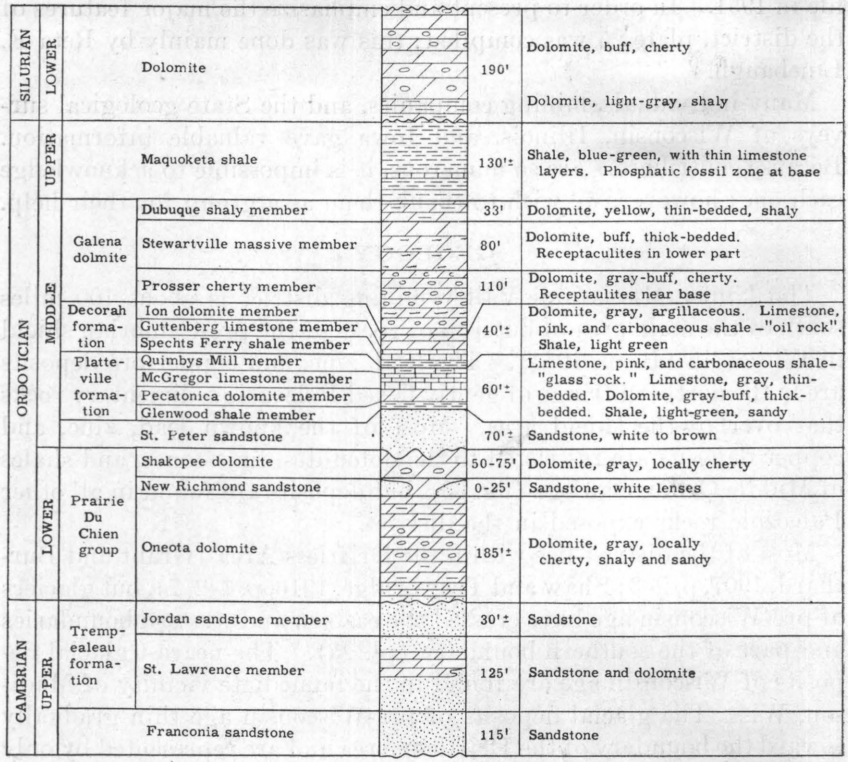

FIGURE 33.—Generalized stratigraphic section of the Upper Mississippi Valley zinc-lead district.

some of the high hills and underlies the long slopes that rise to higher hills capped with Lower Silurian dolomite. Most outcrops of the youngest strata—dolomite of Early Silurian age—occur along a partly incised escarpment along the southern and western boundaries of the district; these strata also form a few isolated erosional outliers within the district (pl. 25).

Some of the details of the stratigraphy are illustrated by the generalized stratigraphic section (fig. 33). The rocks of the Prairie du Chien group, the Platteville, Decorah, and Galena formations, and Lower Silurian rocks in the district are composed mostly of dolomite, although they include some limestone, shale, and a small amount of sandstone. Between these carbonate rocks are the predominately clastic St. Peter sandstone and Maquoketa shale. The Franconia, Trempealeau, and St. Peter formations are permeable sandstones that are widespread aquifers.

Most of the zinc deposits are in the lower part of the Galena dolomite, the Decorah formation, and the upper two-thirds of the Platteville formation. The principal lead deposits are restricted to Galena dolomite. Small lead, zinc, and copper deposits are found locally in the northern part of the district in the Prairie du Chien group (Heyl, Lyons, and Agnew, 1951, p. 1–12) and the Trempealeau and Franconia formations. In places, the St. Peter sandstone is pyritized; it is most heavily pyritized where it directly underlies zinc deposits.

STRUCTURE

The mining district lies about 100 miles south of the north edge of the Paleozoic sedimentary rocks that overlap the North American pre-Cambrian shield. The Wisconsin arch (pl. 25), a broad northward-trending anticlinal structure, lies on the east side of the mining district. The Illinois basin lies south of the district, and the Forest City basin lies to the west and southwest in Iowa.

The regional strike of the sedimentary formations is N. 85° W. throughout most of the district, but in the western part the strike swings to N. 45° W. The regional dip is about 17 feet to the mile towards the south-southwest. The rocks of the district have been folded into low, broad undulations that differ greatly in magnitude. The limbs of the folds rarely have dips greater than 15 degrees.

The largest folds range from 20 to 30 miles in length, 3 to 6 miles in width, and 100 to 200 feet in amplitude. The axes of the largest folds that have been mapped are shown in plate 25. These folds trend northeastward, eastward, and northwestward, the trends changing sharply from place to place across the district. Many of these folds are traceable as continuous structures for miles. The anticlines are commonly asymmetrical with the steeper limbs on the north. The folds of intermediate magnitude and those of small magnitude trend either eastward to northeastward or northwestward (pl. 26). These folds occur throughout the area and form an unusual rhombic pattern.

Most of the faults in the district are small reverse, bedding-plane, normal, and shear faults, having displacements of 1 foot to 10 feet. Some thrust faults on the steep north limbs of the large anticlines have displacements of 25 to 50 feet. A few shear faults that have displacements of 25 to possibly 1,000 feet have been located.

All the rock formations in the district contain vertical and inclined joints (Heyl, Lyons, and Theiler, 1952), the former being particularly well developed in the Galena dolomite. Single vertical joints are traceable for more than 1 mile and cut as much as 300 feet of beds. Most of the vertical joints fall into three general strike groups—N. 77° W., N. 12° W., and N. 25° E. The joints of the N. 77° W. group are generally more open than those of the other two groups. The inclined joints are commonly tight and in many places are in sets of closely spaced parallel fractures. Many of them are probably incipient reverse faults.

Most of the geologic structures observed in the district were formed during a period of diastrophism that was preceded by minor regional deformation and followed by some uplift and tilting.

ORE DEPOSITS

HISTORY AND PRODUCTION

The lead deposits were discovered by the French in the latter part of the 17th century. The French taught the Indians primitive mining methods, and for 150 years small-scale mining operations were carried on by the Indians and French (Thwaites, 1895, p. 271–292). The first American settlers arrived in 1821. The district quickly boomed, and by 1840 most of the mineralized areas had been discovered. During the 1840's this was the principal lead-producing district in the United States, but production afterwards declined, and now lead is recovered only as a byproduct of zinc mining. Most of the lead ore was produced from the gash-vein deposits, and many of the lead mining areas shown in plate 25 are groups of such deposits.

Zinc production began in 1860 and reached a peak during World War I. A revival in zinc mining by small companies occurred in about 1938 and continued until shortly after World War II. Since then a few large companies have developed ample reserves and are mining on a major scale. By 1952 the district had again taken one of the leading positions in production. The known reserves of ore have been increased from about 1,000,000 short tons in 1942 to nearly 10,000,000 short tons in 1950.

Zinc production from 1860 to 1951 was about 1,200,000 short tons of metal from about 43,000,000 tons of ore. The value of the metal on the basis of 15 cents per pound metallic zinc is $363,000,000. Nearly 85 percent of the zinc was mined in Wisconsin, 15 percent in Illinois, and a small amount in Iowa. In recent years, however, Illinois and Wisconsin have produced nearly equal quantities of zinc.

The total recorded lead production from 1795 to 1951 was 821,000 short tons of metallic lead valued at $248,000,000 on the basis of 15 cents per pound. Slightly more than 50 percent of the lead was mined in Wisconsin and the rest was produced in northern Illinois and Iowa.

Copper was mined in Wisconsin in the 19th century, and as much as 10,000 short tons of 15- to 20-percent copper ore may have been produced. Barite was mined in Wisconsin between 1919 and 1930, but data on the total quantity produced and its value are not available.

The lead and the copper ores and some of the zinc ores were smelted locally in the 19th century. In recent years, however, most of the zinc and lead ores have been concentrated in gravity and flotation mills at the mines or custom mills in the district, and the concentrates shipped to central and southern Illinois and to Missouri for smelting.

Tonnage and value of zinc and lead metal produced in Wisconsin and northern Illinois from 1925–50, and in Iowa from 1917–53

[Data from U. S. Bureau of Mines]

Years	Zinc		Lead	
	Short tons	Value	Short tons	Value
Wisconsin				
1925–29	114, 914	$15, 787, 634	8, 726	$1, 225, 156
1930–34	47, 775	3, 922, 158	4, 173	336, 064
1935–39	31, 964	3, 312, 788	2, 989	300, 618
1940–44	51, 370	10, 068, 720	4, 780	692, 400
1945–49	55, 220	13, 425, 566	6, 240	1, 566, 702
1950	5, 722	1, 625, 098	532	143, 640
Total	306, 965	48, 141, 914	27, 438	4, 264, 580
Illinois				
1925–29	5, 503	817, 666	813	136, 852
1930–34	9	844	0	0
1935–39	0	0	0	0
1940–44	6, 269	1, 209, 492	438	59, 782
1945–49	31, 308	7, 762, 914	3, 556	1, 043, 346
1950	21, 071	5, 984, 164	1, 269	342, 630
Total	64, 160	15, 775, 080	6, 094	1, 582, 610
Iowa				
1917	18	3, 672	34	5, 848
1918–52	0	0	0	0
1953	0	0	1	266
Total	18	3, 672	35	6, 114

ORE MINERALS AND TYPES OF DEPOSITS

The main primary minerals have been deposited in the following paragenetic sequence: quartz (chert and other forms of cryptocrystalline silica), dolomite, pyrite, marcasite, sphalerite, galena, barite, chalcopyrite, and calcite. The principal secondary minerals are smithsonite, limonite, and cerussite.

The ore bodies can be classified into three types: "pitch-and-flat"[3] deposits (fig. 34), "gash-vein"[4] deposits (fig. 34), and placer and residual deposits.

Zinc ores are mined principally from the pitch-and-flat deposits, and lead ores from the gash-vein and placer types of deposits. Copper minerals and barite are found locally in the first two types.

[3] A pitch is a mineralized reverse fault; a flat is a mineralized bedding-plane fault or a vein in an opened bedding plane.

[4] The term "gash-vein" for a joint-controlled lead deposit was proposed by Whitney (1854, p. 48), Hall and Whitney (1858, p. 437–438), and later used by Winslow (1894, p. 140) and Chamberlin (1882, p. 453–454). Whitney (Hall and Whitney, 1858) states that "the term 'crevice,' as generally applied, in the lead-region * * * designates the vein-like fissures, or gash-veins as they may be termed, in which the ore is found * * *." Winslow notes, "To these openings [vertical ore-bearing joints] the name of 'gash-vein' so generally given to the deposits of this region [Wisconsin] more particularly applies."

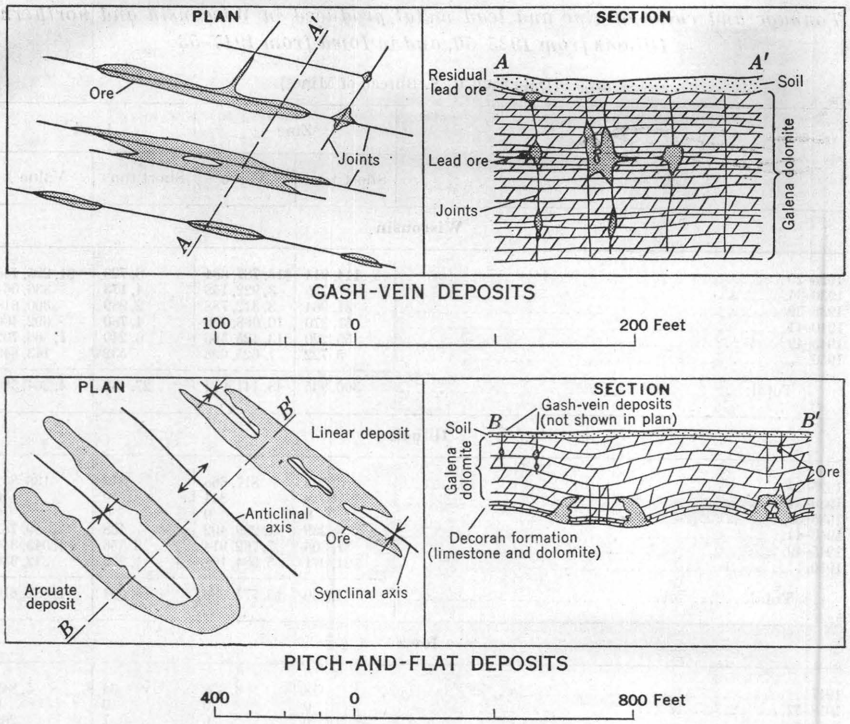

FIGURE 34.—Diagrammatic plans and sections illustrating typical patterns of gash-vein lead deposits, underlying pitch-and-flat zinc deposits of the arcuate and linear types, and their stratigraphic positions relative to one another.

Most zinc ore bodies range in size between 100,000 and 500,000 short tons of ore, but a few contain more than 2,000,000 tons. Most of the ores mined in recent years range from 4 to 8 percent zinc and from 0.5 to 1 percent lead.

Recently mined gash-vein deposits have produced less than 100 short tons of 80 percent lead concentrate. Formerly, individual gash-vein deposits produced as much as 5,000 tons of 80 percent lead concentrate. Present-day operators consider that the gash-vein lead deposits are not generally amenable to large-scale production methods, although one deposit, the Rodham (pl. 25), was mined in this way.

Production from individual placer and residual deposits has never been large, and mining has always been on a very small scale.

PITCH-AND-FLAT DEPOSITS

Most of the ore that has been mined since 1900 has been from the pitch-and-flat deposits. Sphalerite is the main ore mineral, but locally galena or pyrite and marcasite or barite has been produced from these deposits. In 1943 chalcopyrite was discovered in possible commercial quantities in drill-hole samples from a pitch-and-flat zinc ore body on the McIlhon property in the copper area east of Mineral Point, Wis. (pl. 25).

Folds of small and intermediate size that trend northwestward and east to northeastward controlled the localization of the pitch-and-flat zinc ore bodies (pl. 26). These folds occur throughout the district (Agnew, Heyl, Behre, and Lyons, 1948), and the trends of their axes form a marked rhomboidal pattern. Both arcuate and linear ore bodies occur along the flanks and axial areas of some of the synclines and anticlines of intermediate size (fig. 34 and pl. 26). The linear ore bodies occur at fairly regular intervals and are elongate in directions parallel to the folds. The arcuate ore bodies are in echelon, and they are most numerous along the northeastward-trending folds of intermediate size. Localization of some ore bodies also has been controlled by folds of small size not associated with the intermediate folds.

Pitch-and-flat ore bodies occur along reverse and bedding-plane faults (pitches and flats, respectively) that have small displacements. Bedding-plane faults occur in the incompetent uppermost Platteville and lower Decorah strata. The reverse faults curve upward at low angles from these bedding-plane faults, steepening to about 45 degrees in the overlying beds (fig. 34). The faults occur commonly in parallel groups that lie on the flanks of folds, the reverse faults usually dipping toward the anticlinal area. Many such fault zones follow the outlines of a fold to form an arcuate or linear pattern (fig. 34) and are more commonly associated with synclines than with anticlines (Agnew and Heyl, 1944). Most of the fault zones in the southern part of the district are larger and have greater displacements than those in the northern part.

The ore occurs in the fault zones as vein fillings and replacement veins along fractures and bedding planes; as cavity fillings in solution and tectonic breccias; and as disseminations formed by replacement and impregnation of favorable beds by poikilitic crystals of sulfides, particularly the shaly residuum of altered limestone strata. The ore solutions have altered the host limestones and, to a lesser extent, the dolomites within and in the immediate vicinity of the deposits. This has been done by three main processes: silicification; dolomitization; and solution of the carbonate rocks, particularly the limestones. Solution of the carbonate rocks has considerably thinned some of the favorable beds in many ore bodies. The thinning has caused the fractures in the rock to open, thus providing spaces for deposition of the ore. In places the rock has been so altered by solution that the overlying rock has collapsed to form tumbled breccia. Dolomitic rocks within and near the ore bodies have locally been "sanded" (Lovering, and others, 1949, p. 27), that is, changed to a friable or incoherent mass of dolomite crystals by the ore-bearing solutions. The cementing bond between the large dolomite crystals was weakened by intergranular solution, and many of the fine dolomite grains were dissolved by the ore-bearing solutions.

GASH-VEIN DEPOSITS

Most of the ore produced before 1900 was mined from the joint-controlled gash-vein deposits (fig. 34). Lead ores are the main product of these deposits, but in a few places zinc or copper ores have been mined. The joint-controlled ore bodies are confined to the Galena dolomite except for a few deposits in the Lower Silurian dolomite and the Prairie du Chien group. Ore is deposited as narrow gash veins that fill vertical joints and expand into podlike masses in favorable beds along these joints. In the podlike masses, locally known as openings, the ore has replaced the rock, and it fills previously formed solution cavities in sanded dolomite along the joints. The podlike masses may lie one above the other in different favorable beds along the same joint. Single mineralized joints are traceable for more than 1 mile; they have nearly constant strikes, N. 70° W. being most common (Heyl, Lyons, and Theiler, 1952).

The gash-vein deposits contain the same mineral constituents as the pitch-and-flat deposits, but galena rather than sphalerite is the most abundant ore mineral. Before oxidation and leaching, pyrite, marcasite, and perhaps calcite were also abundant. Sphalerite, or its oxidation product, smithsonite, is locally common. In a few places, particularly east of Mineral Point, Wis., chalcopyrite is abundant and galena is absent. Barite, vein dolomite, and jasperoid are rare. Galena is the only abundant sulfide remaining in most gash-vein deposits in the oxidized zone above the water table. It is accompanied by limonite and cerussite, and less commonly by smithsonite, calcite, chalcocite, azurite, and malachite. Sanded dolomite is abundant in many of the gash-vein deposits.

RELATIONS BETWEEN ORE DEPOSITION AND MAJOR GEOLOGIC FEATURES

Plate 25 shows the location of the zinc, lead, and copper mines and most of the old lead and copper mining areas; it does not include the outermost fringe deposits of the district. Most of the fringe mineral deposits and ore bodies are composed of lead, copper, and iron (hematite and limonite) ore bodies that were worked many years ago. Although nearly all of these deposits are small, at least one lead mine and one hematite mine produced considerable quantities of ore. Zinc ore has been found in the fringe areas but not in large enough quantities to be mined commercially. The size of the mineralized district, which includes all of these outlying districts, is about 3,300 square miles; however, the part that was being mined in 1950 comprises a central area of only about 650 square miles.

DISTRIBUTION OF ORE DEPOSITS AT THE DISTRICT BOUNDARIES

The main part of the district is bounded on the south and southwest by a deeply incised cuesta (pl. 25) (Grant and Burchard, 1907; Shaw and Trowbridge, 1916) of Maquoketa shale and Silurian dolomite. These rocks cap the Galena, Decorah, and Platteville strata, which are the most favorable host rocks for lead and zinc deposits. Several mineralized areas have been exposed by erosion in the deep valleys south and west of the northward-facing cuesta, examples being the lead deposits in the Apple River valley near Elizabeth, Apple River, and Warren, Ill.; and other deposits (pl. 25) in Illinois and Iowa. The limit of mineralization is probably many miles south and southwest of the edge of the covered area, as is indicated by the following:

1. The outlying mineralized areas in erosional windows.
2. The abundance of mineralized areas along the main cuesta face, such as at Scales Mound and Galena, Ill., and from Dubuque to Rickardsville, Iowa.
3. Small deposits of lead in the Silurian rocks in Iowa near Lytle Creek, Jackson County, and south of Dyersville, Dubuque County, and still farther south near Clinton, Clinton County (Bain, 1906, p. 66), and Anamosa, Jones County (Calvin, 1895, p. 110).
4. Known deposits that extend beneath the cap rocks—for example, the ore body of the Bautsch mine of the Bautsch mine group (pl. 25) south of Galena, Ill., and the ore bodies of the (New) Blackstone and Calumet mines south of Shullsburg, Wis., which lie beneath a thick cover of Maquoketa shale from which most of the beds of Silurian dolomite have been eroded.

The known southeastern boundary, in Illinois, is determined by large areas of Maquoketa shale and Silurian dolomite that conceal the favorable host rocks, and the overlapping glacial drift that marks the east edge of the Driftless Area. The limit of mineralization may extend many miles to the southeast beyond the present boundary of the main part of the district at Apple River and Warren, Ill.; if so, the deposits probably decrease in size and abundance in that direction. The possibility that undiscovered deposits lie beyond the present defined boundaries of the district is suggested by a number of nearly forgotten deposits near Morseville, Stockton, Elroy, Freeport, and Oneco (pl. 25), and farther south at Mount Carroll, Ill. These deposits undoubtedly were discovered only because erosion had locally exposed the favorable host rocks. Other deposits probably exist in places where the host rocks have not been exposed by erosion.

In Wisconsin the known district boundary on the east is determined by the overlap of the glacial drift marking the east edge of the Driftless Area, and the erosion of the ore-bearing Galena, Platteville, and Decorah formations. Erosion of the ore-bearing formations has been progressively more complete as the formations rise toward the Wisconsin arch, until only a few erosional outliers remain in the least dissected interstream areas. The number and size of the ore deposits also decrease toward the east in some of the remaining outliers of favorable beds, suggesting that the limit of lead deposition may not be far east of the margin of the Driftless Area. The widely spaced deposits south of Mount Horeb, northeast of Monticello, and east and south of Monroe may represent the east limit of mineralization. On the other hand, this limit may be many miles farther east, as suggested by small quantities of sulfides found near Broadhead, and on the east side of the Wisconsin arch near Appleton, Milwaukee, Cambria, and Rio.

The north boundary of the main part of the district lies between the Wisconsin River and Military Ridge, the crest of which is followed by the Chicago and North Western Railroad between Madison and Fennimore, Wis. (pl. 25). Along this boundary the Galena, Decorah, and Platteville beds form a northward-facing cuesta (Grant and Burchard, 1907), north of which they have been partly eroded away. Probably the boundary at one time was many miles north of its present position between Blue Mounds and Highland, because, for about 30 miles to the north, widely scattered lead, copper, and iron (oxidized iron sulfides) deposits are in the partly eroded Lower Ordovician and Cambrian rocks. Examples of such deposits are those near Black Earth, northwest of Ridgeway, along Otter Creek (pl. 25), and north of the Wisconsin River near Orion and Ironton. Similar deposits lie far to the northwest at Mount Sterling, Wis., Lansing and Waukon, Iowa, and Dresbach, Minn., and form a part of the widespread fringe deposits of the district.

Within the main district south of Military Ridge the St. Peter sandstone and Prairie du Chien group crop out in wide belts along the large streams. The principal outcrop areas of these rocks have been mapped by Grant and Burchard (1907) and lie west and south of Mineral Point and near Hollandale, Iowa County, Wis., and north and east of Lancaster, Grant County, Wis. Only a very few ore deposits are known in these outcrop areas.

From Fennimore, Wis., the north boundary of the main district turns toward the southwest, extends through Glenhaven, Wis., and across the Mississippi River into Iowa northwest of Guttenberg, Clayton County. Here is the small Guttenberg mining area. From this point the west boundary extends southward to the Turkey River west of Millville, Iowa, and then southeastward to the cuesta of

Silurian rocks to join the previously described southwest boundary. Between Fennimore and the Silurian cuesta, the boundary appears to coincide with the limits of mineralization beyond which practically no ore was deposited in the favorable Galena, Decorah, and Platteville beds.

The fringe area between the boundaries of the main part of the district and the limit of mineralization is characterized by small, widely spaced lead deposits without zinc. Only one large center of abundant ore deposits, the Beetown area, lies near the limit, and even this area is 6 to 10 miles from the nearest centers of abundant deposits at Cassville and Potosi, Wis.

The deposits at Guttenberg suggest by their mineralogy and other features a very weak type of ore deposition. The mineralogy of the ores is very simple, consisting of thin coatings of pyrite and marcasite on the wall rocks, small galena crystals perched at intervals on the iron sulfide coatings, and a little barite. The rest of the space in the many fractures and cavities in the ore bodies is filled with calcite. Probably the minerals were deposited from weak, low-temperature solutions far from their source, as might be expected of deposits near the limit of mineralization.

DISTRIBUTION OF ORE DEPOSITS WITHIN THE DISTRICT

Within the district are many groups of closely spaced lead and zinc deposits (pl. 25). Two of the groups are designated as subdistricts. The larger subdistrict comprises about 280 square miles and is roughly triangular in shape with Platteville, Wis., its northern point, Shullsburg, Wis., its eastern corner, and Galena, Ill., its southern point. Mines within this area are most numerous between Hazel Green and Shullsburg and near Platteville. Most of the zinc production of the district and a considerable part of the lead production has come from this area.

Northeast of this triangular area is the second large mining subdistrict, which comprises about 215 square miles extending from the southwest corner of Iowa County, Wis., northeastward to Ridgeway, Wis. Here the most important mining areas are Mifflin (mainly zinc), Linden (lead and zinc), Mineral Point (lead, zinc, and copper), and Dodgeville (lead and zinc). Some copper was produced near Mineral Point, Linden, and possibly Highland, Wis.

The boundaries of the two subdistricts are defined chiefly by a decrease in the quantity of ore deposited, but also by erosion of the favorable beds, lack of prospecting, and by beds of Maquoketa shale and Silurian dolomite that cap the principal host rocks. Erosion of the favorable beds cuts off the northern subdistrict northeast of Dodgeville and Highland. There has been little prospecting for either lead or zinc between the northern subdistrict and the small mining area at Montfort. Possibly the southern and northern subdistricts are connected by undiscovered deposits beneath widespread cappings of Maquoketa shale (Grant and Burchard, 1907) and small remnants of Silurian dolomite in the vicinity of Platte Mounds (marked by the patches of Silurian dolomite northeast of Platteville in plate 25). The Potosi mining area west of Platteville may be a westward prong of the southern subdistrict but separated from it by a belt of less abundant deposits and by deep erosion along the Platte River. Prospecting has shown that in places the southern subdistrict extends for miles beneath the Maquoketa and Silurian escarpments to the south and southeast; the Elizabeth and Apple River areas, Illinois, may actually be connected to the subdistrict, at least by lead deposits.

The Guttenberg, Beetown, Sinsinawa, and other small mining areas are probably centers of mineralization surrounded by lands in which there are few or no deposits. However, those at Elizabeth, Warren, and Morseville, Ill., are probably parts of larger mineralized areas exposed in erosional windows in the capping rocks. A few mining areas are situated in erosional outliers of the most favorable strata, as at Highland, Wis., and the Sugar River mine group northeast of Monticello, Green County, Wis. Before erosion of the Galena, Decorah, and Platteville strata, mineralized areas may have connected these deposits with those in adjacent parts of the main district.

The underlying Prairie du Chien rocks are exposed in the deep valleys in the western part of the Highland area (Agnew, Flint, and Allingham, 1953, pl. 3). Here, at the Ohlerking group of mines, the Prairie du Chien is mineralized with lead and iron sulfides (pl. 25, mine no. 55) and forms what may be a mineralized "root" beneath the rich zinc deposits in the partly eroded Galena, Decorah, and Platteville formations. The Demby-Weist mine group (pl. 25, group no. 57) may represent a similar "root" in the Prairie du Chien and Trempealeau strata from which a former overlying mineralized center has now been nearly completely eroded except for one small lead deposit in the Decorah formation west of the main group of mines. Such "root" deposits may mark the location of the channels through which the ore-bearing solutions rose into the overlying rocks.

In the central part of the district the general areas of greatest lead and greatest zinc concentration are nearly identical, although individual gash-vein lead deposits may lie to one side of the pitch-and-flat zinc deposits (fig. 34). Probably this relationship continues nearly to the limits of mineralization. In the western, southern, and eastern parts of the district many areas of gash-vein lead deposits have not been adequately prospected to determine if they are associated with pitch-and-flat zinc deposits. However, in the western part several important pitch-and-flat zinc deposits have been discovered by prospecting in recent years at Tennyson, Wis. (Potosi area in pl. 25), and small deposits are known near Beetown (Heyl, Lyons, and Theiler, 1952); in the eastern part small deposits occur between Waldwick and Blanchardville, Wis. Probably most pitch-and-flat deposits that will be found near the limits of mineralization of the district will be smaller, leaner, and more widely spaced than those in the central part. Copper deposits are restricted to small areas that are scattered from localities near Gratiot, Wis., northwestward through Mineral Point, Linden, and Highland, to Wauzeka and Mount Sterling, north of the Wisconsin River. Many of these are isolated from both the lead and zinc deposits, but near Mineral Point and Highland they are closely associated, and some intermingling of the lead, zinc, and copper ores occurs.

ORE DEPOSITS AND THE MAIN LITHOLOGIC UNITS

Deposits of lead, zinc, copper, and iron sulfides have been found in all the strata of Cambrian, Ordovician, and Silurian age that are exposed in the district. However, all the deposits of lead, zinc, and copper of commercial size occur only in the Prairie du Chien group and the Platteville, Decorah, and Galena formations of Ordovician age. Considerable limonite and hematite, formed by the oxidation of iron sulfides, have been produced from deposits in the sandstones of Cambrian age (Strong, 1882, p. 49–56; Chamberlin, 1882, p. 518–520).

Most of the known deposits in rocks of Cambrian and Early Ordovician age are found in the main outcrop areas of these rocks in the northern fringe of the district. Recent exploratory drilling by the U. S. Geological Survey within the main district has located lean deposits of zinc and iron sulfides in these rocks (Heyl, Lyons, and Agnew, 1951).

The St. Peter sandstone of Middle Ordovician age is locally impregnated with pyrite and traces of galena and sphalerite. None of the deposits is of commercial value. Many known deposits in the St. Peter sandstone are directly below large sulfide deposits in the overlying formations.

Nearly all mineral deposits in the main part of the district are in the Galena, Decorah, and Platteville formations of Middle Ordovician age. The ores are deposited over the same stratigraphic range in these formations both in the northern part of the district where the formations are largely eroded, and in the southern part where the beds are buried beneath the Maquoketa shale and Silurian dolomite.

The Maquoketa shale is only locally mineralized. Small quantities of galena, sphalerate, and barite were found at the Glanville prospect (pl. 25, no. 5) near Scales Mound, Ill.

The few localities where the Silurian rocks are known to contain small deposits of lead or iron sulfides are in Iowa, far to the southwest of the main part of the district. Only a very few tons of ore were produced from any of these deposits.

ORE DEPOSITS AND THE MAJOR FOLDS

The locations of the ore deposits appear to be controlled in a general way by the major folds of the district (pl. 25), particularly in the northern half. Parts of the highly mineralized areas of the district are within, and trend parallel to, the axes of the large synclines. For example, the Crow Branch deposit (pl. 25, no. 50), southwest of Livingston, Wis., is near and parallel to the axis of a large syncline. Also along this syncline are the Coker mine group (pl. 25, no. 45), the Linden area (pl. 25, no. 48), and the Dodgeville area (pl. 25, no. 53), all highly mineralized. Similarly, several deposits are in the large syncline that extends from Potosi, Wis., eastward through Platteville and Calamine. The relationship between mineralized areas and major synclines is particularly apparent from Beetown to Lancaster, Wis. Few of the large and important ore deposits are near the crests of the principal anticlines.

In the southern part of the district most of the principal mining areas lie on the gently dipping south limb of the large anticline extending eastward from Sherrill, Iowa, through Jamestown and Cuba City, Wis. The mines near Dubuque, Iowa, Sinsinawa, Wis., and between Hazel Green and Shullsburg, Wis., are on this structure (Agnew, Heyl, Behre, and Lyons, 1948). The Hazel Green-Shullsburg area, the most concentrated mining center in the district, lies south of and is partly enclosed by a marked northward bow of the axis of the large anticline. An extension of this area to the southwest into Iowa along the Tete des Morts River follows, in part, a southwestward-trending syncline which passes through Galena, Ill. (Willman and Reynolds, 1947).

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